CHAPTER 37

SEAWEEDS AS FUTURE BIO RESOURCES FOR HIGH-VALUE INDUSTRIAL PRODUCT: BIOFUELS, AND BIO- STIMULANTS

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ABSTRACT

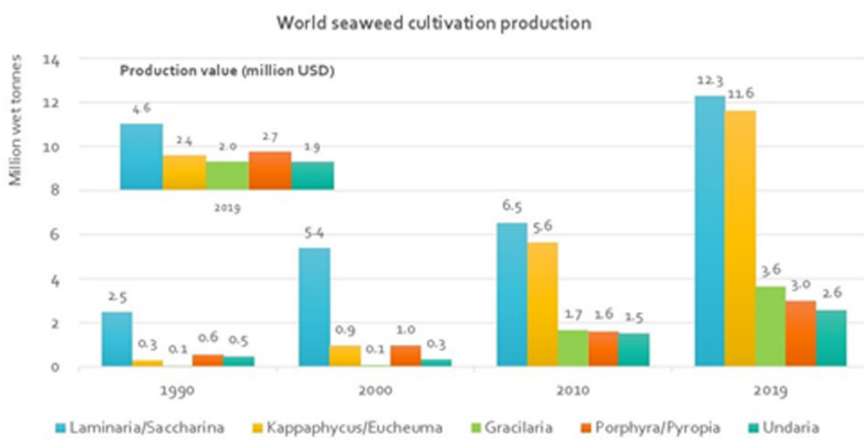
In the pursuit of sustainable and renewable resources, seaweeds have become a central focus of exploration. Classified into brown, red, and green categories based on pigmentation, these marine macroalgae exhibit distinctive morphological, ecological, and biochemical characteristics that render them promising sources for high-value industrial products. This chapter explores the varied applications of seaweeds, with a particular emphasis on their potential as biofuel and bio stimulant sources. Found abundantly in oceans globally, seaweeds undergo harvesting through diverse methods, ranging from traditional hand collection to advanced aquaculture techniques. The adoption of sustainable harvesting practices is imperative to uphold the intricate balance between extraction and regeneration, thereby preserving the health of marine ecosystems. The environmental repercussions of seaweed harvesting are a critical consideration, emphasizing the necessity for meticulous management to avert overharvesting and ecological imbalances. This chapter aims to provide insights into the diverse roles seaweeds can play in addressing global challenges related to high-value industrial products like biofuels and bio stimulants.

Keywords: Seaweeds, Biofuels, Agar, Phycocolloids, Biodiesel, Sulfated polysaccharide

INTRODUCTION

Seaweeds are macroscopic, photosynthetic plant-like organisms that occurring in tidal regions of seas and they are natural renewable resources. Seaweedsbelongs to three broad groups based on their predominant pigmentation: *Phaeophyta* (brown algae), *Rhodophyta* (red algae) and *Chlorophyta* (green algae). Most brown and red seaweeds are strictly marine and the green seaweeds are mainly found in freshwater environments (FAO, 2021). There are several types of polysaccharides found in seaweeds, including agar, algin, carrageenan, etc., that are valued commercially, as well as several bioactive metabolites also found in seaweeds. They have a variety of commercial applications in food, pharmaceutical, cosmetics and mining industry. According to McHugh (2003) about 33 genera of seaweeds are farmed worldwide, primarily, red seaweed and brown seaweed. Majority of the harvest used for direct consumption of human being (West et al., 2016). Around 20 per cent of the harvest is used as a source of the phycocolloids extracted for use in the food, industrial, cosmetic, and medical industry (Browdy et al., 2012, Mouritsen, 2013).

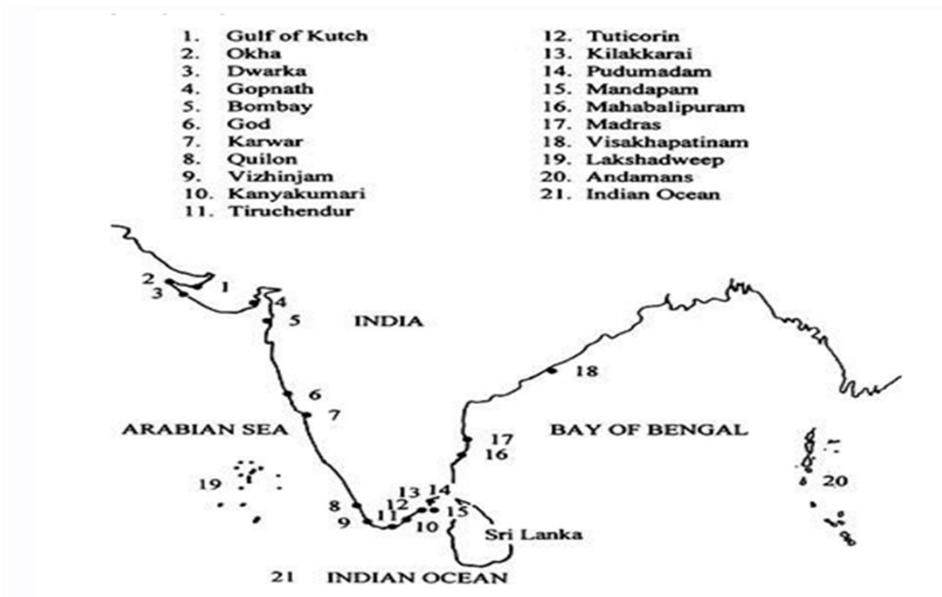
As of 2019, world seaweed cultivation has increased from 4.2 million tonnes to 34.7million tonnes. The growth was largely due to brown seaweed cultivation (from 3.1million tonnes to 16.4 million tonnes) and red seaweed cultivation (from 1 million tonnesto 18.3 million tonnes) during the period of 1990 to 2019 (Junning and Giulia, 2021). Five major species groups contributed over 95 percent of world seaweed cultivationproduction in 2019 and they are Laminaria / Saccharina (35.4 percent); *Kappaphycus /Eucheuma* (33.5 percent); *Gracilaria* (10.5 percent); Porphyra / Pyropia (8.6 percent); and *Undaria* (7.4 percent) (Zhang et al., 2022).



Global seaweed cultivation

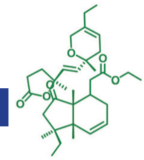
(Adapted from: FAO global fishery and aquaculture production statistics, FishStat, March 2021)

Globally, the cultivation of seaweeds is witnessing a surge, particularly in countries like China, Japan, and South Korea, where large-scale seaweed farming initiatives are underway for applications in food, pharmaceuticals, and biofuel production. In India, seaweed cultivation is gaining momentum as a potential economic opportunity, backed by government initiatives and research collaborations. The major locations of occurrence of seaweeds along the Indian coast is depicted. While challenges such as awareness, infrastructure, and policy support are being addressed to foster the growth of the seaweed industry, the potential economic and environmental benefits are substantial. Seaweeds, with their unique ability to be cultivated in marine environments without competing for arable land, are emerging as promising feedstocks for biofuel production. Various seaweed species, each with distinct biochemical compositions, are being studied for their potential in different biofuel production processes, including bioethanol, biodiesel, biogas, and hydrogen.



Major locations of occurrence of seaweeds along the Indian coast
(Source: Rao et al., 2018)

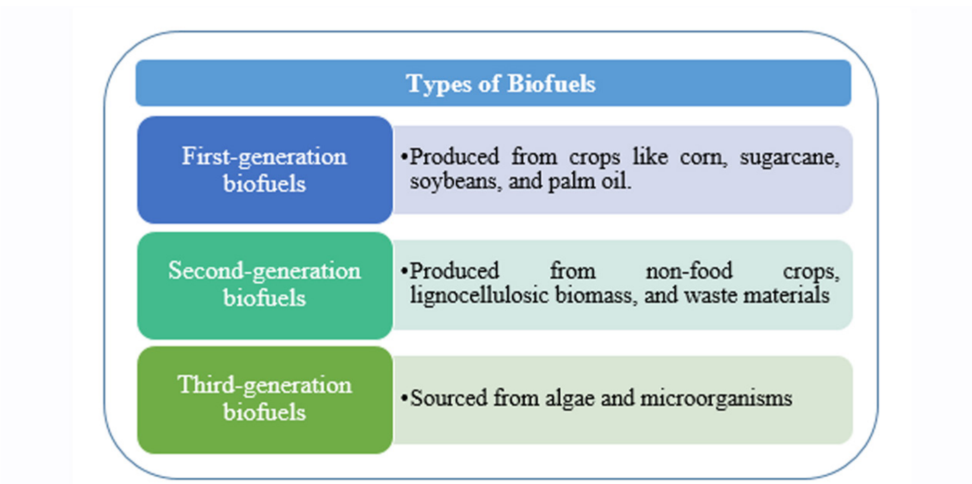
Furthermore, the exploration extends to the field of biostimulants, where seaweeds play a significant role. Biostimulants derived from seaweeds are recognized for their rich composition of bioactive compounds, offering advantages such as enhanced nutrient uptake, stress tolerance, and improved plant growth. The global demand for biostimulants is on the rise, driven by the requisite for sustainable agricultural practices. Major seaweeds utilized for biostimulant production, including *Ascophyllum nodosum*, *Fucus* spp., *Sargassum spp., Ulva spp.,* and *Gracilaria spp*., contribute unique blends of beneficial substances. As the world navigates the complex landscape of bioresources, understanding the variations in harvesting, cultivation practices, and the potential applications of seaweeds becomes imperative for their sustainable and responsible utilization.



BIOFUELS FROM SEAWEEDS

In the contemporary global context, biofuels have gained prominence as a response to escalating concerns surrounding climate change, energy security, and the imperative to mitigate greenhouse gas emissions. These renewable energy sources are derived from organic materials, including crops, agricultural residues, and waste, representing a diverse range of solutions for sustainable energy production.

The biofuel market is categorized into distinct generations as first, second and third generation biofuels (Fig. 3). Third-generation biofuels, sourced from algae and microorganisms, represent a promising avenue for efficiency, reduced land use, and minimized environmental impacts, marking an ongoing evolution toward more sophisticated and sustainable alternatives.



Classification of biofuel generations

PRODUCTION OF BIOFUELS FROM SEAWEEDS

The major steps involved in the production of biofuels from seaweeds are as follows:

Algae production (seeds, production lines, seaweed cultivation) or natural resources

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Harvest (such as post-harvest cleaning, size reduction), storage and preservation

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Activity (biochemical, chemical and thermochemical transformation of algal biomass)

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Processing (biochemical, chemical, and thermochemical conversion of algal biomass)

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Production (biogas, syngas, bioethanol, biodiesel, bio-oil, electricity)

The initial drying stage of macroalgae determines the choice of the proper conversion technology either thermochemical (dry) or microbiological (wet). Direct combustion, pyrolysis, gasification, and transesterification to biodiesel require dry macroalgae, while wet algae biomass can be subjected to hydrothermal processing, fermentation to bioethanol, and anaerobic digestion. Biomass is subjected to preliminary processes such as removal of impurities (rock, sand, etc.), shredding of seaweed to reduce particle size and increase surface area, the dehydration/drying process depends on the wet or dry transformation process. Drying of seaweed should be done by rolling it occasionally in the shade. It will protect bioactive compounds from degradation.

Seaweed drying is a laborious and expensive process. Therefore, the option of wet storage and storage of seaweed is recommended. Silage is a method of storing crops that relies on lactic acid bacteria to convert water-soluble carbohydrates into organic acids (such as lactic acid) under anaerobic conditions. The decrease in pH of silage biomass inhibits the growth of harmful bacteria.

BIOETHANOL

The main steps in bioethanol production from seaweed include pre-treatment (e.g. removal of foreign matter and debris such as stones, sand, snails, or other waste generated during cleaning, chopping or grinding), biomass pre-treatment and hydrolysis of algae, Saccharification (enzymatic/ acid hydrolysis) of polysaccharides (releasing locked sugars in the process of polysaccharides), fermentation (using selected strains of yeast and bacteria), distillation and dehydration. Factors affecting production are many non-acid hydrolysis (e.g. amount of acid (as catalyst) and concentration, hydrolysis temperature and duration) and fermentation (e.g. inoculum concentration, culture medium pH, fermentation time). Fermentation can also be used to produce acetone and butanol using the bacteria *Clostridium acetobutylicum* and *Clostridium beijerinckii* (Van der Wal et al., 2013).

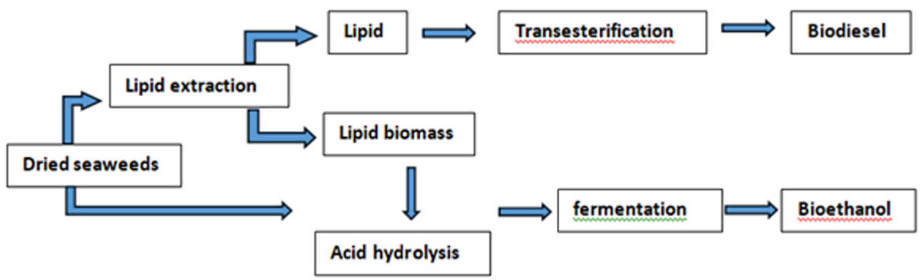
BIODIESEL

Biodiesel serves as an alternative fuel, sharing similarities with traditional fossil diesel. It can be derived from vegetable oils or animal fats, possessing properties similar to those found in petroleum diesel fuels. For the extraction of oil from seaweed biomass two type of methods are mainly used;

1. Mechanical method - Using pressers or expellers

2. Solvent extraction- using suitable solvents (chloroform, hexane, cyclohexane, acetone, and benzene etc.)

Factors affecting extraction include moisture content of algae, appropriate solvent selection, biomass/weight ratio, extraction time, temperature and mixing speed. The processes involved in bioethanol and biodiesel production is given in Fig. 4.



Process of sequential biodiesel and bioethanol production

New extraction methods such as supercritical carbon dioxide extraction and thermochemical liquefaction are also now used. In case of supercritical fluid extraction, dry materials should be used, while in thermochemical liquefaction, wet materials can be used. Using CO_2 for supercritical fluid extraction has advantages because CO_2 is considered "green", is non-toxic, non-corrosive, non-flammable and can be easily separated from the extract and is inert to the product. Microwave-assisted extraction, ultrasonic-assisted extraction, enzyme-assisted extraction, and pressurized liquid extraction can also be used to extract lipids from algae. The choice of extraction machines should be determined by cost, safety, environmental friendliness and efficiency of mass production. Extraction and purification of lipids from algae in biodiesel production is currently not a problem, resulting in high prices and high energy. The advantages and limitations of biofuels from seaweeds is listed in Table 2.

Table 2. Advantages and limitationsof Biofuels from Seaweeds

Advantages	Limitations
1. Rapid Growth and High Biomass Yield	1. Seasonal Variability and Harvesting Challenges

Seaweeds exhibit rapid growth rates, with some species doubling biomass within a few days.	Seaweed growth is subject to seasonal changes, impacting biomass availability.
2. Minimal Land and Freshwater Requirements	**2. Cultivation Costs**
Seaweeds are cultivated in aquatic environments, minimizing competition for land and water.	Initial investment and operational costs for seaweed cultivation can be relatively high.
3. Carbon Neutrality	**3. Technology Development and Scale-Up**
CO_2 released during combustion is roughly equivalent to CO_2 absorbed during seaweed growth.	Many seaweed biofuel technologies are in the developmental stage, scaling up poses challenges.
4. Biochemical Composition	4. Resource Competition with Other Marine Uses
Seaweeds have a diverse composition allowing for various biofuels (biogas, bio-oil, syngas).	Seaweed cultivation may compete with other marine activities, affecting ecosystems.
5. Low Impact on Food Production	5. Variable Biochemical Composition
Cultivation in non-agricultural areas minimizes the impact on food production.	Biochemical composition varies based on species, location, and cultivation conditions.
6. Nutrient Uptake and Environmental Benefits	**6. Energy Intensity of Conversion Technologies**
Seaweeds absorb nutrients, potentially mitigating issues like eutrophication.	Some conversion technologies (e.g., hydrothermal liquefaction) can be energy-intensive.
7. Versatility in Conversion Technologies	**7. Infrastructure and Market Challenges**
Seaweeds can be converted into various biofuels using anaerobic digestion, HTL, pyrolysis.	Establishing infrastructure for cultivation, processing, and distribution may be challenging.

BIOGAS

Seaweeds can be used for the production of biogas (CH_4, CO_2, O_2, H_2 and H_2S) as these grow rapidly. Marine life is rich in stored carbohydrates that are easily digested). It has also been reported that using macroalgae to produce biogas is technically more suitable than other biofuels. Methane can be produced through thermal gasification and bio gasification (called anaerobic digestion). *Bio gasification* is often chosen for processing high moisture biomass. Wet algal biomass can also be used to produce methane in a process called "catalytic supercritical water gasification" using supercritical water (40^{0}C, ~30 MPa) to exceed 2 wt% for 60 min.

Most anaerobic digesters are used to produce biogas using biomass, freshwater substrate and microbial seeds. Anaerobic digestion of seaweed is a complex process that involves the interaction of many organisms and consists of four stages: hydrolysis, acidogenesis, acetogenesis and methanogenesis. Since high salinity inhibits methane production from anaerobic digestion (collection of sodium and potassium cations) in the digester, natural seaweed must be washed with tap water before biogas production. Washing will help remove chlorine and sodium. Various physical (e.g. mechanical, thermal), chemical (e.g. alkaline, acidic), biological (e.g. microbial, enzymatic digestion) methods differ in single and combined methods to improve methane production from seaweed biomass.

BIO STIMULANTS FROM SEAWEEDS

Natural biological ingredients offer an alternative to chemotherapy and synthetic drugs currently used to treat global health problems such as cancer, diabetes, bloating and heartburn. Seaweeds are rich sources of bioactive compounds, and their extracts are commonly used in the production of bio stimulants. Bioactive components include polysaccharides, unsaturated fatty acids, phenols, peptides, terpenoids and other compounds with unique structures and properties, possessing antioxidant, antiviral, anticoagulant, antibacterial and anti-tumour properties. These metabolites are commonly found in red seaweed, brown seaweed, and green seaweed.

The global demand for bio stimulants is on the rise, propelled by increasing awareness among farmers about their benefits in enhancing plant growth, nutrient uptake, and stress tolerance. This surge is driven by the imperative for sustainable agricultural practices amid a growing global population. Regulatory support in various regions, advocating for bio-based and environmentally friendly agricultural inputs like bio stimulants, further contributes to the market potential. These versatile products find use in diverse crops, including cereals, fruits, vegetables, row crops, and ornamentals, fostering improved yield and quality. Regional trends indicate Europe as a leading market, with Spain and Italy playing significant roles, while North America and Asia-Pacific are also witnessing growth due to an increased emphasis on sustainable agriculture.

MAJOR SEAWEEDS USED FOR PRODUCTION OF BIO STIMULANTS

Different types of seaweeds provide unique compositions of beneficial substances, and some of the major seaweeds used for the production of bio stimulants include:

RED SEAWEED

Mostly red seaweed grows in the deep sea, being the largest marine macroalgae and has many biological effects. Its bioactive properties include immune regulation, anti-inflammatory, anti-proliferative, anti-cancer, anti-aging, and alleviating allergy symptoms. The major group of red seaweeds, bio stimulants and their mode of action is summarized in Table 3.

Table 3 Major bio stimulants from red algae and their mode of action

Compound	Algae source	Activity	Mechanism of action	Reference
Polysac-charide	*Gracilaria lemaneiformis*	Anti-aging	Via the insulin pathway	Wang et al., 2019
	charide	Anti-inflammatory	Inflammatory responses were reduced by decreasing levels of TNF-α, IL-6, and IL-1β in the colon and MPO activity	Han et al., 2020
Carrageenan	*Gigartina pistillata*	Antitumour	Identified the area and structure of tumour spheres and viability were evaluated	Cotas et al., 2020
	Laurencia papillosa	Anti-proliferative	The inhibition of proliferating cells was monitored	Jazzara et al., 2016
Agar	Red seaweed	Anti-colon cancer	Induces proliferation and apoptosis, inhibition of human colon cancer cells	Yun et al., 2021
	Gelidium amansii	Anti-inflammatory	Increasing the production of levels of lipolysis proteins and anti-inflammatory cytokines	Lee et al., 2018

<table>
<tr><td rowspan="7">Spiro-compounds

Sulfated pyruvylated polysaccharide

Highly oxygenated antioxidative 2H-chromen derivative

Cyclooxygenase-2 and 5-lipoxygenase inhibitory halogen derivatives

Oxygenated merote rpenoids

Drimanes

Abeo-oleanenes</td><td>Gracilaria salicornia</td><td>Anti-inflammatory</td><td>Attenuate 5- lipoxygenase and cyclooxygenase-2.</td><td>Chakraborty and Antony, 2021</td></tr>
<tr><td>Hydropuntia edulis</td><td>Anti-hyperglycemic</td><td>Regulates glucose metabolism by degrading incretins</td><td>Thambi and Chakraborty, 2022</td></tr>
<tr><td>Gracilaria opuntia</td><td>Anti-inflammatory</td><td>Inhibits cyclooxygenase and lipoxygenase</td><td>Chakraborty and Makkar, 2018.</td></tr>
<tr><td>Kappaphycus alvarezii</td><td>Antioxidative</td><td>High free radical scavenging potential.</td><td>Makkar and Chakraborty, 2018.</td></tr>
<tr><td>Kappaphycus alvarezii</td><td>Antioxidant and anti-inflammatory</td><td></td><td>Chakraborty and Makkar, 2018</td></tr>
<tr><td>Gracilaria salicornia</td><td>Anti-inflammatory</td><td>Attenuates 5-lipoxygenase</td><td>Chakraborty et al., 2019</td></tr>
<tr><td>Gracilaria salicornia</td><td>Antioxidant,
Anti hyperglycemic</td><td>Inhibitors of starch digestive enzymes</td><td>Chakraborty and Antony, 2019
Chakraborty, Kajal and Antony, Tima (2019) First report of antioxidative abeo-oleanenes from red seaweed Gracilaria salicornia as dual inhibitors of starch digestive enzymes. Medicinal Chemistry Research, 28 (5). pp. 696-710.</td></tr>
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BROWN SEAWEEDS

Brown Algae are multicellular algae found in cold coastal waters. The major species of brown seaweeds include *Laminaria digitalata, Sargassum, Ascophylla nodosa, Undaria pinnata*, and Kelp (Li et al. 2021). The bio compounds from brown seaweeds possessanti-inflammatory, anti-hyperlipidemic, anti-tumour and antioxidant activities. The Table 4 shows the bioactive compounds of brown algae and their main activities.

Table 4 : Bioactive compounds from brown algae and their main activities.

Compound	Algae source	Activity	Mechanism of action	Reference
Polysaccharide	*Sargassum fusiforme*	Immune regulation	Enhance immunity via CD14/ IKK/NF-κB and P38/NF-κB signalling pathways	Chen et al., 2018
	Laminaria japonica	Anti-hyperlipidemia	Regulate mRNA transcription and protein expression levels associated with liver lipid metabolism	Lee et al., 2022
Sulfated polysaccharide	*Sargassum henslowianum C. Agardh,* *Fucus vesiculosus*	Antitumor	Inhibiting proliferation and apoptosis of melanoma cells	Ale et al., 2011
	Sargassum cristaefolium	Anti-inflammatory	Inhibit the expression of inducible nitric oxide synthase by inhibition of phosphorylation of P-38, ERK and JNK signaling proteins	Wu et al., 2016
Dolabellanes and dolastanes from dual	*Padina tetrastro-matica*	Antioxidative, anti-diabetic	inhibitors of starch digestive enzymes	Antony et al., 2021
Sulfated galactofucan (TCP-3) Sulfated galactofucan	*Turbinaria conoides*	Immunomodu-latory potential	Attenuated inflammatory cyto-kines and chemokines	Dhara, and Chakraborty, 2023
	Padina tetrastro-matica	Anti-hyperglycemic	Potential inhibitory properties against carbolytic enzymes α-amylase and α-glucosidase	Antony et al., 2022

Sulfated polygalactofucan	*Turbinaria decurrens*	Anti-inflammatory	Attenuates inflammatory cytokines on THP-1 human monocytic macrophages.	Chakraborty et al, 2023
Alginate	*Laminaria japonica*	Antiallergic	Mast cell degranulation inhibition in the jejunum and maintaining T cell balance	Yu et al., 2020
	Brown seaweed	Anti-inflammatory, antioxidant	Inhibiting TGFβ1/p-Smad2 signaling pathway	Feng et al., 2020
Fucoidan	*Fucus vesiculosus*	Anti-inflammatory	Inhibiting NF-κB, MAPK and Akt activation	Park et al., 2011
	Sargassum wightii	Antioxidant, anticancer	Evaluated antioxidant properties of Fucoidan rich seaweed extract	Sajina et al., 2019
Spirornatas A-C	*Turbinaria ornata*	Anti-hypertensive	Attenuate angiotensin-I converting enzyme	Chakraborty and Dhara, 2021
Polygalacto-fucopyranose	*Sargassum wightii*	Antihypertensive		Surabhi et al., 2021
Furanyl-Substituted Isochromanyl Class of Turbinoch romanone	*Turbinaria conoides*	Anti-Inflammatory	5-lipoxygenase and cyclooxygenase-2 inhibitor	Dhara and Chakraborty, 202)
Xenicanes	*Padina tetrastromatica*	Anti-inflammatory	Attenuate pro-inflammatory 5-lipoxygenase	Antony and Chakraborty, 2019
Xenicane-type diterpenoid	*Sargassum ilicifolium*	Anti-inflammatory	Attenuate pro-inflammatory 5-lipoxygenase	Dhara and Chakraborty, 2020

GREEN SEAWEED

There are more than 6700 species of green algae in the world, most of which are found in freshwater. It is praised as the best food of the 21st century by the Food and Agriculture Organization of the United Nations because it contains high protein, low fat, sugar-free and low cholesterol. They have a variety of activities, including antihyperuricemic, hypoglycaemic, anti-ageing, anticoagulant, antiviral, and anti-inflammatory. A summary of bioactive components of green seaweed and their key bioactivities is given in Table 5.

Table 5. Bioactive components of green seaweed and their main bioactivities

Compound	Algae source	Activity	Mechanism of action	Reference
Polysaccharide	*Ulva lactuca*	Antihyperuricemic	Regulating urate transporters	Li et al., 2021
	Ulva lactuca	Hypoglycaemic, anti-ageing	By regulating the expression levels of GLP-1/GLP-1R, GLUT4 etc and improve diabetes status and the aging	Chen et al., 2022
Sulphated Polysaccharide	*Monostroma angicava*	Anticoagulant	Analyse thrombin inhibitor	Li et al., 2017
	Monostroma nitidum	Antiviral	Targeting the PI3K/Akt pathway and inhibited Viral infection	Wang et al., 2020
Carotenoid	*Codium cylindricum*	Antioxidative	Restoring the antioxidant signal regulated by Nrf2 and protect the body stress caused by obesity	Zheng et al., 2020
Organic extracts	*Ulva lactuca, Halimeda macroloba*	Antimicrobial activity	Extracts of *U. lactuca* and *H. macrobola* showed antimicrobial activities against Vibrio parahaemolyticus	Elizabeth et al., 2021

EXTRACTION OF BIOACTIVE COMPONENTS

Research on the extraction of bioactive components from natural sources has attracted attention in recent years. Research has shown that many compounds have many biological properties and potential uses. Therefore, instead of choosing the extraction process, which is time-consuming, less selective, ineffective and dangerous for human health, new ways must be found to increase the benefits of algae extraction. Seaweed bio stimulants are typically obtained through extraction processes involving water or solvents. Technologies such as microwave-assisted extraction (MAE), ultrasonic-assisted extraction (BAE), and supercritical fluid. extraction (SFE), pressurized solvent extraction (PSE), and enzyme-assisted extraction (EAE) are also utilized (Table 6). The advantages and limitations of seaweed based bio stimulants is listed in Table 7.

Table 6. Technologies used for the extraction of bioactive compounds

Technology	Advantage	Shortage	Species	Reference
Solid phase microextraction	Simple and fast operation; Solvent-free sampling technique; Low sample demand; Widely used analyses for volatile compounds	Insensitive to low volatile substances	Green, brown, and red algae	Alonso et al., 2003
Microwave-assisted extraction	Less solvent use; short extraction time; high extraction rate and low cost	Energy is needed to provide radiant power; Sensitive to heat and pressure; to remove solids or unwanted materials from the solvent, additional separation processes are required	Brown seaweeds	Delazar et al., 2012; Michalak & Chojnacka, 2014

Ultrasound-assisted extraction	Faster; Easier to operate; Mass production; Energy saving and environmental protection; Good solubilizing effect	Influence of solid liquid ratio and used for heat resistant compounds	Brown alga *Sargassum*	Chandrapalaet al.,2013; Surin et al., 2020
Supercritical fluid extraction	Widely available, environmental protection, time-saving, non-flammable,	The machine is difficult to clean; high cost; Polar compounds are not applicable; The extraction range of compounds is small	Brown algae *Fucus vesiculosus; Nannochloropsis* sp.; marine algae *Fucus vesiculosus; Laminaria*	Dmytryk et al., 2018
Enzyme-assisted extraction	High catalytic efficiency; Biocompatibility, environmental protection; non-toxic; Retain the properties of the compound	High temperature and Long time needed, low extraction efficiency	*Nordic* seaweeds; *Scenedesmus* sp. brown macroalgae	Marathe et al., 2017; Nguyen et al., 2020

Table 7: Advantages and limitations of seaweed based bio stimulants

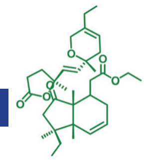
Advantages of Seaweed bio stimulants	
Rich in bioactive compounds	Seaweeds are rich sources of bioactive compounds, including plant growth regulators, amino acids, vitamins, minerals, and polysaccharides. These compounds contribute to the overall health and growth of plants.
Enhanced nutrient uptake	Seaweed bio stimulants can improve the absorption of nutrients by plants. They contain compounds that enhance the activity of nutrient transporters in plant roots, leading to increased nutrient uptake.

Stress tolerance	Seaweed extracts help plants cope with various environmental stresses, such as drought, salinity, and temperature extremes. The bioactive compounds in seaweeds can activate stress response mechanisms in plants, improving their resilience.
Improved Soil Structure	The application of seaweed bio stimulants can positively impact soil structure. They contribute to the formation of stable aggregates, which enhances water retention, aeration, and nutrient availability in the soil.
Environmental Sustainability	Seaweeds are a renewable resource that can be harvested without causing harm to ecosystems when done sustainably. The use of seaweed bio stimulants aligns with environmentally friendly agricultural practices.
Compatibility with Organic Farming	Seaweed bio stimulants are often used in organic farming due to their natural origin and low environmental impact. They offer a sustainable alternative to synthetic fertilizers and chemicals.
Promotion of Beneficial Microorganisms	Seaweed extracts can stimulate the growth and activity of beneficial soil microorganisms, including *mycorrhizal* fungi and nitrogen-fixing bacteria. This enhances nutrient cycling and improves soil health.
Increased Crop Yields and Quality	Application of seaweed bio stimulants has been associated with improved crop yields, as well as enhanced quality parameters such as fruit size, colour, and nutritional content.
Limitations of Seaweed Bio stimulants	
Variable Composition	The composition of seaweed bio stimulants can vary based on factors such as seaweed species, geographical location, harvesting time, and extraction methods. This variability may lead to inconsistent effects on plants.
Regulatory Challenges	The regulatory framework for bio stimulants can be complex and varies between regions. Standardizing regulations and ensuring proper labelling can be challenging for the seaweed bio stimulant industry.

Cost of Production	The production of high-quality seaweed bio stimulants can involve complex extraction processes and quality control measures, which may contribute to higher production costs.
Residue Concerns	Some seaweed bio stimulants produced using solvent extraction methods may contain residual solvents. Ensuring that these residues meet regulatory standards is essential for product safety.
Limited Understanding of Mechanisms	While the positive effects of seaweed bio stimulants are evident, there is still ongoing research to fully understand the mechanisms behind their action, including interactions with plant physiology and soil microbiota.
Application Timing and Frequency	The effectiveness of seaweed bio stimulants may be influenced by the timing and frequency of application. Determining the optimal application conditions can be a complex task and may vary across different crops and environments.
Storage Stability	Some formulations of seaweed bio stimulants may have limited shelf life or stability, especially in liquid forms. Proper storage conditions are crucial to maintain their efficacy.
Interaction with Other Inputs	The interaction of seaweed bio stimulants with other agricultural inputs, such as fertilizers and pesticides, requires careful consideration to avoid negative synergies or interference.

CONCLUSION

Seaweeds stand as a promising solution to the increasing demand for sustainable resources globally. This chapter explored their applications in biofuels and bio stimulants, showcasing the diverse potential of these marine organisms. With distinct types categorized as brown, red, and green, seaweeds bring unique qualities to the forefront. Sustainable harvesting practices are crucial, and countries like China and Japan have successfully turned seaweed cultivation into thriving industries, with India also recognizing its potential. In the realm of biofuels, seaweeds excel in rapid growth, high yield, and marine adaptability, making species like Saccharina and Ulva promising candidates for bioethanol, biodiesel, and biogas production. Seaweed bio stimulants offer a green approach to agriculture, enhancing nutrient absorption and stress tolerance, with species like *Ascophyllum nodosum* and *Fucus* spp. providing



valuable bioactive compounds. Despite challenges in variable composition, regulations, and production costs, ongoing research positions seaweeds as valuable bioresources, poised to contribute significantly to a greener and more sustainable future across diverse industries.

SUGGESTED READINGS

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