International Journal of Science and Research Archive
eISSN: 2582-8185
Cross Ref DOI: 10.30574/ijsra
Journal homepage: https://ijsra.net/

(Research Article)

Sargassum as a Renewable Marine Resource: Ecological Role and Potential Applications in the Red Sea Region

Kauser Perveen *

Department of Biology, Faculty of Science, Jazan University, Jazan, Kingdom of Saudi Arabia.

International Journal of Science and Research Archive, 2026, 18(02), 071-084

Publication history: Received on 21 December 2025; revised on 28 January 2026; accepted on 31 January 2026

Article DOI: https://doi.org/10.30574/ijsra.2026.18.2.0180

Abstract

Widespread and quick reliance on fossil fuels results from the world's population expansion, which raises energy demands. But these resources continue to run out every day, and their use is contributing to global warming problems that require attention. We look for sustainable, eco-friendly, economical, and efficient biofuels with lower greenhouse gas emissions in order to fulfill such energy demands and safeguard the environment.

Macroalgae, or green, brown, and red sea seaweed, are becoming recognized as a viable and potential alternative energy source for the production of biofuels. The potential of macroalgae to produce a variety of bioproducts, including biofuels, has been the subject of several studies. The presence of compounds like lipids and carbohydrates make macroalgae an ideal raw material for the production of biofuels. Biofuels, such as bioethanol and biodiesel, account for over 40% of the total amount of energy consumed worldwide. A sustainable fuel, bioethanol is made from the biomass of algae, sugar, starch, and lignocellulosic materials. This study provides a brief discussion of potential *Sargassum* species that facilitate the production of biofuel and their cultivation methods in the Red Sea Region. It also shows the effectiveness of the biofuel generating process and the latest methods for increasing product output.

Keywords: Macroalgae; *Sargassum;* Economical importance; Biofuel; Bioethanol

1. Introduction

Numerous bioactive substances may be found in both terrestrial and marine natural resources. These chemicals have many medicinal, therapeutic, and other industrial uses which drawn the interest of several researchers today. Analytical science pays close attention to the extraction, purification and identification of the characteristics and physical descriptions of natural chemicals because of their significant health impacts. Cultivating medicinal plants for testing is an essential first step in producing high-quality research results (Ali Rajabiyan, 2025).

Marine creatures are prospective sources of innovative medicinal substances because a variety of compounds having pharmacological action are produced by them, such as anticancer, antibacterial, antifungal, antiviral, and anti-inflammatory properties. In a harsh and competitive environment, marine species thrive and coexist in intricate communities. Some of these substances are antimicrobials, which prevent or restrict the growth and development of other competing microbes (Perez, 2016).

Algae are a vast and varied collection of microorganisms that are capable of performing photosynthesis as they absorb energy from sunlight. In agriculture algae are utilized as soil stabilizers and bio fertilizers. When algae, especially seaweeds, are employed as fertilizers, less nitrogen and phosphorus runoff is produced than when cattle dung is used. As a result, the water entering rivers and seas is of higher quality. These organisms are grown all over the world and added to human diets (Sanjita Gurau, 2025) .

* Corresponding author: Kauser Perveen

Algae can be classified as macroalgae and microalgae due to their genetic diversity. Proteins, fibers, vitamins, lipids, minerals, and other elements necessary for human nutrition are found in macroalgae, sometimes referred to as seaweed. Compared to terrestrial plants, these macroalgae can develop more quickly and independently of land areas (A. Nagababu, 2022).

Like terrestrial species, seaweeds have important ecological functions in maintaining aquatic ecosystems by acting as biological indicators of water and participating in the processes of bioremediation and biomass buildup (Anh Quynh Nguyen, 2025). Seaweeds not only support marine ecosystems but also produce almost 80% of the oxygen in the atmosphere, which terrestrial creatures utilize for respiration (Dipankar Ghosh, 2022).

In many nations, macroalgae have become a substitute food and medicinal source. The world's top producers of seaweed are China, the Republic of the Philippines, and Indonesian (Aline Frumi Camargo, 2025).

2. Macroalgae, Brief Review

Macroalgae are a diversified collection of multicellular sea organisms that have been traditionally used and cultivated in many parts of the world for a long time. Although macroalgae are abundant in polysaccharides, various kinds of macroalgae usually have varied types and concentrations of carbohydrates (Sanjay Kumar Joshi, 2022). Based on their photosynthetic colors, they are divided into three main phyla: Ochrophyta (brown algae), Chlorophyta (green algae), and Rhodophyta (red algae). Everyone from these phyla has distinct characteristics and bioactive substances. Phycobiliproteins, phycolectins, mycosporine, pigments, polyunsaturated fatty acids, polysaccharides, carbohydrates, minerals, and vitamins are all abundant in red algae. While brown algae have a high phlorotannin concentration, red and green algae are rich in the compounds bromophenols, phenolic acid, and flavonoids (Sivakumar Adarshan, 2024) .

A nutraceutical is a chemical that can either prevent certain chronic illnesses or have biological benefits. This may be used to enhance the body's metabolism, prolong life, prevent senility, or improve health. Macroalgae are essential because of their size, which increases the surface area available for better biosorption of dangerous substances regardless of low concentrations (Ty Shitanaka, 2025).

In the maritime environment, seaweeds constitute a significant source of high-quality proteins, which are crucial for nutraceutical compositions. Macroalgae include many types of amino acids, such as threonine glutamic acids like arginine, and aspartic acid. These creatures also include macronutrients including phlorotannin, catechol, and quercetin, as well as micronutrients like manganese, copper, cadmium, zinc, and lead (Ana C. Freitas, 2012).

Table 1 Nutrient concentrations macroalgae species

Macroalgal species	Weight/g	C%	N%	Zn%	K g/Kg	P g/Kg
Macrocystis pyrifera	4.2	38.93	7.34	4.15	1.630	4.193
Sargassum sp.	4.2	29.48	5.82	2.65	1.373	12.468
Ulva lactuca	4.2	31.31	5.76	2.53	1.582	6.631
Saccharina latissima	3.1	31.68	4.24	2.83	1.383	6.042
Ascophyllum nodosum	4.2	29.22	6.93	2.72	1.739	6.185
Palmaria palmata	3.1	32.29	4.88	1.98	1.566	3.87

Seaweeds, particularly brown algae, contain over seven hundred biochemicals with a range of therapeutic properties, such as anti-carcinogenic, antioxidant, anti-inflammatory, anticoagulant, anti-HIV, diabetes-fighting, and anti-allergic effects. (Perez, 2016). *Saccharina japonica* produces fucoidan, which has anti-inflammatory, antiviral, and anticancer properties (Ana C. Freitas D. R.-S., 2012).

3. *Sargassum*: Important Marine Brown Alga

With 360 recognized species, *Sargassum*, *C. Agardh* (*Sargassaceae, Fucales*) is an extremely diverse genus of Ochrophyta (brown algae), that is widely distributed in warm, temperate seas, especially within the Indian Ocean, the Emirate of Oman, and the Persian Gulf. Additionally, it is found throughout the Western Pacific's warm-temperate coastal regions, particularly in the nations of China, the Republic of Korea, and Japan. It is recognized in the Sub-Arabian parts of this ocean (Clara Riquelme, 2025) .

Sargassum species are valuable commercially, particularly in Asian nations where the agro-food, textile, cosmetic, and pharmaceutical sectors use them. It may be used as an alternative source of phycocolloids, namely alginate, has several uses in the food industry, beverage, dentistry, cosmetic, and pharmaceutical industries. Vegetable soup also uses it. In the northern Philippines, young shoots are also frequently used as a component in fish recipes (Sargazi, 2021).

S. fusiforme is highly valued for its medicinal qualities as traditional Chinese medicine. It includes bioactive substances with anticancer, anti-inflammatory, antibacterial, and antiviral properties, especially fucoidans. Through allelopathic effects, *S. fusiforme* extracts have been proven in studies to decrease toxic algal blooms (Siqi Sun, 2021). Additionally, a molecule from *S. fusiforme* called α-linolenic acid has been shown to decrease electron transport and chlorophyll fluorescence in hazardous dinoflagellates, indicating that growth of *S. fusiforme* may have an impact on the organization of communities of phytoplankton (Yurong Zhang, 2025).

3.1. Composition and Nutritional qualities of Sargassum Seaweed

Sargassum is a common brown macroalgae that grows along coasts all over the world. It is well-known for having a high nutritional profile that is necessary for the development of plants. Its protein concentration fluctuates between 11.20%-13.46% of the dry weight, making it a great source of organic nitrogen (Oyesiku, 2014). In addition, calcium, magnesium, phosphorus, potassium, account for 17.58% - 36.18 % of *Sargassum*'s ash content. A wide variety of micro and macro nutrients necessary for plant growth may be found in *sargassum*. Its protein content, which is an excellent source of organic nitrogen1, usually ranges from 11% to 13% of dry weight (Marianne Debue, 2025).

Table 2 Chemical constitution of S. fluitans

Components	Values (%, w/w)
Ash content	25.18
Specific Proteins	21.73
Fats	1.98
Total volume of carbohydrates	36.29
Carbohydrate soluble in water	31.74
Hydrophilic glycoprotein	19.62
Total fiber in food	5.92

Along with notable concentrations of calcium and magnesium, the ash content is especially high in potassium and phosphorus, with levels ranging from 17 to 35%. In terms of nutrition, Sargassum stands out for having a high carbohydrate content (about36-38% of its dry weight), a moderate protein content (20–22%), and a low-fat content (1-2%) (B. E. Lapointe, 2021).

3.1.1. Bioactive Compounds

Sargassum contains chemical compounds such polysaccharides and alginates, and growth regulators like auxins, gibberellins, and cytokinin along with to its nutritional significance. These bioactive compounds promote root elongation, boost nutrient absorption, and fortify plants' defenses against environmental stresses (Gege Liu, 2022). These organic compounds improve soil structure by boosting moisture retention and promoting the formation of stable soil aggregates. Improved nutrient availability and oxygenation follow, creating the perfect environment for root growth. (Soha Mohammed, 2023).

3.1.2. Mineral Contents

Several mineral elements were investigated using inductively coupled plasma- optical emission spectroscopy (ICP-OES). Several elements like, sodium, potassium, calcium, phosphorus, iron, zinc, copper, manganese, and cadmium. Potassium was the most common element in sargassum. which followed closely by sodium, calcium phosphorus, and (Subhash R Yende, 2014).

Table 3 Mineral Contents of S*argassum fluitans* (mg/100 g)

Minerals	**Contents**
Potassium	4190
Sodium	3350
Calcium	68.43
Phosphorous	130
Iron	127
Zinc	8.98
Mangnese	4.65
Copper	0.38
Cadmeium	0.17

3.1.3. Polysaccharide Properties

The hydrophilic polysaccharide content of *S. fluitans* is 21.01%. The polysaccharide infrared emission spectrum produced by a potassium bromine pellet was recorded using an IR spectrophotometer. Stretching vibrations of O–H and C–H shows major peaks at 3415 cm^{-1} and a minor peak at 2930 cm^{-1} in the infrared spectrum. Carboxylate-mediated O–C–O asymmetrical stretching and C–OH deformation vibrations were identified as the causes of the peaks at 1613 and 1415 cm−1, respectively. The pyranose ring's C–O and C–C vibrations of stretching were identified as the source of the absorbance at 1039 cm−1.

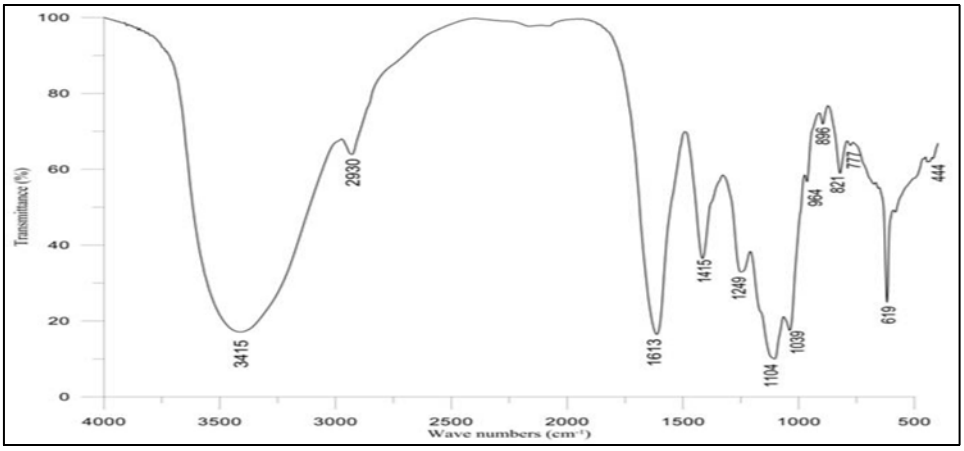

Figure 1 Water-soluble polysaccharides FT-IR spectrum of S. fluitans

3.2. Potential Applications of *Sargassum* in the Red Sea Region

Typically, the biggest and most complex of all algae, brown seaweeds (class: Phaeophyceae, or brown algae) are distinguished by the presence of many active compounds. Sargassum species are found in tropical and subtropical waterways, where they produce massive floating mats or "rafts" that can extend for miles (Muhamed Abdullah Helal, 2023). *Sargassum* biomass is a significant source of polysaccharides (such as alginates, laminarins, and fucans), carotenoids (primarily fucoxanthin), and dietary fibers that may have therapeutic benefits such as anti-cancer, anti-inflammatory, antibacterial, antiviral, antioxidant, and immune-stimulating effects. *Sargassum* biomass has several industrial uses, such as the manufacture of food, beverages, and fertilizers, (Muhamed Abdullah Helal, 2023)in addition to its therapeutic qualities (Siti Ari Budhiyanti, 2012).

Sargassum dentifolium is widely found in Hurghada, Egypt, on the western Shore of the Red Sea. This widespread species of *Sargassum* is well-known for its capacity to create thick mats in shallow water. Because it offers food and habitat to a variety of creatures, such as fish, crabs, and mollusks, Sargassum sp. represents an important group in the marine ecosystem (S. Kumar Chandini, 2008).

3.2.1. Antioxidant Properties

Sargassum sp. is a kind of seaweed that is a member of the Phaeophyceae family of brown algae. Fucoidan, one of the sulfated polysaccharides found in Sargassum sp., has cancer-preventing, disinfectant, blood thinner, antioxidant, anti-inflammatory, antiviral, and hepato-protective properties. (Butterfield et al., 2002).

Secondary metabolites, particularly phenolic and terpenoid chemicals with potent antioxidant bioactivity, are found in brown algae, such as Sargassum sp.

These substances offer a significant contribution to innovation, such as the creation of novel components to stop product degradation, especially in food items, cosmetics, or bio stimulants to increase agricultural yield and resistance to abiotic stress (Kefeng Wu, 2025).

lung disease, rheumatoid arthritis, osteoarthritis, and cancer are among the inflammatory disorders that continue to have a comparatively high occurrence. This emphasizes the need to investigate natural alternatives, such as the bioactive components of *Sargassum polycystum*. Because of their ability to combat free radicals, which lead to inflammation, several compounds, such phenolics and flavonoids in particular, have been shown to have a connection with antioxidant activity (Jing Zhou, 2008).

3.2.2. Antibacterial and Antiviral Properties

The main issue in aquacultures is diseases brought on by these harmful bacteria. Although bacterial infections have been treated with a variety of vaccinations, chemotherapy probiotics, and immune stimulants, drug-resistant microbes and mutations have become a major issue. Alkaloids, flavonoids, tannins, phenolics, plant proteins, lipids, terpenes, and other naturally occurring bioactive secondary metabolites have long been recognized to be produced in large quantities by seaweeds, which showed significant antibacterial, anthelmintic, antiviral, antifungal, anti-inflammatory, antioxidant, and antibiotic properties. In comparison to terrestrial plant alkaloids, brown algae are being shown to have more marine phenolic compounds, flavonoids, and alkaloids, among which saltwater algal alkaloids are comparatively uncommon (Amirsharifi M, 2018) .

By disrupting the complex symbiotic relationship between a group of bacteria, coral animals, and endobiotic algae, coral-related illnesses are one of the major risks associated with the imbalances of the coral's holobiont integrity (Xin Liu, 2025). These illnesses are often linked to a variety of bacterial infections that cause severe lesions in corals that exhibit antibiotic resistance. As a result, researchers are focusing increasingly on the therapeutic chemicals found in natural resources, such as seaweed and herbal plants, as alternatives to artificial antibacterial agents (Nadine MS Moubayed, 2016).

3.2.3. Anti-obesity Effect

Obesity is a collection of complex metabolic disorders marked by elevated body weight, excessive cholesterol, and a propensity for adipose cells to secrete harmful hormones. In overweight or obese individuals, excessive body fat accumulation has detrimental consequences and significantly raises the risk of metabolic disorders such as type 2 diabetes, heart disease, nonalcoholic fatty liver disease, and neurodegenerative disease. Consequently, cutting back on food consumption, lipid buildup, lipogenesis, or anti-obesity medication intake may help lower obesity. Nowadays, obesity is treated using synthetic anti-obesity medications like sibutramine and orlistat (Saioa Gómez-Zorita, 2020).

One common brown alga is *Sargassum thunbergii*. The effects of the bioactive substances present in S. thunbergii, including complex carbohydrates, lipids, and phenolic compounds, have been detailed in earlier research. Among them, *Sargassum* species' sulfated polysaccharide has hypolipidemic and anti-obesity properties (Afzan Naquiah Awang, 2014).

3.2.4. Anti-Inflammatory Properties

Sargassum has been identified as a possible anti-inflammatory substance by both scientific and empirical research. The body uses inflammation as a vital defense against a number of threats to homeostasis, including infections caused by bacteria, tissue strain, and certain injuries. The pathophysiology of many illnesses can be impacted by excessive and unchecked inflammatory states. Research investigates the possible anti-inflammatory properties of *Sargassum* in sulfated polysaccharides, refined compounds, and crude extracts (Hassou Najwa, 2025).

Because of its environment, which promotes seaweed development throughout the year, the tropical area offers a potential supply of *Sargassum* biomass. Subtropical species continue to dominate research on *Sargassum's* anti-inflammatory properties. (Saraswati, 2019).

3.2.5. Pharmacological Applications o Sargassum

Numerous seaweed species' extracts have undergone pharmacological activity screening. Among them, *Sargassum* species that were extracted using different solvents shown anti-inflammatory, anti-allergic, antibacterial, antiviral, antiplasmodial, anticancer, hypoglycemic, hepatic, gastric, bone, skin-whitening, anti-Alzheimer's, and antioxidant properties (Michael Heinrich, 2012).

3.2.6. Soil Fertility Improvement

Due to the significant amount of organic compounds, nutrients, and hormones that support plant development, the brown seaweed species *Sargassum* has attracted attention as a biofertilizer. Examined are the effects of using *Sargassum* seaweed as biofertilizers on soil health, crop yields, and nutrient availability (Dannielle Haye, 2025). By examining the biochemical properties of *Sargassum* and its impact on plant development, research indicates that using Sargassum-based biofertilizers can enhance soil structure, increase nutrient absorption, and reduce dependency on conventional fertilizers (Amy Williams, 2010).

3.2.7. Seaweed Application in Wastewater Treatment

Adsorption is chosen as the best approach because to its many advantages, including simple availability, handling, and better efficiency at a lower cost than alternative treatments. However, it has been demonstrated that biosorption utilizing naturally occurring seaweeds may effectively remove contaminants. Seaweed was extensively investigated and utilized in the treatment of wastewater as an adsorbent that substitutes the functional activated carbon, in addition to contributing to its application in many sectors (Nithiya Arumugam, 2018). A byproduct of any activity or process is wastewater. It may originate from homes, manufacturing, petrochemical, textile, aquaculture, agricultural, and other sectors.

Organic pollution is described as the presence of significant amounts of organic compounds; this also applies to inorganic pollution, which includes heavy metals from diverse sources, nitrogen, phosphorus, and phenolic chemicals, and colors from the textile, paper, and printing industries. Seaweed biosorption has emerged as a viable alternative to current methods for efficiently eliminating these contaminants from wastewater because of its environmentally favorable characteristics as well as the accessibility and affordability of raw materials (Mohamed Farghali, 2023).

3.2.8. Habitat Formation

In the marine ecosystem *Sargassum* plays a vital role for habitat formation. In tropical and subtropical oceans, it makes dense floating mates. In open waters these mats and beds provide a different type of shelter to the predators. The marine species like crabs, molars, shrimps, fishes and the small invertebrates stay around these mats and beds. The predators hide themselves in the complex routing and branching system of these plants (Yurong Zhang N. X., 2021).

Just like the coral reefs this floating sargassum plants provide a defense from the waves and current. During the different stages of life cycles of marine organisms these plants provide food and protection. *Sargassum* plants are a safe zone for the development and growth of juvenile fish. In the surrounding areas of these plants the microorganisms develop their tissues which provides a boost to the biodiversity. It provides the food storage for the living organisms (Mathilde Teyssier, 2025)

Predators also get a lot of food from this complex plant system. Marine organisms are disbursed due to the continuous movement of these moths and beds throughout the ocean. The complexity of the marine ecosystem increases due to this plant. *Sargassum* provides reach nutrients to the poor-quality water and increases the productivity for the marine life (Yanna Alexia Fidai, 2025).

3.2.9. Carbon sequestration

In the marine ecosystem *Sargassum* plays a crucial part in squeezing carbon. From the sea water it absorbs the carbon dioxide during the process of photosynthesis. This plant is helpful for converting the carbon into the organic matter and then its storage in the biomass. *Sargassum* plants and its floating beds absorb a reasonable amount of carbon (Lili Xu, 2025).

The parts of dead *sargassum* plants sink in the different layers of the ocean. In such a way this plant cleans the carbon from the marine atmosphere. The concentration and effects of greenhouse gases becomes minimal due to this process of *sargassum*. Thus, we can say that sir awesome plant is a climate regulator. It regulates the carbon cycles of oceans (Ilmauwati Qurniasih, 2024).

3.2.10. Nutrient Cycling

In a marine ecosystem *sargassum* plant is a factory for the recycling of nutrients. From the seawater it absorbs the essential nutrients like phosphorus and nitrogen. This plant stores the important nutrients in it during its growth period. It is a favorite food for the marine animals and they get important nutrients from this plant. During the decomposition of the *sargassum* plants these nutrients are released back in the seawater. *sargassum* absorbs the nutrients from the coastal water and then shift into the different layers of seawater (Masahiro Ohtake, 2020).

4. Ecological importance of *Sargassum*

A sustainable and environmentally friendly method of producing food and safeguarding the marine environment is through seaweed farming. Sargassum fusiforme production on a big scale has an impact on the quality of saltwater and phytoplankton, because they are the foundation of marine food networks, these species are significant. Farming S. fusiforme reduced excessive quantities of nutrients like nitrogen and phosphate and increased oxygen levels. Additionally, farming promoted a more varied and balanced phytoplankton population and reduced the overgrowth of some dominating species (Eun Kyoung Hwang1, 2020).

As a result, Sargassum species are crucial primary producers as well as biological markers for evaluating changes in water habitats and the health of ecosystems. The need to better control the ecological effects of macroalgae cultivation is developing due to its fast spread (Yurong Zhang 2017).

Macroalgae are essential to marine environments because they provide a variety of purposes. Large algae beds that form sea forests and enhance the 3-dimensional diversity and spatial variation of littoral or sublittoral regions are made possible by their high production capacity and large biomass. They also provide primary production and nutrient-absorption services, as well as breeding areas, nursery farms, conservation, and spaces for other marine organisms. (O Hoegh-Guldberg 1, 2007).

Additionally, macroalgae support the survival of these habitats by maintaining a number of elements of the water's quality, including as pH, temperature, dissolved oxygen concentration, downward lighting, flow of water, and water purification. (Jing Zhou N, 2008).

4.1. Biofuel Production

Due to massive population growth and expanding demands in the renewable energy sector, the primary fuel sources in the planet are rapidly and unpredictably running out.. The main energy source is fossil fuels, which are not renewable (Anuj Kumar Chandel, 2018). The careless use of fossil fuels causes global climate change, low quality air, and environmental effects that primarily lead to ecological imbalances and health consequences. It is projected that between 2010 and 2040, consumption for fossil fuels would increase by 40%. Therefore, it is crucial to provide a distinctive source of sustainable energy (Manoranjan Nayak, 2019).

Numerous biomasses have demonstrated notable advancements and have the potential to be environmentally acceptable base products among the prospective substitutes for fossil fuels. Biofuel is a specific energy product produced by biorefineries using biomass. Based on the kinds of feedstock utilized, biofuels are classified as first, second, and third generation fuels. (Elena Holl, 2022).

Feedstocks utilized for human consumption are used to make first-generation biofuels. Products like wheat, sugarcane, maize, rice, beet sugar, and sorghum are included in this category. In response to commercial and industrial uses, second-generation biofuels are developed. The trash from this crop's cultivation is mostly utilized to make biofuels. Woody crops and agricultural residues are examples of highly exploited non-consumable foods that are more challenging to extract and call for advanced conversion technologies (Wai Siong Chai, 2021). Because third-generation biofuel can offer greater production rates with less resource input, marine assets such as marine algae, and cyanobacteria are intriguing possibilities. The algal biofuel is sulfur-free, highly biodegradable, and safe (Nurul Syahirah Mat Aron, 2020).

Because of their rapid growth, high CO2 capture, and simplicity of production—particularly in dry regions—algae-based biofuels are considered third-generation fuels with the potential to solve the energy crisis. The lipids and acyl glycerides found in algal biomass are used to make biofuel, which lessens the demand for fossil fuels. (Godvin Sharmila V, 2021).

4.1.1. Bioethanol Production

Pretreatment, hydrolysis (either enzymatic or acidic), filtering, fermentation, and purification (i.e., distillation) are the steps in the microbial breakdown of any sugar-containing substance to generate bioethanol, a liquid biofuel (Sri Suhartini, 2024). The production of bioethanol from from initial to second- generation biomass substrates has been the subject of several investigations. However, it has performed poorly because of competition from food crops, problems with land usage, and an expensive, lengthy delignification (Panagiotis Fotios Chatzimaliakas, 2025).

As a result, Currently, it is thought to be an attractive approach to produce the fuel from third- generation organic matter or algal biomass because it has a higher yield than terrestrial plants, doesn't compete with the use of land to provide food supply, can be grown in freshwater and wastewater, and can accumulate significant amounts of lipids and carbohydrates (Ho Myeong Kim, 2015).

5. Experimental

5.1. Materials and Techniques

The pre-treatment of the feedstocks from biomass is the first stage in the multi-step process that produces bioethanol. They can be shrunk or the biomass can be broken down and sugars released using chemicals and bacteria. In the next step, these polysaccharides are broken down into simpler forms using intense or diluted acid or enzymes. After that, fungi, bacteria, or yeast ferment these simpler sugars to create ethanol. In order to synthesize bioethanol from algal biomass, preparation, degradation, alcoholic fermentation, and separation are essential processes that need special consideration. The circumstances that are present and the capacity of microorganisms (enzymes and yeasts) that break down these sugars have a significant impact on the ethanol yields.

5.2. Sample Collection and preparation

Handpicking was used to gather sargassum wastes, which included pelagic species *S. vulgare* and *S. fusiforme*. For preprocessing, the feedstock was sent in an ice chest. The biomass was prepared by washing it with tap water to get rid of any sand or other particles. Following three days of sun drying, the biomass was pulverized in a grinding mill and filtered to a particle size of 0.6 mm in compliance with published research. Until it was needed for the studies, the powdery biomass was kept in zip-lock bags.

5.3. Analysis of biomass composition

The biomass was analyzed to find out how much moisture, ash, fiber, protein, fat, and carbohydrates it contained. To ascertain the moisture content, specimens were dried out at 106 degrees Celsius until they attained a constant weight. Samples were burned for five hours at 500°C to determine the amount of ash. Sulfuric acid and sodium hydroxide, respectively, were used to hydrolyze crude fiber, and the residue was then heated to 450 °C. Lastly, the Soxhlet extraction technique was used with petroleum-based ether as the solvent to assess the crude fat content.

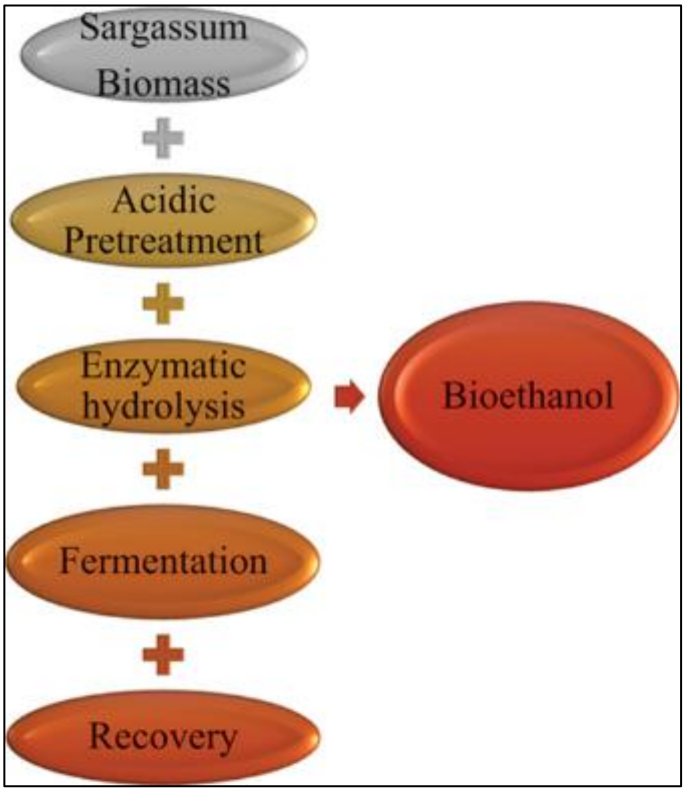

Figure 2 Bioethanol production pathway by *Sargassum sp*.

5.4. Pretreatment

Using techniques that include mechanical (heating, milling) to chemicals (acid/alkali baths) or biological processing, that purify, modify, or break down materials prior to the main process is called pretreatment, with the objective of removing impurities, improving efficiency, enhancing output (like sugar yield), and preventing problems in later stages.

The pretreatment procedure for the production of bioethanol involves breakdown of complex carbohydrates into cellulose enabling efficient hydrolysis by enzymes. It also reduces the production of deterrents, that decreases the yield of ethanol production.

In physical pre-treatment process biomass is ground and milled to increase surface area and promote enzymatic hydrolysis. In chemical pretreatment approach organic solvents, acids, or alkali uses to breakdown down the plant biomass matrix selectively

5.5. Hydrolysis of *Sargassum*

In hydrolysis step, cellulose is mostly broken down into simple sugars. Acids or enzymes can be used to complete this procedure. Enzymes are used in enzymatic hydrolysis for gently breaking down complicated sugars into sugar monomers.

Based on research published in the literature, the experimental conditions were carefully selected. One hundred milliliters of fluid were utilized, and the ambient temperature was kept at 110 degrees Celsius for forty-five minutes. After hydrolysis, the biomass remnant was disposed of and the hydrolysate was filtered. The quantity of H_2SO_4 utilized was 0.8 mol/L, and the total amount of reactive sugars (TRS) in the solution were subsequently measured using a UV-Vis molH_2SO_4.

Enzyme selection must be adapted to the chemical makeup of the treated biomass in order to achieve optimal performance, which calls for certain incubation temperatures, pH levels, and residence periods. The procedure provides two options: simultaneous saccharification along with fermentation (SSF) and separate fermentation with hydrolysis (SHF). Researchers are investigating the utilization of natural and artificial microbes that may secrete cellulolytic enzymes, such as *Clostridium* species, *Bacillus*, *Trichoderma*, as well as and *Schizophillum*, and *Dunaliella salina*, in order to reduce expenses. The simultaneous the saccharification process and fermentation (PSSF) method converted glucose from *Sargassum sp*. to bioethanol with a yield of 78.23 ± 4.78%. Furthermore, independent hydrolysis and fermentation using *Sargassum vulgare* and *Sargassum fusiforme* produced impressive bioethanol outputs of 96% and 74%, respectively, and glucose conversion rates of 76%.

Hydrolysis frequently uses acid-catalyzed techniques that use either concentrated or diluted acids, such as HCl and H_2SO_4. At lower temperatures and greater acid concentrations, concentrated acid hydrolysis guarantees quick sugar recovery. It also entails the danger of sugar breakdown, which might affect the fermentation process, especially for macroalgae biomass. Conversely, smaller acid concentrations and greater temperatures are needed for dilute acid hydrolysis, which is the recommended option. When compared to highly concentrated acid hydrolysis, this process yields less inhibitor.

5.6. *Sargassum* Fermentation Process

Fermentation is a biological process that uses microorganisms like yeast, fungus, or bacteria to hydrolyze single-molecule carbohydrates (such as glucose, fructose, or mannose) into ethanol and other compounds is important during fermentation since raising it can speed up the process, but raising it too high could destroy the microbes. Because of its high ethanol output and tolerance limitations, *Saccharomyces cerevisiae*, sometimes referred to as brewer's yeast, is frequently used in this method. At this phase of production, a variety of technologies can be used, such as batch, continuous, and fed-batch techniques, as well as seperate fermentation and hydrolysis (SHF), simultaneous fermentation and saccharification (SSF), and simultaneous co-fermentation and saccharification (SSCF).

5.7. Recovery of Ethanol

The next step is to recover ethanol from the broth that is fermented after monomeric sugars have been fermented. This is accomplished by reducing the broth's water content to create anhydrous ethanol. However, the ethanol-water solution's azeotropic composition presents difficulties. This restriction can be bypassed by using distillation methods, which take use of the various boiling temperatures of solution components. By adding an isolating agent that alters the main component's relative volatility, the azeotropic solution challenge can be addressed.

Table 4 Biofuel production from different Sargassum Species

Type of Biofuel	Species Type	Pretreatment methods or Conversion techniques	Pretreatment or conversion technique conditions	Biofuel Yield or production potential
Bioethanol	*Sargassum natans*	moist oxidizing technique	Temperature – 180°C	40 g C_2H_5OH/100 g glucan
	Sargassum fluitans	Dilute acid pretreatment	H_2SO_4-0.06% Temperature – 170°C Time – 15 min	6.55 gram/liter
	Sargassum muticum	Hydrolysis by heated acids	Acid – 40 mM Sulphuric acid Temperature-120°C Time – 60 min	8.7 gram/liter
	Sargassum polycystum	Heating in oven	Temperature – 60°C,Time –70 h	12.6 ± 0.3 microL/g
	Sargassum vulgare	Hydrolysis by light acids	Acidic condition – 2% Sulphuric acid	11.98%

6. Challenges and Prospectives

Manufacture of bioethanol from *Sargassum* species has enormous potential as a sustainable energy source. However, there are still issues that need to be addressed, such as inadequate infrastructure for seaweed cultivation, harvesting, and processing (fermentation, hydrolysis, and pretreatment), supporting policies in research, and scale-up production. The majority of macroalgal biofuel production techniques, such as growing, harvesting, processing following harvest, product preservation, and implementation, as well as macroalgal bioproduct tests, would get funding to help raise user knowledge of macroalgal biorefineries. Concerns about biologic processing methods, environmental sustainability, and limitations that may have an acknowledged influence on policy or law should be taken into consideration in addition to biological and engineering challenges.

However, compared to generation from crops that are edible and lignocellulosic materials, its prospects are still better, supporting waste management, economic growth, and sustainable energy generation.

7. Conclusion

Recently, algae bioethanol has emerged as a compelling and sustainable substitute for fossil fuels. Because of their quick growth, abundant carbohydrate content, and independence from land, macroalgae farming stands out as an excellent replacement feedstock for the generation of this fuel. It would be a fantastic alternative to demonstrate a combined method of biofuels generation from macroalgae in the future. Numerous different macro algal species from all three taxonomic groups have been discovered as viable biochemical processing procedures for the generation of biofuels, bioproducts, and high-value biochemicals. The intense trend in macroalgal property rights implementations highlights its innovative potential to contribute to the biological economy by offering an environmentally friendly renewable energy source, and perhaps a growing demand for sponsored research projects that cover the complete macroalgal biorefinery route. Macroalgae availability and significant seasonal variations in its biochemical and nutritional value are two of the many issues that arise when utilizing macroalgae to produce fuels and chemicals. There are still certain restrictions, such as inadequate technology and the volatility of macroalgae biomass quantity and quality. The amount of products and product types produced by macroalgae vary by species, season, and geographic location, and they are heavily dependent on processing technologies.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] A. Nagababu, D. S. (2022). Toxic chrome removal from industrial effluents using marine algae: Modeling and optimization. Journal of Industrial and Engineering Chemistry, 377-390.

[2] Afzan Naquiah Awang, J. L. (2014). Anti-obesity property of the brown seaweed, Sargassum polycystum using an in vivo animal model. Journal of Applied Phycology , 1043–1048.

[3] Ali Rajabiyan, D. B. (2025). A Methodological Review of Extraction, Purification, and Identification Techniques for Natural Bioactive Compounds. Organic process research and development, 50-62.

[4] Aline Frumi Camargo, V. T. (2025). Trichoderma-based extract from microalgae digestate effect in cancer cell lines. Next Research, 100-107.

[5] Amirsharifi M, J. S. (2018). Antimicrobial activity of various extracts of Sargassum. Iranian Journal of Fisheries Sciences, 1359-1372.

[6] Amy Williams, R. F. (2010). Sargassum as a natural solution to enhance dune plant growth . Environ Manage, 738-747.

[7] Ana C. Freitas, D. R.-S. (2012). Marine biotechnology advances towards applications in new functional foods. Biotechnology Advances, 1506-1515.

[8] Ana C. Freitas, D. R.-S. (2012). Marine Biotechnology Advances Towards Applications in New Functional Foods. Biotechnology Advances, 1506-1515.

[9] Angela Paul Peter, K. S.-H. (2021). Microalgae for biofuels, wastewater treatment and environmental monitoring. Environ Chem Lett, 2891–2904.

[10] Anh Quynh Nguyen, A. L. (2025). Potential of algae as fertilizers and plant stimulants for sustainable and eco-friendly agriculture. Algal Research, 104-137.

[11] Anuj Kumar Chandel, V. K. (2018). The path forward for lignocellulose biorefineries: Bottlenecks, solutions, and perspective on commercialization. Bioresource Technology, 370-381.

[12] B. E. Lapointe, R. A. (2021). Nutrient content and stoichiometry of pelagic Sargassum reflects increasing nitrogen availability in the Atlantic Basin. Nature Communications , 30-60.

[13] Clara Riquelme, K. J. (2025). Utilizing Sargassum Seaweed as a Biofertilizer for Sustainable Agriculture: A Review. Case Studies in Chemical and Environmental Engineering, 101-152.

[14] Clara Riquelme, K. J. (2025). Utilizing Sargassum Seaweed as a Biofertilizer for Sustainable Agriculture: A Review. Agricultural Research and Technology, 556-578.

[15] Dannielle Haye, C. B. (2025). Influence of Pelagic Sargassum spp. On Soil Amelioration for Seed Germination and Seedling Growth of Corn (Zea mays), Scotch Bonnet Pepper (Capsicum chinense), and Tomato (Solanum lycopersicum) . Phycology, 44-56.

[16] Dipankar Ghosh, P. G. (2022). Algal biofertilizer towards green sustainable agriculture. Microbial Biotechnology and Bioengineering, 27-45.

[17] Elena Holl, J. S. (2022). Two-stage anaerobic digestion: State of technology and perspective roles in future energy systems. Bioresource Technology, 127633.

[18] Eun Kyoung Hwang1, C. S. (2020). Seaweed cultivation and utilization of Korea. Algae, 107-121.

[19] Felix Offei, M. M. (2018). Seaweed Bioethanol Production: A Process Selection Review on Hydrolysis and Fermentation . Fermentation, 4(4), 99.

[20] Gege Liu, J. W. (2022). The potential therapeutic value and application prospect of engineered exosomes in human diseases. Front Cell Dev Bio, 105-138.

[21] Godvin Sharmila V, D. K. (2021). Biofuel production from Macroalgae: present scenario and future scope. Bioengineered, 9216–9238.

[22] Hassou Najwa, R. R. (2025). Marine algae as a source of bioactive compounds: unlocking anticancer potential. Cancer Biomarkers and Oncoviruses, Pages 375-390.

[23] Hidayat, T. (2017). Identification of Bioactive Compounds of Seaweed Sargassum sp. and Eucheuma cottonii Doty as a Raw Sunscreen Cream. Life and Environmental Science, 311-318.

[24] Ho Myeong Kim, S. G.-J. (2015). Efficient approach for bioethanol production from red seaweed Gelidiumamansii. Bioresource Technology, 128-134.

[25] Ilmauwati Qurniasih, B. Y. (2024). Carbon Absorption Potential in Sargassum sp. and Padina sp. in The Waters of East Melano Bay, Lemukutan Island, Bengkayang District, West Kalimantan Province. Journal of Marine Biotechonology and Immunology, 387-395.

[26] Jing Zhou, N. H.-l.-j.-r. (2008). Preliminary studies on the chemical characterization and antioxidant properties of acidic polysaccharides from Sargassum fusiforme . J Zhejiang Univ Sci B, 721–727.

[27] Jing Zhou, Y.-l. W. (2008). Preliminary studies on the chemical characterization and antioxidant properties of acidic polysaccharides from Sargassum fusiforme. Journal of Zhejiang University SCIENCE B, 721-727.

[28] Kefeng Wu, L. C. (2025). Recent Advances in the Structure, Extraction, and Biological Activity of Sargassum fusiforme Polysaccharides. Marine Drugs, 98-105.

[29] Lei Liu, M. H. (2012). Towards a better understanding of medicinal uses of the brown seaweed Sargassum in Traditional Chinese Medicine: A phytochemical and pharmacological review. Journal of Ethnopharmacology, 591-619.

[30] Lili Xu, X. S. (2025). Effects of Sargassum beds on carbon sequestration and microbial community structure in the adjacent sediment cores. Algal Research, 104-145.

[31] M.C. Santos-Silva, E. M.-K. (2018). M.C. Santos-Silva a, E.C. Machado, M. Wallner-Kersanach, M.G. Camargo . Andrade , F. Sá c, F. Pellizzari . Marine Pollution Bulletin, 923-931.

[32] Manoranjan Nayak, D. K. (2019). Strategic valorization of de-oiled microalgal biomass waste as biofertilizer for sustainable and improved agriculture of rice (Oryza sativa L.) crop. Science of The Total Environment, 475-484.

[33] Marianne Debue, T. G. (2025). Understanding the Sargassum phenomenon in the Tropical Atlantic Ocean: From satellite monitoring to stranding forecast. Marine Pollution Bulletin, 918-923.

[34] Masahiro Ohtake, N. N. (2020). Growth and nutrient uptake characteristics of Sargassum macrocarpum cultivated with phosphorus-replete wastewater. Aquatic Botany, 163-172.

[35] Mathilde Teyssier, C. D. (2025). Assessing sargassum pressure on coastal habitats using a spatial and temporal approach at the territorial scale. Ecological Indicators, 113-117.

[36] Michael Heinrich, S. M. (2012). Towards a better understanding of medicinal uses of the brown seaweed Sargassum in Traditional Chinese Medicine: A phytochemical and pharmacological review. Journal of Ethnopharmacology, 591-619.

[37] Mohamed Farghali, I. M. (2023). Seaweed for climate mitigation, wastewater treatment, bioenergy, bioplastic, biochar, food, pharmaceuticals, and cosmetics: a review. Environmental Chemistry Letters, 97–152.

[38] Muhamed Abdullah Helal, A. D.-G. (2023). Biochemical composition and bioactivity of the crude extract of Sargassum dentifolium (Turner) C. Agardh, of Western Coast of the Red Sea, Hurghada, Egypt. Biomass conversion and biorefinery, 14(20):1-20.

[39] Nadine MS Moubayed, H. J. (2016). Antimicrobial, antioxidant properties and chemical composition of seaweeds collected from Saudi Arabia (Red Sea and Arabian Gulf). Saudi J Biol Sci, 162–169.

[40] Nithiya Arumugam, S. C. (2018). Treatment of Wastewater Using Seaweed: A Review. nternational Journal of Environmental Research and Public Health (IJERPH), 15(12):2851.

[41] Nurul Syahirah Mat Aron, K. S. (2020). Sustainability of the four generations of biofuels – a review. Int J Ener Res., 1-17.

[42] O Hoegh-Guldberg 1, P. J. (2007). Coral reefs under rapid climate change and ocean acidification. Science, 1737-1742.

[43] Oyesiku, O. O. (2014). Identification and chemical studies of pelagic masses of Sargassum natans (Linnaeus) Gaillon and S. fluitans (Borgessen) Borgesen (brown algae), found offshore in Ondo State, Nigeria. African Journal Of Biotechnology, 1188-1193.

[44] Panagiotis Fotios Chatzimaliakas, S. M. (2025). Biorefinery-Based Energy Recovery from Algae: Comparative Evaluation of Liquid and Gaseous Biofuels. Fermentation, 11(8):448.

[45] Perez, M. j. (2016). Antimicrobial Action of Compounds from Marine Seaweed. Marine Drugs, 65-74.

[46] S. Kumar Chandini, P. G. (2008). In vitro antioxidant activities of three selected brown seaweeds of India. Food Chemistry, 707-713.

[47] Saioa Gómez-Zorita, M. G.-A. (2020). Anti-Obesity Effects of Macroalgae. Nutrients, 2378.

[48] Sanjay Kumar Joshi, A. K. (2022). Global biofertilizer market: Emerging trends and opportunities. Sustainable Economy, 689-697.

[49] Sanjita Gurau, M. I. (2025). Algae: A cutting-edge solution for enhancing soil health and accelerating carbon sequestration – A review. Environmental Technology & Innovation, 980-994.

[50] Saraswati, P. E. (2019). Sargassum Seaweed as a Source of Anti-Inflammatory Substances and the Potential Insight of the Tropical Species: A Review. Marine Drugs, 762-783.

[51] Sargazi, F. (2021). Morphological diversity of Sargassum species of Oman Sea Coasts. Iranian Journal Of Botany , 60-72.

[52] Siqi Sun, S. H. (2021). Allelopathic effects and potential allelochemical of Sargassum fusiforme on red tide microalgae Heterosigma akashiwo. Marine Pollution Bulletin, 112-123.

[53] Siti Ari Budhiyanti, S. R. (2012). Antioxidant activity of brown algae Sargassum species extract from the coastline of Java Island. American Journal of Agricultural and Biological Sciences, 337-346.

[54] Sivakumar Adarshan, V. S. (2024). Understanding Macroalgae: A Comprehensive Exploration of Nutraceutical, Pharmaceutical, and Omics Dimensions . plants, 113-119.

[55] Soha Mohammed, M. M.-S.-H. (2023). Inductive role of the brown alga Sargassum polycystum on growth and biosynthesis of imperative metabolites and antioxidants of two crop plants. Front Plant Sci, 14:1136325.

[56] Sri Suhartini, M. B. (2024). Valorisation of macroalgae for biofuels in Indonesia: an integrated biorefinery approach. Environmental Technology Reviews, 269-304.

[57] Subhash R Yende, U. N. (2014). Therapeutic potential and health benefits of Sargassum species. Pharmacogn Rev, 1-7.

[58] Ty Shitanaka, S. K. (2025). Macroalgae-derived bioactive compounds for functional food and pharmaceutical applications—a critical review. Critical Reviews in Food Science and Nutrition , 452-459.

[59] Wai Siong Chai, Y. B. (2021). A review on ammonia, ammonia-hydrogen and ammonia-methane fuels. Renewable Sustainable Energy . Renewable and Sustainable Energy Reviews, 111-154.

[60] Xin Liu, Q. Y. (2025). Antimicrobial effect and mechanism of Sargassum carpophyllum extract against fish spoilage Pseudomonas sp. CL2. Food Bioscience, 107-141.

[61] Yan Peng, E. X. (2012). Nutritional and chemical composition and antiviral activity of cultivated seaweed Sargassum naozhouense Tseng et Lu. Mar Drugs, 20-32.

[62] Yanna Alexia Fidai, J. D. (2025). Sargassum Biomass Movement and Proliferation in the Eastern Tropical Atlantic. phycology, 17-34.

[63] Yurong Zhang, N. X. (2021). Evaluation of the correlation of Sargassum fusiforme cultivation and biodiversity and network structure of marine bacteria in the coastal waters of Dongtou Island of China. Aquaculture, 737-757.

[64] Yurong Zhang, R. J. (2025). Ecological Effects of Sargassum fusiforme Cultivation on Coastal Phytoplankton Community Structure and Water Quality: A Study Based on Microscopic Analysis. Biology, 844-853.

[65] Yurong Zhang, R. J. (2025). Ecological Effects of Sargassum fusiforme Cultivation on Coastal Phytoplankton Community Structure and Water Quality: A Study Based on Microscopic Analysis. Biology, 844-856.