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Exploring the potential of macroalgae in bioindustrial sector: A review

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Abstract

In light of the escalating environmental concerns associated with the depletion of finite resources, this review article explores the transformative potential of macroalgae, particularly seaweed, across multiple bioindustrial applications. It argues that seaweed could be instrumental in fostering a sustainable global economy by contributing to the development of sectors such as biopesticides, biofertilizers, biofuels, and biodegradable or edible bioplastics. The review assesses the diverse applications of seaweed, ranging from its use in food industries to its role in biofuel production, underscoring its significance in promoting environmental sustainability. Despite the promising research outcomes, significant challenges remain, including the need for scalable production methods and the mitigation of environmental impacts. Advancements in large-scale cultivation techniques and innovative technologies are critical for realizing the full potential of seaweed as a global resource. This review paper gives a deep and current knowledge on the various beneficial applications of seaweeds, emphasizing their potential to advance human welfare and contribute to a greener economy. It also highlights the application of seaweed in providing the alternative livelihood and sustenance to humans.

Keywords: Macroalgae; Bioindustry; Biofuel; Energy production; Biomass.

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1. Introduction

Chemical engineering techniques, ranging from chemical and mechanical to biological, biochemical, thermal, and microbial treatments, either individually or combined, have created new opportunities for the sustainable and cost-effective conversion of biomass into valuable products and bioenergy. Marine macroalgae, which grow naturally but can also be cultivated commercially, are becoming increasingly significant as their market expands. Their rapid growth and composition make them ideal for advancing towards a biobased, sustainable, and circular economy. Seaweed is found in every ocean and sea globally and is now recognized for its potential in mitigating climate change and enhancing food security. Consequently, relying solely on natural seaweed harvests is inadequate, leading to the common practice of cultivating seaweed both on the onshore and offshore areas. Various seaweed farming methods, including pillar systems, semi-floating rafts, full floating rafts (Zhang *et al*., 2022a), tube nets, off-bottom monolines, PVC pipe rafts, cage systems, and spider webs, are utilized. Asia leads in seaweed production, primarily for food purposes. Seaweeds are also cultivated industrially for food, nutritional supplements, cosmetics, pharmaceuticals, and biofuel production (Hyderi *et.al.*, 2024). Macroalgae are considered suitable for biofuel production due to their rich content of biopolymers like agar, carrageenans, and fatty acids, including eicosapentaenoic (EPA), docosahexaenoic (DHA), and alpha-linolenic (ALA) acids, among other molecules (da Rosa *et al.*, 2023).

Over the past century, automation, robots, and cutting-edge technology have significantly changed the industrial sector (Yong *et al*., 2024). The contemporary world has been shaped by these developments, which have significantly increased production and efficiency across a range of sectors. Nonetheless, there are drawbacks to this era of technological progress, including pollution, resource depletion, global warming, and unchecked population expansion. These problems have spurred the hunt for more environmentally friendly substitutes to let the various businesses expand quickly. Seaweed presents itself as a resource that is both eco-friendly and promising in this context. It has the potential to significantly increase industrial sustainability and revolutionize a variety of bio-industrial uses, making it a valuable tool in the ongoing push for a green revolution.

Macroalgae, also known as seaweed, is a highly adaptable organism that thrives in aquatic and marine settings. According to (Peñalver *et al*., 2020) it is a historically significant food that is consumed as a staple in Western countries and as a nutritious supplement in Asian countries. Seaweed hydrocolloids are used extensively in cosmetics and medicine in addition to its culinary usage. Seaweed's economic worth is emphasized by its adaptability, especially in Asian countries where seaweed aquaculture is highly integrated. This illustrates the increasing significance of seaweed as a food source and nutritional supplement as well as an important industrial and commercial resource that has the potential to have an influence on many different areas of the world economy and fuel the growth of the seaweed-based bioindustry (Figure 1).

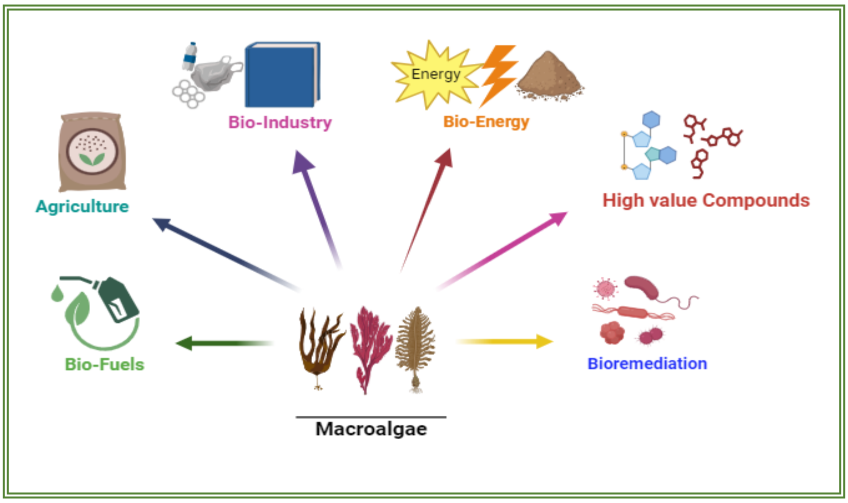

Figure 1. Illustration of various bioindustrial applications of Seaweed (Figure was created in BioRender)

The purpose of this review is to present seaweed as a major force behind the global bioindustry's advancement. It examines the seaweed aquaculture industry's transformative potential and highlights the vital role of seaweed in sustainable bioindustrial applications. Seaweed aquaculture has the potential to sustain a diverse bioindustry with consistent and resilient growth if it is managed effectively. The growing list of uses for seaweed as biopesticides and fertilizers is creating new research opportunities. The potential of seaweed as a biofuel has drawn interest, demonstrating its feasibility as a substitute for non-renewable and fossil fuels. Seaweed biomass is useful to the bioindustry because it can be used to produce gaseous and liquid fuels that can be used to generate heat or electricity. This highlights the resource's sustainability in the quest for more environmentally friendly energy sources (Yong *et al*., 2024). Clearly, the seaweed business is poised for considerable growth, with exciting possibilities for new applications. This review takes a thorough approach to investigating seaweed's wide potential for bioindustrial uses.

2. Body

2.1. Seaweed growth, distribution, and cultivation

Growing macroalgae has several benefits, including shorter life cycles, lower costs, and fewer adverse effects on the environment. They may flourish without access to clean water and make no alterations to the soil. Compared to microalgae, their volumetric production rate is higher, and the biomass density they generate is also greater. The physiological processes in macroalgae serve as the foundation for the growth model. In order to explain the physiological activities and operational differences between nutrition and carbon uptakes, we are using three state variables as an explanation (nitrogen, carbon, and phosphorus). Nutrients are the main factor in controlling the physiological functions of seaweeds (Roleda and Hurd, 2019). Nitrogen is vital as it restricts growth in temperate waters. Within the temperature-acceptable limit of a species, physiological rates follow the

Arrhenius rule and grow exponentially whenever the temperature rises. Biomass increased from early to mid-summer, peaked in early October, and subsequently declined, following a typical seasonal pattern. On the other hand, the N-quotient is believed to be highest in the winter and reduced throughout the summer peak growth period. Bioremediation through bioabsorption and bioaccumulation is a potential application for some species of macroalgae, and some might even be used as bioindicators of water quality (Henriques *et al.*, 2017).

Tropical and subtropical reefs in northwest Australia teem with macroalgae, which cover vast areas and provide shelter for most marine organisms. Nonetheless, the diversity of seaweeds in the north is not as high as in the southwest, which is recognized as a centre of algal biodiversity. According to contemporary museum records, 110 Chlorophyta and 61 Phaeophyceae species cover from Coral Bay (Ningaloo) to the Northern Territory boundary (Wilson *et al*., 2019). For some coastal and rural communities, seaweed-related activities constitute a significant source of money and a source of livelihood, as well as part of a cultural heritage. Numerous nations in European Union currently import seaweed for human consumption, either fresh or dried (e.g., dressings, sauces, canned seafood, bread, pasta, and salt). Historically, people have eaten Laminaria digitata, Chondrus crispus, and Palmaria palmata. Coastal communities have relied on marine macroalgae for food, illness treatment, and to get organic fertilizer since the dawn of time (Menaa *et al.*, 2020). In southern Chile, people as early as 13,000 years ago relied on foods and medicines obtained from Ochrophyta, Rhodophyta, and Chlorophyta (Sánchez *et al.*, 2019). Additionally, macroalgae have been consumed as food in nations such as Japan, Korea, China, Indonesia, and Malaysia. Macroalgae harvesting from the sea has long been a popular activity. Moreover, in the last five decades, macroalgae cultivation technologies have enhanced the quality of all types of sea-based and seawater pond-grown macroalgae. This has led to a tremendous rise in macroalgae production during the past 20 years (Sánchez *et al*., 2019).

From 2000 to 2015, global output increased from 10.51 million to 30.45 million tons, virtually all of this increase attributable to macroalgae cultivation. Global macroalgae production in 2014 was 27.22 Metric tons (Mt), according to Food and Agriculture Organization. In 2015, when the total output of macroalgae production was 30.45 million metric tons (Mt) worldwide, European nations only provided 0.75 percent of that total (0.23 Mt). The primary production countries were Norway, France, and Ireland (65 percent). In this regard, Gracilaria spp. (3.75 Mt) and Porphyra spp. (2.36 Mt) Saccharina japonica (7.65 Mt) and Sargassum fusiforme (0.175 Mt) were the most cultivated macroalgae species. Macroalgae production is significantly contributed by countries like South Korea (5.8%), the Philippines (5.8%), Indonesia (34.6%), and China (50.1%). The total global production of macroalgae for the year 2020-2021 was estimated to be nearly 31 Mt. (Zhang *et al*., 2022b).

2.2. Application of macroalgae in the industrial sector

Due to their distinct qualities and future sustainability, macroalgae have recently found new uses in the industry. The production of biofuels from macroalgae is one of the most exciting uses of this renewable resource (Godvin Sharmila *et al*., 2021). Macroalgae also has the potential to be a sustainable resource for producing fertilizers, animal feed, and medicines. Additives for food, cosmetics, and industrial chemicals can all be made with their help. Macroalgae are poised to become an important part of the industrial landscape due to the rising demand for sustainable and environmentally friendly products (Table 1). Here are some of the main fields where macroalgae is being used.

Table 1. Industrial uses of seaweeds of different species

S. No.	Products	Seaweed species	Properties	Reference(s)
1	Carrageenan (Kappa, Iota and Lambda), ice creams, yogurts and jellies.	*Gigartina skottsbergii.*	Used as Thickening, gelling and viscosifier agent	(Freitas *et al*., 2022)
2	Agar	*Gelidium sp., Gracilaria sp., Pterocladiella sp.*	Vegetable jelly, Gelling	(Mendes *et al*., 2022)
3	Alginate yogurts, ice creams	*Lessonia spp., Macrocystis sp.*	Emulsifying, Gelling, Stabilizer	(Subbiah *et al*., 2022)

2.2.1 Process of Phycoremediation

Marine macroalgae can clear up heavy metal contamination, assist with wastewater treatment, reduce atmospheric CO_2 levels through photosynthesis, and produce biomass for industrial use (Dehbi *et al*., 2023). Several types of marine algae could be utilized to clear up heavy metal contamination. Sargassum spp. has a high copper biosorption ability, making it a feasible option for copper pollution management effluent treatment procedures (Mahmood *et al*., 2017). Marine phytoremediation is only getting started, and it's not yet obvious whether marine macroalgae or microalgae will emerge as the frontrunners. So far as can be told, marine macroalgae will be the first monopoly in this sector, just as they have been in others since the start of marine algal industrialization.

2.2.2 Photoprotective

The distinctive bioactive components that macroalgae have generated as a result of their adaptation to the harsh maritime environment and their diverse physical properties have led to a great deal of interest in them as natural photoprotective agents. Some of the photoprotective substances obtained from seaweeds are carotenoids, polyphenols, mycosporine-like amino acids (MAAs) and sulfated oligosaccharides (Patel *et al*., 2020). The biological functions of marine macroalgae photo-protective chemicals include UV absorption, antioxidants, matrix metalloproteinase inhibitors, anti-aging, and immunomodulatory effects.

2.2.3 Papermaking

Papermaking using cellulose extracted from macroalgae is a relatively new topic, although it has been the subject of extensive study. Lignin is a polymer that is found in cell walls intercalated with cellulose. Lignified pulp is commonly used to manufacture low-quality papers, such as newsprint. Because algae have no or very little lignin in their cell walls, the lignin removal phase is avoided when they are used in papermaking, making them excellent candidates for long-term and profitable papermaking, provided that the techniques of cultivation are economical (Mariana *et al*., 2021).

2.2.4 Bioplastics

Organic resources such as corn, vegetable oil, potatoes, and marine algae, mostly macroalgae, are used to make bioplastics. Macroalgal polysaccharides such as carrageenan, agar, and alginate are important sources in the production of bioplastics. Bioplastics made from marine algae have the following benefits: There is no competition with food resources, it is easy to grow in a variety of conditions, it produces a high yield/biomass, it is cost-effective, it reduces CO_2 emissions, and it is environmentally benign (Lim *et al*., 2021). These consist of Hybrid plastics and cellulose-based plastics.

2.3. Application of macroalgae in Agriculture

Seaweeds can be utilized as a natural fertilizer because of their high nutrient content (especially nitrogen, phosphorus, and potassium) (Pei *et al*., 2024). Due to their high protein, vitamin, and mineral content, macroalgae are also utilized as livestock feed to boost animal health and productivity. Macroalgae have been shown to increase agricultural yields, decrease soil erosion, and improve soil structure, in addition to their nutritional benefits. Extracts from macroalgae can be utilized as biostimulants to increase crop yields and as biocontrols to reduce the prevalence of damaging insects and illnesses. The biofuels obtained from macroalgae can serve as a sustainable energy source for agricultural endeavors while also lowering greenhouse gas emissions. As a result of their versatility, macroalgae are an important component of environmentally friendly farming practices.

2.3.1 Biofertilizers

As a result of public interest in organic farming, the usage of macroalgae as a fertilizer has been increased. Macroalgae are high in minerals and nutrients, and they help plants thrive by assisting in nitrogen fixation and phosphate solubilization. Macroalgae have been utilized as a natural fertilizer on the beach and nearby land, including green algae in some areas of Argentina, brown algae in some parts of the United Kingdom and France, *Ascophyllum spp.* in Scotland, *Sargassum spp.* in the Philippines, and *Ascophyllum spp*. in the Philippines (Ammar *et al*., 2022). These seaweeds were used as organic fertilizers after being buried in the sand at the beach or surrounding land. Moreover, Brown algae, such as *Ascophyllum, Ecklonia,* and*Fucus species*, are commonly used to produce organic compost.

2.4. Application of macroalgae in energy production

Renewable energy from seaweed has considerable promise. Macroalgae cultivation is appealing for energy production because of its fast growth rate, high biomass yield, and low inputs (Kammler *et al*., 2024). Many processes, including combustion, gasification, and fermentation, can extract energy from macroalgae. Anaerobic digestion, which entails breaking down organic matter without oxygen, is the most promising approach for converting macroalgae into energy. Due to its high methane content, the generated biogas can be utilized to power generators, heat buildings, or power vehicles. The high lipid and carbohydrate content of macroalgae makes them a promising biofuel feedstock. Macroalgae can sequester carbon dioxide and other air pollutants and be a possible energy source. Therefore, seaweeds are potentially useful resource for carbon capture and storage, a technique that can contribute to the fight against climate change. Overall, using macroalgae as a renewable energy source can reduce our reliance on harmful fossil fuels while still meeting our energy needs. Macroalgae, with more study and development, could play a significant role in the shift to a low-carbon economy.

2.4.1 Biomass Resource Production

Despite producing less than red and brown seaweeds, global green macroalgae aquaculture is predicted to yield about 20,000 metric tons of fresh weight each year. Unique variety, high abiotic environment resistance, high biofiltration capacity, simplicity of obtaining quality seed, exclusive bioactive compounds, and increased market value are only a few advantages of cultivating diverse green macroalgal taxa (Hou *et al*., 2022). Due to their broad biochemical profiles and organoleptic features, high nutrient intake and multiplication capabilities, various growing tactics, and resistance to extreme temperatures, *ulvo phycean* macroalgae have a significant potential for innovation in macroalgal aquaculture. Bioremediation and biomonitoring, as well as biopolymer generation are some of the innovative applications of algal biomass now being researched. Algae are used for a range of things, including biofilters to remove nutrients and other pollutants from wastewater, water quality monitoring, environmental change indicators, space technology, and laboratory research systems. Macroalgae can also be used to produce good quality vegetable oil than traditional terrestrial crops. It is also capable of producing hydrogen. Using macroalgae as a marine biomass energy source can reduce fossil fuel usage considerably.

2.4.2 Macroalgae in Biorefinery:

Biorefinery is a promising method for producing several products from a single source in a short period of time. Macroalgae have a high photosynthetic rate and can produce a lot of biomass. Macroalgae have much potential for a zero-waste biorefinery (Rajak *et al*., 2020). Production of biorefinery using macroalgae as the source is an environment-friendly approach and a cost-effective alternative to finite fossil fuel resources. It necessitates the development of sustainable biorefinery processes, many of which use macroalgae as feedstock and show promising and viable prospects (Javed *et al.*, 2022). Yet, research into macroalgal biorefineries is still in its early stages compared to lignocellulosic biorefineries that utilize terrestrial plants. The significance of maintaining research and development efforts is to fill the gap between fundamental laboratory bioscience and the efficient commercial implementation of suitable technology and research and to fortify the macroalgae industry. Macroalgae biorefineries could help expand and diversify traditional industries changing market dynamics and creating new business opportunities. The development and impact of macroalgae biorefineries will be aided by interdisciplinary collaborations.

2.4.3 Macroalgae in Electricity generation

One of the ways in which macroalgae can be used to generate electricity is through a process called marine biomass energy. Energy from macroalgae can be converted into useful forms like thermal or electrical energy. Several strategies exist for extracting energy from macroalgae. One way involves harnessing the energy stored in the algae to produce biogas, which can be burned to generate electricity. Another technique is using algae to make biofuels, such as ethanol or biodiesel, for power generation (Nath, 2024). Growing macroalgae in the sea has the added benefit of not competing with land-based agricultural production for limited water and nutrients. Moreover, macroalgae may develop rapidly and have a large biomass production, making it a potentially cost-effective renewable energy source. In a microbial fuel cell, researchers investigated the potential of the macroalgae *Laminaria digitata* to act as a substrate for bioelectricity production. A maximum voltage of 0.5 V was achieved with no lag time due to the high content of glucose and mannitol in the hydrolysate.By the conclusion of the batch run, the overall efficiency of reducing the chemical oxygen requirement was greater than 95%. To bridge the gap between the breakdown of glucose and mannitol, isobutryrate was utilized. The complex microbial composition that was revealed by 16S rRNA gene high across anodic biofilm sequencing study was dominated by Bacteroidetes, Firmicutes, Proteobacteria, Euryarchaeota, Deferribacteres, Spirochaetes, Chloroflexi, Actinobacteria, and other organisms (Zhao *et al.*, 2018). Bacteroidetes, Firmicutes, and Proteobacteria are important for substrate breakdown and concomitant power generation, as evidenced by their abundance. These results point toward the potential use of macroalgae hydrolysate as a renewable carbon source in microbial electrochemical systems for a variety of ecological functions.

2.5. Seaweeds in Biofuel Production

Biofuel is made from organic matter of natural resources. Seaweeds are biofuel feed stocks due to their high lipid content. Seaweeds can make biofuels in numerous ways. Seaweed polysaccharides can be fermented into bioethanol (Godvin Sharmila *et al.*, 2021). Pyrolysis (heating seaweed without oxygen) can also produce bio-oil, and further Biodiesel, bioethanol, and biogas can be made from bio-oil (Suhartini *et al.*, 2024). Cultivating and collecting seaweeds for biofuel is an expensive as well as difficult process. Despite these challenges, seaweed-based biofuel research continues, with many experts seeing great potential in this area. Due to technology breakthroughs and investment, seaweed-based biofuels may become a major renewable energy source in the future. The utilization of macroalgae for biofuel production also aids in the reduction of greenhouse gas emissions and does not interfere with food production. They also proliferate and produce much oil compared to traditional oil crops. It is possible to discriminate between the thermochemical (dry) and microbiological (wet) conversion methods of macroalgae for biofuels (Sikarwar *et al.*, 2017). The quantity and quality of the biofuel generated depend on the chemical composition of the macroalgae used in the pre-treatment process. Triacylglycerol (TAG) content is the best indicator of an algae's aptitude for biodiesel generation. TAGs have a high rate of biodiesel conversion, a high percentage of fatty acids, and no phosphorus, sulphur, or nitrogen. Although there is still room for development in the processes, it has been demonstrated that macroalgae may be a helpful material in conversion procedures.

2.5.1 Biodiesel

Biodiesel is traditionally produced by first extracting and purifying oil from raw material, after which the oil is treated by transesterification. Pure algal oil is too viscous and volatile to burn completely in engines, so it is transesterified (Liu *et al.*, 2018). When sunflower and two macroalgal species (*Gracilariopsis longissima* and *Chaetomorpha linum*), were used in biodiesel synthesis, natural resource consumption increased by almost 30 times. This was ascribed to the use of chemicals for the extraction of oil and the high energy needs of solvent recovery. Macroalgae's biodiesel generation also depends on lipid concentration, TAGs, and fatty acid unsaturation. Due to its favorable lipid composition, the brown alga *Sargassum myriocystum* is a promising biodiesel feedstock. New biodiesel production methods use metal oxide microspheres as catalysts to esterify and transesterify free fatty acids and triacylglycerides to biodiesel (Dong and Krohn, 2016). To prove its economic viability, macroalgal-based biodiesel manufacturing needs further optimization.

2.5.2 Biogas

Anaerobic digestion of macroalgae produces biogases, mostly methane and carbon dioxide and some H2S and NH3 is produced. Green algae have high Sulpher content, which may increase biogas H2S. The initial research on the anaerobic digestion of marine macroalgae to produce methane found high conversion rates and efficiency (Narayanan, 2024). Many studies have examined the methane production capacity of brown, red, and green macroalgae, showing great variation between species (Godvin Sharmila *et al.*, 2021). In contrast to ethanol synthesis, anaerobic digestion requires alginic acid, mannitol, and laminarin. Since the optimal process method appears to be species-specific, it is difficult to determine which species is the best raw material. Laminariaceae releases more methane in the fall than spring. Researchers looked at batch fermentations and semicontinuous mesophilic and thermophilic environments for green algae methane synthesis, and they discovered that mesophilic fermentation produced slightly more methane. Research indicates that mesophilic conditions promote methane generation for brown, red, and green algae prior to thermophilic fermentation of macroalgal biomass, resulting in methane outputs exceeding 60% of the theoretical maximum (Godvin Sharmila *et al*., 2021). The biogas has 60–70% methane and 18% CO_2, resulting in a CH_4/CO_2 ratio greater than one, which is sufficient for energy recovery. Methane output can be affected by the acid-soluble carbohydrate composition, Mannitol in brown algae and agar in red algae. Co-digesting macroalgae with N-rich substrates may boost biogas output. Studies suggest that nitrogen-deficient macroalgae had more soluble carbohydrates and produced more biogas and methane in batch digesters. Scientists also explored multiple strategies for treating ethanol residuals with the red alga *Gelidium amansii* to maximize macroalgal biomass consumption (Wen and Hsieh, 2016). Therefore, using macroalgae for biofuel production is necessary for economic upliftment, and more research is needed for development of this field.

2.6. Seaweed in Bioremediation

Bioremediation uses biological processes to degrade or change dangerous substances and reduces environmental pollutants and is therefore becoming more common. Seaweeds efficiently remove most waste water nutrients. Seaweed species like *Gracilaria verrucosa* removes Biological oxygen demand (BOD) and chemical oxygen demand (COD) better than *Ulva faciata*, although *Ulva faciata* removes ammonia better (Rahhou *et al.*, 2023). Seaweed has been widely studied and used as a waste water absorber to replace functionally activated carbon. Seaweeds remove the dye, COD, BOD, phenols, heavy metals, etc., from natural habitats (Arumugam *et al*., 2018). Macroalgae can adsorp poisonous and radioactive metal ions and recover gold and silver (Periyasamy *et al*., 2024). Seaweed biomass uses Ion exchange, complex formation, and electrostatic interaction for the biosorption of heavy metal ions, but ion exchange is the most valuable and important. Metal-binding sites in the cell walls of algae are provided by proteins and polysaccharides. The sorption capacity of a seaweed cell surface is influenced by various factors such as the number of functional groups present in the algae matrix, the coordination number of the metal ion to be sorbed, the availability of binding groups for metal ions, the formation of complexes, the affinity constants of the metal with the functional group, and the chemical state of these sites (Foday *et al*., 2021).

Physical or chemical treatments that alter seaweed cell surface structure and add binding sites can increase algal biomass heavy metal ion uptake. Marine macroalgae can remove inorganic nutrients from wastewater, making it a suitable substitute for environmentally viable aquaculture, food, and aquatic bioremediation. Green seaweed '*Ulva clathrate'* has been found to remove inorganic nutrients from water effluents efficiently. *Chaeotomorpha, Polysiphora, Ulva,* and *Cytoseria* seaweeds have been used to remove copper from synthetic aquatic medium (Deniz and Ersanli, 2018). It has been studied that powdered green and red algae (*Ulva spp. & Gelidium spp.*) removed up to 80% of DDT from soil after a period of six weeks. Seaweeds can reduce eutrophication, improve water quality, and boost low-cost aquaculture. Seaweeds can remove 90% of nutrients from intensive fish cultivation. Macroalgae has been long used in Sewage treatment, especially in tropical developing nations (Hemavathy *et al*., 2025). Red algae *Porphyra leucostica* reduces environmental and wastewater heavy metal pollution. *Porphyra leucosticta* is beneficial for biological enrichment and biological precipitation of Cd(II) and Pb(II) ions from wastewater (Ye *et al*., 2015). Marine algae biofilters have become increasingly popular for removing inorganic nutrients from fish pond effluent in integrated aquaculture systems or heavy metals from industrial discharge. *Caulerpa recemosa and Ulva lactuca* bioremediate heavy metals such as boron, lead, cadmium, and copper. They remove and absorb ammonia, phosphate, nitrate, and nitrite from nutrient-rich aquaculture, wastewater, and industrial wastewater for development and growth. Study suggests that *Caulerpa racemosa and Ulva lactuca* bioremediation of industrial dye effluents. It shows that bioremediation may completely remove pollutants from environmentally beneficial polluted saltwater, despite the technical challenges of large-scale implementation.

2.7. *Seaweed as alternative livelihood and sustenance*

Seaweeds could give alternate livelihoods for coastal communities globally. In impoverished nations with few other jobs, seaweed farming and harvesting can provide money, food, cosmetics, medicines, and bioenergy. To determine population counts depending on seaweeds, a good survey is needed. Asia-Pacific countries make and consume more seaweed products. Coastal people in this region have harvested seaweed for millennia. China, Indonesia, the Philippines, and South Korea lead Asia-Pacific and India seaweed production (FAO[2], 2019). Fujian, Shandong, and Liaoning are major seaweed producers in China. China grew 18.4 million tons of seaweed in 2018, up from 3.9 million tons in 2000. Seaweed is utilized in cosmetics, medicine, and food, such as nori, wakame, and kombu. In Indonesia, seaweed is found in coastal communities of Sulawesi, Nusa Tenggara, and Maluku. Indonesian seaweed production increased from 3.8 million tons in 2010 to 11.5 million in 2018. Seaweed agriculture is important in the Philippines, especially in Mindanao and the Visayas. From 2000 to 2018, Philippine seaweed production increased from 1.2 million to 2.5 million tons. In southern Jeollanam-do and Jeju Island, seaweed cultivation is a traditional industry. South Korea grew seaweed from 300,000 tons in 2000 to 620,000 in 2018 (FAO. 2019).

Seaweed gardening in Africa helps coastal communities survive overfishing and climate change. Zanzibar and Pemba Island are major seaweed producers in Tanzania. Seaweed agriculture has helped restore the environment and build communities in Latin America (D’Andrea *et al*., 2023). Seaweed cultivation is growing in Europe as a sustainable biomass for bioenergy and a climate change mitigation technique. Asia accounts for 90% of global seaweed production and consumption. Traditional coastal livelihoods in several Asian countries include seaweed cultivation. Since the 1970s, Indonesian coastal communities have relied on seaweed production. In the Philippines, seaweed gardening has been advocated as a sustainable alternative to fishing, reducing poverty and community development (Padilla *et al*., 2019). Sustainable seaweed cultivation practices, such as using eco-friendly farming methods, monitoring and managing environmental impacts, and

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[2] Food and Agriculture Organization

promoting local value chains and markets, can help build resilient and sustainable coastal communities and promote the blue economy, which is essential for achieving the sustainable development goals and conserving marine systems. It can provide protein and other nutrients, especially in areas where traditional fisheries are declining due to overfishing, pollution, and climate change (Vikbladh *et al.*, 2019). In conclusion, the above statements suggest that cultivation, processing and marketing of seaweeds can provide jobs to huge population and can therefore help in economical as well as social development.

3. Conclusion and Future perspective

The features of macroalgae and their different compounds are covered in this review along with information on their potential and existing commercial applications. Since algae have the potential to produce new chemicals and bioactive compounds it is critical to step up research and development efforts in this field in order to overcome technological challenges. Algae also have a plethora of uses in the biotechnology sector. It is important to use the wide variety of algae for various purposes. Algae exhibit considerable commercial potential as sources of valuable molecules and bioactive compounds that may be used to develop novel pharmaceuticals. To fully exploit them it is imperative to utilize the entire biomass of algae and investigate various potential applications. The availability of sufficient biomass at reasonable prices continues to be the primary advantage of macroalgae in production of various products having promising potential. Furthermore, its critical to keep raising the productivity of specific macroalgal species. Without requiring a lot of water or agricultural land, macroalgae are considered as a suitableresource that can be used for a wide range of products. However, further study in the area of offshore macroalgae growth is required to properly understand and evaluate these production methods. Recent advances in macroalgae-biorefineries might have a substantial impact on how sustainable resources are used.

The effective extraction, processing, and conversion of macroalgae biomass is made possible by the integration of cutting-edge technologies like enzymatic hydrolysis, high-pressure processing (HPP), supercritical fluid extraction (SFE), ultrasound-assisted extraction (UAE), microwave-assisted processing, anaerobic digestion, fermentation technologies, genetic engineering and synthetic biology, AI and machine learning in process optimization, membrane separation technologies, and hydrothermal liquefaction (HTL) in biorefinery techniques. These methods have not only increased overall productivity and efficiency, but have also encouraged ecologically and environmentally responsible behavior. Therefore, macroalgaebiorefineries are crucial to the worldwide shift towards a circular bioeconomy in accordance with the 2030 Agenda for Sustainable Development. A number of facets of the macroalgae sector, like as environmental legislation, permits for aquaculture and harvesting, the promotion of ecologically friendly methods, and research, development and innovation, may be impacted by changes in policy and regulations. Moreover, significant progress has been made in seaweed aquaculture technologies in the last few decades and a great deal of research is still being done to find useful biological and human-related compounds from macroalgae. However, there are still a number of areas that need to be investigated and assessed including the potential of metabolites to address drug resistance: a burden for humans now (Hyderi *et al*. 2025), infectious diseases, obesity and modern severe viruses.

Because of poor aquaculture management industrialization and increased urbanization, we are witnessing a decline in the quality of our water. Therefore, in order to protect the macroalgae for use in the future a more effective management system is needed. Alternatively, proactive protection of macroalgae through manual cultivation can benefit from other strategies like preserving germ plasm DNA and gene editing. Moreover, the application of contemporary technologies like artificial intelligence and process engineering need to be followed in research institutions for innovative research and development.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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