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Seaweed: A Multifaceted Marvel Driving Global Sustainability and Environmental Health

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Abstract. This article delves into the untapped potential of seaweed as a sustainable resource for the environment. Seaweed has been traditionally consumed as food by coastal communities and used as animal feed, but it also has applications in other industries. Seaweed can capture carbon and can also provide a habitat for fish species. Its benefits extend to health by reducing the use of antibiotics and boost the immune system. Several types of seaweed are often utilized in medications in their raw form. It is an important biorefinery feedstock it is used to produce a variety of materials like cosmetic products, polymeric substances (Protein, cellulose), agrifood, and food supplements with several health advantages. Seaweed has the best nutritional profile and higher polysaccharide content making it the best choice to use as a fuel resource. Seaweed farming is a simple eco-friendly approach to sustainable development and provides massive biomass for the production of food and related products in the food, pharmaceutical, cosmetic, and agro-industries. Seaweed production significantly contributes to catalyzing sustainable aquaculture by providing food to aquaculture species. All three types of red, brown, and green seaweeds have been extensively used in various wastewater treatment processes as they can store high concentrations of nitrogen in their tissues. Seaweed is an enriched source of bioactive compounds that affect the rumen microbiome, enhance rumen digestibility, and check the levels of CH_4 production in livestock. Seaweeds also act as bioindicators and bioremediation of eutrophied areas. Ultimately, seaweed represents a renewable energy powerhouse, poised to redefine the landscape of sustainable resources.

Keywords: Seaweed, Environmental sustainability, Food security, Methane emission, Eutrophication.

1. Introduction

Seaweed is a photosynthetic macroalga that can be found in mainly three groups: Phaeophyceae (Brown Seaweed), Chlorophyceae (Green Seaweed), and Rhodophyceae (Red Seaweed). They do not possess plant-like roots, but their fibrous part attaches to the bottom of the ocean or any solid structure using holdfasts. These holdfasts cannot act as nutrient absorbers as seaweed absorbs their nutrients by their leaves from water columns(Quinton, 2019).It is often consumed by coastal people for their feeding purposes and as well as for animal feed (Evans & Critchley, 2014). The requirement of seaweed as a bio-active substance and as a food progressing globally, but still it has to be cultivated and utilized more efficiently (Camus, Infante, & Buschmann, 2019; Keating, Herrero, Carberry, Gardner, & Cole, 2014). Seaweed has been a part of the human diet since the Neolithic era (7000-1700 BCE). Chinese Japanese and Korean people traditionally add seaweed to their diets for many years(FAO, Food, & Nations, 2012).

Carbon can be captured by seaweeds as the result of photosynthesis or by burying their allochthonous and autochthonous sources (Lyimo, 2016). The chemical and fuel industries are looking towards the sea for sustainable alternatives as a large amount of seaweed is grown in the Seaweed may not seem enough but research shows that it will play a significant role in future green production (M. Torres, Kraan, Domínguez, & Bio/Technology, 2019). The most important fact of all the known species of seaweed (red, brown, green) is that it contains very little amount of lignin (van Hal, Huijgen, & López-Contreras, 2014) that's why seaweed is well known for the production of 3rd generation biofuels (Offei, Mensah, Thygesen, & Kemausuor, 2018).

Kelp can provide a habitat for both native and exotic fish species that feed on seaweeds. A profuse growth of seaweeds can provide a habitat for many fish species and other invertebrates in aquaculture and natural ecosystems(Barrett, Dempster, & Swearer, 2019; O'Brien, Mello, Litterer, Dijkstra, & Ecology, 2018). By producing high-value specialized chemicals and nutraceuticals alongside lower-value goods like fuels, fertilizers, polymers, and fillers, it is possible to establish a sustainable manufacturing system with little to no waste flow, reducing adverse environmental effects and boosting economic viability (Balina, Romagnoli, & Blumberga, 2017; Diep *et al*., 2012).

Algal species are naturally effective producers of lipids, proteins, pigments, and secondary metabolites used in industry (Koyande *et al*., 2019).Wastes from aquaculture and agriculture cause eutrophication, which is the nutrient enrichment in water bodies also called nutrient pollution. This ultimately leads to a disturbance in community structure through the loss of biodiversity. Therefore, it needs to be addressed to avoid disturbance in the ecosystem. Seaweed plays a major role in eutrophication mitigation due to its ability to store and degrade organic wastes (Sompa, Tuwo, Lukman, & Yasir).

Moreover, research has proven the role of seaweed especially red seaweed *Asparagopsis taxiformis* the in reduction of CH_4 emission with its inclusion at 0.2% of dry matter intake (Kinley *et al*., 2020). In addition, seaweed is also used as a renewable energy source because of its use in biofuel production, cosmetics, and various practices after processing such as pelletizing process (M. Nazemi, R. Unnthorsson, & C. Richter, 2023; F. Pagels, A. Arias, A. Guerreiro, A. C. Guedes, & M. T. Moreira, 2022).Seaweed manufacturers rely on policymakers for assistance in managing market demand and getting over challenges including planning, policy, financial, and market constraints(Farghali, Mohamed, Osman & Rooney, 2023). The databases we used to find our data are the following: Scopus, PubMed, and Google Scholar using the keywords: Seaweed or macroalga, Environmental Sustainability, methane emission, Eutrophication, and Food security. We cited the articles to avoid copyright strikes. Moreover, those references also help us in finding more relevant data. Our review paper aimed to combine all the possible available data about seaweed, particularly for the sustainability of the environment.

2. Seaweed Contribution to Global Food Security

Global food security is a flexible operational concept that has been developing for decades. Four factors related to food security include the availability of food supply, physical and economic access to food, utilization of food, and stability of food (Mathiesen, 2015). Edible seaweeds can be an ideal dietary component for humans, especially in countries where they comprise one-fifth of the daily meal, as they provide sufficient amounts of essential micronutrients and macronutrients (MacArtain, Gill, Brooks, Campbell, & Rowland, 2007; Rebours *et al.*, 2014). As per different research, it possesses a significant amount of essential nutrients such as carbohydrates, proteins, fat, minerals, and fiber. The percentage of these nutrients per dry mass of seaweed is shown in Figure 1. The production of seaweed is annually about 32 million tons from aquaculture and cast seaweed, which makes it more important rather it is not only a healthy addition to soup, salad, and sushi (M. D. Torres, Flórez-Fernández, & Domínguez, 2019).

The production of seaweed is expected about 500 million tonnes by forecasts by 2050 (Bjerregaard *et al.*, 2016). The seaweed market is anticipated to expand by 8.9% per year until 2050 and represent 96% of the global aquaculture market (FAO *et al.*, 2012). We can extract different types of soluble fibers from seaweeds. Agar, Carrageenans, and porphyrin are present in some species of red seaweeds, and fibers such as Alginate, Fucoidan, as well as laminarin, can be found in brown seaweeds. Reportedly two species (Ulva lactuca, Enteromorpha spp.) of green seaweed provide Ulvan (Rajapakse, Kim, & research, 2011). As seaweeds provide a noticeable amount of dietary fiber, multiple studies have observed that alginate can make you feel full, leading to lower food consumption. Additionally, fucoxanthin, which is extracted from brown seaweed, may decrease the level of white adipose tissue (Lange, Hauser, Nakamura, Kanaya, & Wellness, 2015). The need to find sustainable food sources due to the growing human population and the constraints of modern food production systems has spurred the search for alternatives.

Seaweeds, which can be harvested from coastal regions or grown in offshore aquaculture systems, offer a viable and sustainable solution (Figueroa, Farfán, & Aguilera, 2021). Even cultivation of seaweed does not have typical requirements such as soil, fertilizers, and freshwater. That's why it causes fewer environmental hazards compared to other food supplies(Bapuly & Sharma, 2023). Seaweed's distinctive textures and flavors, which differ from those of traditional land crops, have brought it into the culinary spotlight, featuring it on restaurant menus, cooking shows, and even dedicated recipe books (Mauritsen, 2013).

2.1 Carbon Sequestration

Carbon sequestration, which involves the uptake of carbon dioxide from the atmosphere and its storage in solid or liquid form, is an active process aimed at reducing the amount of carbon in the atmosphere (Arehart, Hart, Pomponi, D'Amico, & Consumption, 2021). There have been speculations that the seaweed aquaculture sector may expand and cultivate seaweed offshore (beyond the shelf break), which would result in massive blue carbon (or carbon dioxide) sequestration in the ocean (Ross, Tarbuck, & Macreadie, 2022). Research conducted in 2014 identified several countries with the potential for carbon sequestration. China could capture 1,411,425 metric tonnes of carbon annually using seaweed, while Indonesia, Japan, and the Philippines have potentials of 1,109,477, 37,397, and 170,608 metric tonnes of carbon per year, respectively and others shown in Figure 2 (Sondak *et al.*, 2017). A separate study has indicated that numerous species of seaweed can fix carbon dioxide. *Gracilaria corticate*was found to have the highest percentage of CO_2 fixation, at 100%, when exposed to a dissolved CO_2 level of 5 mg/l. Nevertheless, for the majority of the species examined, CO_2 fixation was not possible in the absence of light, or under dark conditions (Kaladharan, Veena, & Vivekanandan, 2009).

Seaweed communities exhibit high levels of autotrophy, producing a surplus of organic matter via photosynthesis that surpasses the amount consumed by respiration within the ecosystem. As a result, they play a significant role in sequestering CO_2 in marine vegetated habitats (Duarte, Cebrián, & oceanography, 1996). Around 30% of greenhouse gas emissions are attributed to agriculture, which includes land-use changes resulting in the conversion of natural ecosystems into farmlands, significant emissions associated with the manufacturing and use of synthetic fertilizers, and the release of gases from cattle (Robertson, Paul, & Harwood, 2000). However cultivating seaweed in aquaculture settings provides a means of producing food that reduces the negative consequences often associated with land-based methods of food production (Duarte, Middelburg, & Caraco, 2005). BECCS, which involves the integration of bioenergy and carbon capture and storage, has been recognized as a potential approach for generating energy while reducing atmospheric carbon emissions to a net negative level (Hughes *et al*., 2012).

Seaweed can be a replacement forcarbon-intensive products with very few disadvantages but a number of advantages. We can increase the carbon sequestration efficiency of seaweed which is highly profitable and technically feasible (Pessarrodona, Howard, Pidgeon, Wernberg, & Filbee-Dexter, 2024)Both the public and private sectors have started considering the growth of seaweed farming as one of the possible Carbon dioxide removal (CDR) opportunities (Pessarrodona *et al*., 2024)

2.2 Supporting Ecological Services

The establishment of a seaweed farm has the potential to alter the intricate web of food interactions that exist within the surrounding ecosystem. The ability of an ecosystem to adapt and endure in the face of environmental changes is closely linked to its level of resilience, which is known to be influenced by biodiversity factors such as species richness (Hasselström, Visch, Gröndahl, Nylund, & Pavia, 2018). Evidence suggests that bivalve and seaweed aquaculture could offer valuable habitats for wild fish and mobile invertebrates and possibly improve their production by expanding forage, breeding, and/or predator refuge habitats (Theuerkauf *et al*., 2022). *Saccharina latissima* is a vital contributor to the biodiversity of sublittoral marine ecosystems and performs essential ecosystem functions on a macro level (Smale *et al*., 2013). These ecosystems offer a wide range of benefits to associated organisms, including other seaweeds, invertebrates, crustaceans, echinoderms, and diverse fish species, by providing shelter, feeding areas, and nurseries (Christie, Norderhaug, & Fredriksen, 2009).

Seaweed farms have the potential to create a new habitat for fish species such as Lumpfish (*Cylopterus lupus*), which is of particular interest in controlling sea-lice populations in salmon farming (Powell *et al*., 2018). Marine algae also support communities of herbivorous animals, including invertebrates such as sea urchins and gastropods, as well as vertebrates such as herbivorous fish. These animals rely on marine algae as a food source and for shelter from predators and play a key role in the complex aquatic trophic web (Butt, Méline, Pérès, & Research, 2020; Randall, Johnson, Ross, Hermand, & Ecology, 2020). Seaweeds are crucial for the establishment of submerged vegetation habitats in deep-sea, coastal, and estuarine environments, as their growth and development are primarily limited by light availability and nutrient availability (García-Poza *et al*., 2022; García-Poza *et al*., 2022).

Hence seaweed communities were discovered at depths of 295 meters in the Bahamas, which is significantly deeper than most seaweed communities typically found at depths above 100 meters (Lane *et al*., 2010). These habitats are widely recognized as the most productive on Earth, serving as critical ecosystems that support the survival and sustenance of numerous animal species, including those with economic value (Heck Jr, Hays, & Orth, 2003; Lefcheck *et al*., 2019).

2.4 Seaweed Reduces the Use of Antibiotics

Several types of seaweed are often utilized in medications in their raw form(Jamal, Olorunnisola, Jaswir, Tijani, & Ansari, 2017). The seaweed's nutritional profile and non-animal nature make it best for animal feed as a "nutraceutical" (it reduces the risk of disease and improves health) (Pomin, 2012),(Laudadio *et al*., 2015). Today many efforts are being taken to reduce the use of antibiotics in fish for this there is a recent change in immunostimulants. Seaweed is a very important immunostimulant because there are many different types of seaweed almost 11000 or more species are present and each type contains a compound that is beneficial for health. (Thepot, Campbell, & Rimmer). Dried seaweed or kelp meal as animal feed is not as common as it used to be. But some people still think that kelp meal is good for the health of the animals.(Evans & Critchley, 2014) In pig farming, farmers add antibiotics to pig feed to enhance the growth and avoid sickness but there is a risk that pigs become antibiotic-resistant for that purpose farmers add seaweed to pig feed which reduces the need for antibiotics. (Katayama *et al*., 2011) Although many kinds of species can fight against viruses & bacteria in fish and shrimp two specific types of seaweed red seaweed (Asparagopsis) and brown seaweed (Sargassum)are good against bacterial attack (Vatsos & Rebours, 2015).

2.3 Seaweed is an Important Biorefinery Feedstock

Seaweed is an important biorefinery feedstock it is used to produce a variety of materials like cosmetic products, polymeric substances (Protein, cellulose), agrifood, and food supplements with several health advantages (Abenavoli, Cuzzupoli, Chiaravalloti, & Proto, 2016),(Davis, Volesky, & Mucci, 2003). Seaweed is the most common food resource grown in the ocean good point of seaweed is that it doesn't need many resources to grow like corn maize etc. that's why it can be easily grown in large quantities *(Khounani et al*., 2019). The components that are present in seaweed biomass are up to 70% or more sugar, sugar alcohol, and sugar acids (Jang, Shirai, Uchida, & Wakisaka, 2012). Most of the components are present in the form of polysaccharides while fewer are present in the form of monomers. By the extraction of seaweed raw material is produced that is also rich in sugars. This extracted seaweed is not used for fermentation much because it has several drawbacks the number of carbohydrates is not similar in each seaweed it depends on the season and type of seaweed. Sugar present in seaweed is involved in the production of biofuels and plastic poly (3-hydroxybutyrate).

Seaweed contains sugars but due to the presence of polymers microbes are unable to utilize it. Some studies show that biofuel and poly (3-hydroxybutyrate) can be produced directly by the breakdown of seaweed polymers (Wargacki *et al*., 2012),(Lim *et al*., 2019),(Yamaguchi *et al*., 2019). Brown macroalgae are the most abundant type of seaweedand arerich in carbohydrates (Yazdani, Zamani, Karimi, & Taherzadeh, 2015). Brown seaweed is the most important feedstock that is used to produce biofuel (R. Zhang, Yuen, de Nys, Masters, & Maschmeyer, 2020),(Greene, Gulden, Wood, Huesemann, & Quinn, 2020). But for now, there are fewer studies about the cost and benefits of biofuel from brown seaweed (R. Zhang *et al*., 2020).Biogas as a biofuel that is produced from seaweed is less toxic as it helps to reduce greenhouse gases that are released into the environment by 42%-82% as compared to natural gas (Florentinus, Hamelinck, de Lint, & van Iersel, 2008),(Pechsiri *et al*., 2016).

2.5 Seaweed into Biofuel

Seaweed has been grown for centuries in some places of the world. It has many benefits including use for food, beauty products, pharmaceutical products, biofuels, and many more (Buschmann *et al*., 2017b), (Ghadiryanfar, Rosentrater, Keyhani, Omid, & Reviews, 2016), (Soleymani & Rosentrater, 2017). Seaweed has the best nutritional profile and higher polysaccharides percentage due to which it is used as a fuel resource(Lang, Hodac, Friedl, & Feussner, 2011). Almost all types of macroalgae have 0% lignin, making it best for producing third-generation biofuel (Offei *et al*., 2018)For this purpose, seaweed is processed through enzymatic activities just after the harvesting, as a result, polysaccharides are separated. After that separated polysaccharides are fermented to produce various types of biofuels. In the past, people thought that seaweed was only used to produce bioethanol although this is a very alarming situation for the economy. The cascading approach is used to overcome this problem (van Hal *et al*., 2014).

Bioethanol production from seaweed is very beneficial for the environment as it doesn't need freshwater consumption and chemical fertilizers. When seaweed is processed, it leaves pulp, which is rich in carbohydrates used to produce bioethanol (Chung, Beardall, Mehta, Sahoo, & Stojkovic, 2011).In 2013 scientists discovered that when seaweed biomass is being processed about 25% of pulp is left of which 40% is cellulosic material and 20% is hemi cellulosic material (Kumar, Gupta, Kumar, Sahoo, & Kuhad, 2013).On consecutive enzymatic hydrolysis, about 88% of cellulose is converted into sugars. These sugars are then used to produce bioethanol during fermentation with an efficiency of 86% in the term of generating bioethanol (McHugh, 2003). Many scientists work on how bioethanol is produced from seaweed pulp. For this purpose, scientists used different types of seaweed and observe which works best.

In 2016 Yeon and other scientists produced bioethanol from *Sargassum sagamianum* seaweed pulp they observed that about 0.386g of bioethanol is produced from each gram of seaweed pulp (Lee *et al*., 2011).On the other hand, in 2011 Yanagisawa and his colleagues produced bioethanol by using a group of plants which include *Ulva pertussa*, *Gelsemium elegans*, and *Bergenia crassifolia*, they observed that about 0.381g, 0.376g, and 0.281g bioethanol produced by respective plants (Yanagisawa, Nakamura, Ariga, & Nakasaki, 2011).In 2013 Kumar and his colleagues discovered that the highest amount of bioethanol (that is 0.46g) is produced by *Gracilaria verrucosa*seaweed pulp (Kumar *et al*., 2013).In 2015 Kim and his colleagues discovered that a very important source of bioethanol production is red seaweed (*Gelidium amansii*) (Gomes-Dias, Romaní, Teixeira, Rocha, & Engineering, 2020) This species is rich in carbohydrates sugar will be produced by the process of hydrolysis. After that, it is converted into bioethanol after fermentation. (Kim, Wi, Jung, Song, & Bae, 2015) There is a new approach called seaweed biorefinery is used to convert seaweed into an excessive amount of biofuel and biogas *(Geldermann et al*., 2016).

An innovative approach to green energy is the production of sustainable bioethanol from residual carrageenan found in *Eucheuma cottonii.* Bioethanol production from seaweed waste contributes to waste reduction and environmentally friendly energy production, supporting sustainable practices and the objectives of the circular economy (Hasan & Technology, 2024)

2.6 Seaweed-based Products and their Environmental Benefits

Algae are water-dwelling species with about 3000 different breeds and have the fastest rate of reproduction, making them more diversified than terrestrial plants (Suganya, Varman, Masjuki, & Renganathan, 2016). Seaweed farming is an easy, environment-friendly, and sustainable way to produce a lot of biomass that can be used for food and other products, helps to relieve pressure on land, aids in ocean recovery, and removes nutrients from eutrophic water (Jagtap & Meena, 2022). Seaweed farming produces biomass which is then used to make various novel products in different industries such as food, medicine, cosmetics, and agriculture as well as provides hydrocolloids such as agar, alginate, and carrageenan (Jagtap & Meena, 2022).

Seaweeds can be considered a viable option in contrast to conventional biomass feedstock like corn or soybean, as they grow quickly and yield high volumes without posing a risk to food and land resources also seaweeds are nutritious containing protein, dietary fibers, and phytochemicals that can be added to animal feed(Morais *et al*., 2020). Algae have natural pigments called carotenoids, chlorophylls, and phycobiliproteins that can be used to make vitamins, cosmetics, pharmaceuticals, coloring agents, and animal feed (Chew *et al*., 2017). In the skin care industry extracts from arthrosis and chlorella are commonly used for their emollient, refreshing, or regenerative products, anti-irritants in peelers, anti-aging creams, and sun protection creams (Trivedi, Aila, Bangwal, Kaul, & Garg, 2015). These algae are frequently added to foods including bread, ice cream, noodles, candies, and biscuits to boost their nutritional and health benefits (Mobin & Alam, 2017). The pharmaceutical and food sectors utilize almost 99% of all the farmed seaweed for producing substances that can thicken or gel (Buschmann *et al*., 2017a). Biofuels are being hailed as the most effective short-term alternative to petroleum because of the negative impact of fossil fuels on the environment and the rising global energy demand (Wang *et al*., 2020). Microalgae biopolymer offers an advantage over other feedstocks because of its unique self-sustaining system which helps to reduce greenhouse gas emissions (Devadas *et al*., 2021).The use of seaweed feedstock can lessen our dependence on fossil fuels, create affordable and environmentally friendly products and biofuels, and promote the development of sustainable biorefinery methods (Farghali *et al*., 2023)Seaweed in medical products can help reduce dependence on chemicals, and combat antimicrobial resistance, and improve human and animal health (Farghali *et al*., 2023).

2.7 Seaweed in Aquaculture and Sustainable Fisheries

Aquaculture is one of the rapidly growing methods of food production which involves finfish, shellfish, and seaweed farming in both freshwater and saltwater environments (In, 2020). Seaweed production can significantly contribute to catalyzing sustainable aquaculture in many developing countries (Chowdhury, Hossain, AftabUddin, Alamgir, & Sharifuzzaman, 2022). Fish and shrimps in aquaculture are fed with algae as they possess advantageous properties (Suganya *et al*., 2016) such as improved fertility, improved immune response, maintaining healthy skin, aiding in weight control, and providing a shiny coat. China leads the cultivation of seaweed with an approximate percentage of 56.82 while some other countries also contribute to cultivation such as the Philippines, South Korea, Japan, etc, and their rate of production is shown in Fig. 3 (Adeniyi, Azimov, & Burluka, 2018).

An integrated multi-trophic aquaculture (IMTA) technique which is used in offshore aquaculture (Biswas *et al*., 2020) can be utilized to get rid of inorganic compounds and mitigate their harmful impact on the environment (Califano, Kwantes, Abreu, Costa & Wichard, 2020). Due to the significant rise in annual seafood consumption and human population growth problems like coastal eutrophication have become more severe because of the rapid expansion of fed aquaculture (such as fish and shrimp) and the emission of nutrient-rich effluents of aquaculture (Read & Fernandes, 2003; Troell, Kautsky, & Folke, 1999). Seaweed aquaculture which accounts for 51.3% of the Mari culture world and has grown by 6.2% annually from 2000 to 2018 provides a versatile, environmentally friendly way to combat eutrophication, conserve biodiversity, and mitigate the effects of climate change (Duarte, Bruhn, & Krause-Jensen, 2022).Seaweed can replace soybeans in fish meals, offering both nutritional and economic advantages for fish and shrimp farms (Farghali *et al*., 2023). Seaweed offers vital nutrients as a sustainable and cost-effective addition to fish feed, promoting better growth, health, and disease resistance against invasive pathogens in farmed fish(Siddik *et al*., 2023)

2.8 Seaweed as a Solution for Waste Management

Algae are a wide variety of organisms that can make their food through photosynthesis and can exist as single-celled or multi-celled organisms in both freshwater and marine habitat (Bharathiraja *et al*., 2015). There are three kinds of seaweed called red, brown, and green seaweeds that have been extensively used in a variety of ways to clean up dirty or wastewater to replace functional activated carbon as an adsorbent (Arumugam *et al*., 2018). High nutrient input into the sea is a result of industrialization and intensive agriculture (Jagtap & Meena, 2022). Seaweed's important ability is the capability to store large amounts of nitrogen in its tissue (He *et al*., 2008).To reduce nutrients and their negative effects on the waters, the idea of growing seaweed in wastewater was driven (Stedt, Pavia, & Toth, 2022). In addition to the removal of nutrients, phenolic compounds, and dyes are also removed from wastewater (Arumugam *et al*., 2018). Wastewater can be treated through range of technological approaches like reverse osmosis, photodegradation, adsorption, coagulation, electrochemical, biochemical degradation, and ion exchange (Hernandez-Ramirez & Holmes, 2008). Among these technological approaches adsorption is viewed as highly practical, economical and easily manageable approach to purify and treating wastewater(Yadav, Thakore, & Jadeja, 2022). Adsorption is the process where adsorbate (like particles, atoms, or ions) clings to the surface of another substance called an adsorbent (Aljamali, Khdur, & Alfatlawi, 2021).A sustainable method for producing environmentally friendly adsorbents has emerged using algal and seaweed biomass (Znad, Awual, & Martini, 2022).Biochar has proven to be an effective adsorbent. Its ability to capture heavy metals is attributed to its distinctive characteristics such as porous structure, extensive surface area, reactive functional groups, and chemical properties stability (Xiao *et al*., 2020). Studies show that *Fucus vesiculosus* seaweed bio adsorbent (FVSB) effectively removed 98.71% of Methylene Blue (MB) and 96.68% of Rhodamine B (RB) from water (Yadav *et al*., 2022).

2.9 Effect of Seaweed and their Derived Bioactives on the Microbiome of Ruminant Livestock

Rumen is an anaerobic and methanogenic fermentation chamber of the gastrointestinal tract containing microorganisms.These microorganisms make the nutrients available to their host by breaking down the feed the host animal takes (Matthews *et al*., 2019).Microorganisms in the rumen include unicellular bacteria, multicellular ciliates and fungi, and non-cellular viruses (Firkins & Yu, 2015). This community of microbes is necessary for the ruminants to sustain life because the enzymes that host genetic material encode are unable to degrade cellulose contained in their feed. The microbiome produces amino acids and volatile fatty acids that the host uses to obtain energy and biosynthesis (Taxis *et al*., 2015).

Moreover, bioactive compounds are also present in seaweed which are used in dietary choices (Venkatesan *et al*., 2015).One of the analyses showed that *Asparagopsis taxiformis* contains largeconcentrations of the halo form,dibromo methane, and bromoform and dibromochloromethane are present to a measurable degree. This seaweed specie was reported to contain more than 100 halogenated compounds(Nørskov, Bruhn, Cole, & Nielsen, 2021). Iodine and bromine-containing compounds were also found in several seaweed species, *Dictyota dichotoma, Saccharina latissima*, and *Laminaria digitate*(Nørskov *et al*., 2021). The profile of bioactive compounds and nutrition of seaweed shows algal polysaccharides i.e. fucoidan, laminarin, carrageenan, alginate, agar, and ulvan as important components not only for human health but also for animals as food additives. Different species of seaweed have different protein content in them (Healy *et al*., 2023).

Ascophyllum nodosum, brown seaweed, affects the microbiome of the rumen by reducing the population of *E.coli*shedding in feces. Thus, brown seaweed changes the rumen microbial population and rumen fermentation (Zhou *et al*., 2018).The real-time PCR assay result showed that brown seaweed extracts notably affected the bacteria (i.e.*Fibrobacter succinogenes, Ruminococcus flavefaciens, Ruminococcus albus)*methanogens which are ciliate associated and methanogenic archaea enhanced rumen digestibility. This improvement is made possible by the natural bioactive compounds present in seaweed species, which change the metabolic activities of microorganisms (Y. Y. Choi *et al*., 2021). According to another study, red seaweeds do not significantly affect the total population of bacteria, protozoa, and archaea (Molina-Alcaide *et al*., 2017). Seaweeds can lead a state in achieving sustainable objectives because it takes less cultivation time, yield high biomass, and are enriched sources of dietary fibers and secondary metabolites (Nørskov *et al*., 2021).

2.10 Reduction of Methane Emission

Methane produced from rumen fermentation contributes as a major factor to greenhouse gases in the environment. Different seaweed species were found to reduce CH4 production when used as feed additives. Red seaweed *Asparagopsis taxiformis* was found effective in CH_4 reduction in lactating dairy cattle, and sheep (Roque *et al*., 2021). Besides *A.taxiformis* other seaweed species of the genus *Asparagopsis* are potential anti-methanogens with low inclusion rates i.e. 2% inclusion of seaweed decreased CH_4 production by 99%. Species of the genus *Oedogonium* are also found anti-methanogenic but they have less potential as compared to *Asparagopsis* species (Machado *et al*., 2016). Therefore, commercial production of *Aparsagopsis* species could be very beneficial for the environment and could improve the economy of the agriculture sector as this seaweed could have a revolutionary effect on the management of emission of greenhouse gas (Kinley *et al*., 2020). Brown seaweed *Zonaria farlowii* was also determined for its potential to mitigate CH_4 production. *A.taxiformis* and *Zonaria farlowii* now fall under promising strategies for methane reduction in California which produces milk on the largest scale in the US(Brooke *et al*., 2020).Another seaweed species *Eucheuma cottonii* has been found to decrease CH_4 production by up to 16.74% and increase digestibility by up to 11.17% (Widiawati & Hikmawan, 2021). On the whole, Differences in seaweed quality based on bromoform concentration and the percentage of seaweed inclusion determine CH_4 reduction levels in livestock (Roque *et al*., 2021).A dietary treatment was conducted to observe effects on rumen fermentation which concluded that Ascophyllum nodosum extract had a mitigating effect on methane emissions by enhancing volatile fatty acids production(VFA)(Roskam *et al*., 2024).

2.11 Eutrophication Mitigation

Eutrophication is a process in which nutrients (mainly nitrogen and phosphorus) become enriched in waterbodies and promote algal growth. Thus, it is also referred to as nutrient pollution (Rose *et al*., 2015). Fish aquaculture causes eutrophication because feeds contain nitrogen and phosphorus which eventually enter into the environment, causing nutrient enrichment and disturbing the equilibrium of the natural aquatic community (Herath & Satoh, 2015). Seaweeds also contribute to the bioremediation of phosphorus and nitrogen. According to research, seven seaweeds remove 70615t nitrogen and 8515 t phosphorus per annum (Gao, Gao, Jiang, Jian, & He, 2021).

Additionally, an analysis showed that seaweed harvesting on large scale can alleviate 8% of yearlong net nitrogen and 60% of yearlong net phosphorus from the Swedish West Coast basins(Hasselström *et al*., 2020). Following a study in China, *Laminaria* alleviated the highest amount of nitrogen and phosphorus among all seaweed species. However, the nitrogen removal capacity of *Laminaria* was next to *Gracilaria* which has the highest nitrogen removal capacity. *Gracilaria* is, therefore, an excellent tool for extraction because of its easier cultivation, comparably high growth rate, great tolerance of surrounding physical environmental parameters, and greater ability to store nitrogen in its tissues *(Rose et al*., 2015). *Undariawas* was positioned third as a nutrient removal contributor. Pophyra was found to have comparably low removal capacity. Additionally, the phosphorus removal capacity of *Eucheuma* was highest and three times higher than that of *Laminaria (Zheng et al*., 2019).*Saccharina altissimo,commonly named sugar kelp seaweed, also acts as bioremediation by removing 0.4-kilogram phosphorus and 4.08-kilogram of nitrogen for every tone of freshly cultivated biomass (Thomas et al., 2021).* Moreover, Seaweed was found hyperaccumulator of heavy metals, thus, considered an important bio-indicator for atrophied areas (El-Mahrouk *et al*., 2023). Another method of removing endogenous eutrophication of seawater is artificial upwelling. In this nutrients are released from sediments in an orderly manner which becomes available to the kelp or seaweed on the surface layer and seaweed then converts these nutrients into biomass, thus, improving the marine environment (Fan *et al*., 2019).

2.12 Seaweed as a Renewable Resource for the Environment

Seaweed biomass can lead to a sustainable future by replacing fossil-based materials and fertilizers, considered a need of the hour. Seaweed biomass may be among the most important sources of renewable energy (bio-resource) for the next generations (Hasselström *et al*., 2020). Seaweed can serve in the field of agriculture through its usage in the manufacture of bio-fertilizers and bio-stimulants for plant growth. It can also be used for the production of renewable energy such as biogas (Michalak, 2020).

Moreover, seaweeds are also used in the production of bioplastic films especially Kappa-carrageenan obtained from *Kappaphycus alvarezii* seaweed plays a key role in the production of bioplastic film. This is due to seaweed's characteristic of being rich in polysaccharides. Further, the mechanical strength and physical properties of bioplastic films can be improved by using plasticizers because the carrageenan component of seaweed makes the bond with plasticizers forming bioplastic film (Sudhakar, Magesh Peter, Dharani, & Research, 2021). Seaweeds also provide cellulose nanofibers (CNFs) rich in alginate, which is used in the production of aerogels due to its natural flame-retardant activity. This process of isolating CNFs is combined with two other procedures (Non-toxic crosslinking $CaCl_2$and ice-templating) to synthesize an anisotropic gel with good mechanical features for insulation applications, without using harmful additives. Thus, this multifunctional green insulation material (aerogel) acts as a renewable resource (Berglund *et al*., 2021).

Thermochemical characterization showed that macroalgae species i.e. seaweeds, with fixed carbon, high volatile matter, and less content of ash can bea renewable resource for the production of biofuel because they are rapidly growing crops independent of arable land for cultivation. A specie *Porphyra purpurea* showed the best thermochemical profile being balanced in the composition of carbohydrate and protein content (Cassani *et al*., 2022). As fossil fuels are depleting and the search for alternative sources for biofuels is a major concern, seaweed biomass is attracting attention because of its high growth rate, efficient photosynthesis, and carbon-neutral emissions. Therefore, the feasibility of seaweed biorefinery should be a key concern for emerging green technologies (Del Río *et al*., 2020).

Seaweed is also used efficiently in biofuel production i.e. biodiesel and bioethanol when it is used as a biostimulant of algal species. Seaweed stimulates the growth of microalgae *Chlorella variabilis*, thus, enhancing the productivity of lipids and carbohydrates which is then further used to produce biodiesel and bioethanol (Sati, Chokshi, Soundarya, Ghosh, & Mishra, 2021). Seaweeds are also valuable sources of compounds used in cosmetics such as minerals, amino acids, vitamins, trace elements, antioxidants, *etc*.; with anti-inflammatory, hydrating, and rejuvenating results. LCA (Life Cycle Assessment) methodology showed that the extract from brown algae, *Fucus vesiculosus,* has less impact on the environment as compared to vitamin C and green tea(F. Pagels, A. Arias, A. Guerreiro, A. C. Guedes, & M. T. J. P. Moreira, 2022). Moreover, in research, *Alaria esculenta* represented the highest concentration of phenolic and flavonoid compounds, with the peak activity as an antioxidant. In addition, *A. esculenta* showed great anti-enzymatic activity as compared to *P. palmaria* and *U. lactuca*, promising their sustainable role in products that result in skin whitening and anti-aging and potential active ingredients in cosmetic and cosmeceutical formulations (Castejón, Thorarinsdottir, Einarsdóttir, Kristbergsson, & Marteinsdóttir, 2021).

Seaweed is also used as a cosmetic ingredient in the preparation of face masks used to treat skin damage caused by UV radiation. The seaweed-based face mask forms a gel that can maintain the mask preparation due to its thermos-reversibility (Prima & Andriyono, 2021). Furthermore, seaweed pellets are also used as a renewable fuel feedstock as their combustion produces heat in Combined heat and power plants (CHP plants). Also making seaweed pellets has been proven very economical and beneficial because the storage and transportation of pellets are easier and more cost-effective due to their low humidity and high density than raw biomass (M. Nazemi, R. Unnthorsson, & C. J. B. Richter, 2023).

Nutrients	Red seaweed	Brown seaweed	Green seaweed	
carbohydrates	36-74	4-70	15-65	(Holdt & Kraan, 2011)
Proteins	30-40	15	30	(Murata & Nakazoe, 2001)
Lipids	1.56	7.98	11.17	(Khotimchenko, 2005), (Gosch, Magnusson, Paul, & De Nys, 2012), (K. Choi, Nakhost, Barzana, & Karel, 1987)
Minerals	7–31.15	5–29.78	3.15–25.23	(Alghazeer *et al*., 2022)
fibers	10–59	10–75	29–67	(Charoensiddhi, Abraham, Su, Zhang, & Research, 2020)

Fig. 1. Table shows the Percentage of essential Nutrients per dry mass of seaweeds.

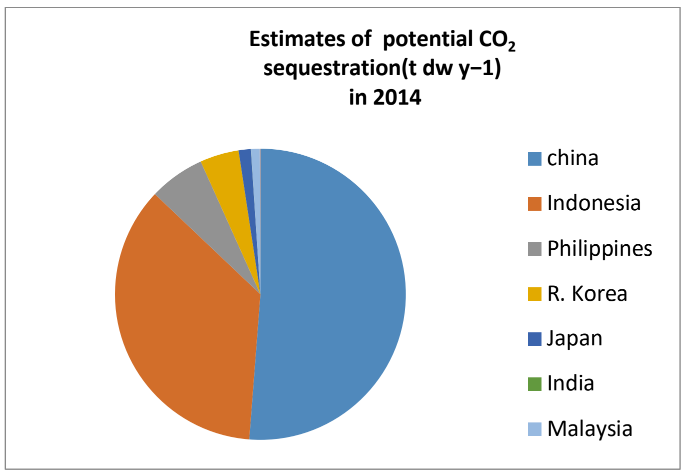

Fig. 2. Piechart show the Estimates of potential CO_2 sequestration(t dw y−1) in 2014 (Sondak *et al*., 2017).

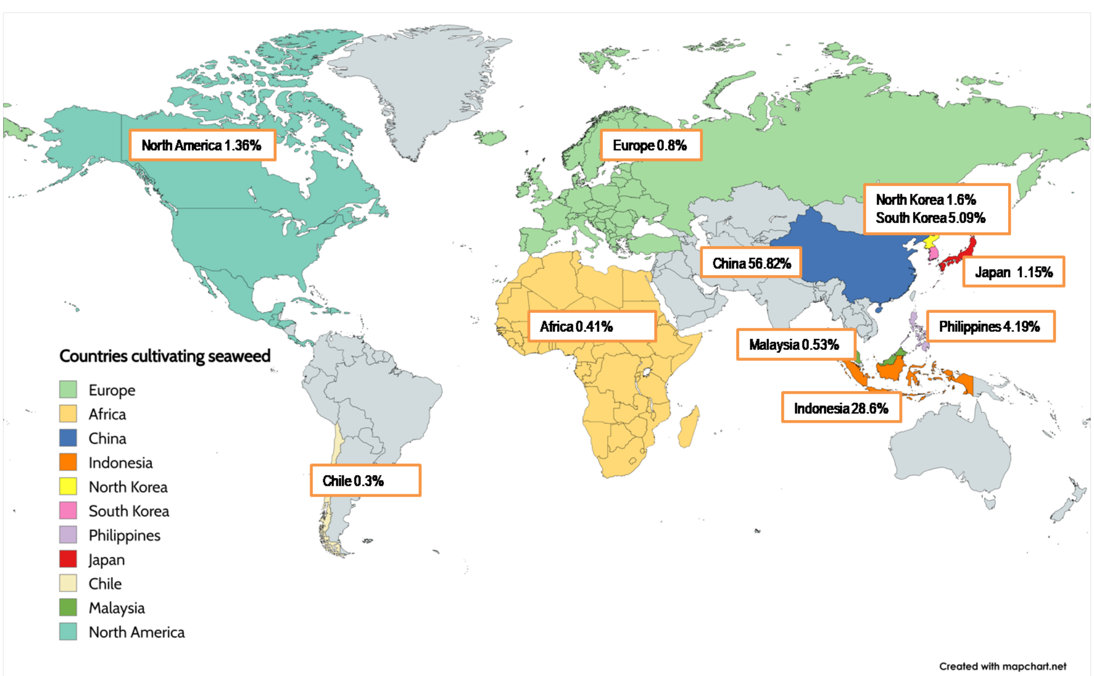

Fig. 3. Map shows countries around the world that cultivate seaweed and global seaweed cultivation in the year 2019. Created using Map chart(https://www.mapchart.net/) with data from (L. Zhang *et al*., 2022).

3. Conclusion

Our environment is facing many environmental problems like greenhouse effect, Global warming, and others climate changes. The multidimensional benefits of seaweed emphasize its pivotal role in addressing these critical global challenges while promoting sustainability. Furthermore, integrating seaweed into aquaculture and sustainable fisheries practices can enhance the production of seaweed-derived products while reducing environmental impact.Seaweed may be a better option to tackle environmental issues but further research and investment are crucial. Looking ahead, policy makers and industries should consider promoting seaweed cultivation as a renewable resource. By harnessing the full potential of seaweed, we can not only address current environmental challenges but also pave the way towards a more resilient and sustainable future.

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الأعشاب البحرية: أعجوبة متعددة الأوجه تدفع عجلة الاستدامة العالمية والصحة البيئية

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المستخلص. تتعمق هذه المقالة في الإمكانات غير المستغلة للأعشاب البحرية كمورد مستدام للبيئة. كانت الأعشاب البحرية تستهلك تقليديًا كغذاء من قبل المجتمعات الساحلية وتستخدم كعلف للحيوانات، ولكن لها أيضًا تطبيقات في صناعات أخرى. يمكن للأعشاب البحرية التقاط الكربون ويمكنها أيضًا توفير موطن لأنواع الأسماك. تمتد فوائدها إلى الصحة من خلال تقليل استخدام المضادات الحيوية وتعزيز جهاز المناعة. غالبًا ما يتم استخدام عدة أنواع من الأعشاب البحرية في الأدوية في شكلها الخام. إنها مادة خام مهمة للتكرير الحيوي تُستخدم لإنتاج مجموعة متنوعة من المواد، مثل مستحضرات التجميل والمواد البوليمرية (البروتين والسليلوز)، والأغذية الزراعية، والمكملات الغذائية ذات الفوائد الصحية العديدة. تتمتع الأعشاب البحرية بأفضل ملف غذائي ومحتوى أعلى من السكاريد، مما يجعلها الخيار الأفضل للاستخدام كمورد للوقود. تعد تربية الأعشاب البحرية نهجًا بسيطًا صديقًا للبيئة للتنمية المستدامة، وتوفر كتلة حيوية ضخمة لإنتاج الغذاء والمنتجات ذات الصلة في الصناعات الغذائية والصيدلانية ومستحضرات التجميل والزراعة. يساهم إنتاج الأعشاب البحرية بشكل كبير في تحفيز تربية الأحياء المائية المستدامة من خلال توفير الغذاء لأنواع تربية الأحياء المائية. تم استخدام جميع الأنواع الثلاثة من الأعشاب البحرية الحمراء والبنية والخضراء على نطاق واسع في عمليات معالجة مياه الصرف الصحي المختلفة، حيث يمكنها تخزين تركيزات عالية من النيتروجين في أنسجتها. الأعشاب البحرية هي مصدر غني بالمركبات النشطة بيولوجيًا التي تؤثر على ميكروبيوم الكرش وتعزز قابلية هضم الكرش، وتتحقق من مستويات إنتاج الميثان في الماشية. كما تعمل الأعشاب البحرية كمؤشرات بيولوجية وتطهير بيولوجي للمناطق الملوثة. وفي نهاية المطاف، تمثل الأعشاب البحرية قوة طاقة متجددة، وهي مستعدة لإعادة تعريف مشهد الموارد المستدامة.

الكلمات المفتاحية: الأعشاب البحرية، الاستدامة البيئية، الأمن الغذائي، انبعاث غاز الميثان.