

Seaweed Biorefining to Generate Climate and Livelihoods Benefits with Minimal Waste

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Summary

Seaweed farming has the potential to absorb and sequester climate-warming carbon while contributing to nature-positive industries and coastal livelihoods. Most farmed seaweed is either sold directly as human food or is processed into products for the food, pharmaceutical, and cosmetic sectors. For many seaweed products, only one compound is extracted (“single-stream processing”) and up to 75-80% of seaweed biomass is discarded. Single-stream processing can limit the types of seaweed products that come to market to those with the highest economic value (such as the use of hydrocolloids as a thickening agent), rather than lower-value products with higher climate mitigation potential (such as biomass used in bioplastics and construction materials).

Seaweed biorefineries are a way to create value from material that would otherwise be discarded as waste. In a biorefinery setting, compounds left over from one extraction process serve as feedstock for subsequent products. Waste in seaweed processing is reduced and companies can increase revenue through the sale of additional products. Importantly, a biorefinery setting may enable manufacturers to co-produce low-value products with high climate mitigation potential alongside higher value products.

The seaweed biorefining industry is currently in the early stages of development, and this report seeks to inform manufacturers and investors about potential opportunities of biorefining, with the goal of catalyzing growth in the seaweed sector. Four companies currently exploring commercial-scale seaweed biorefining are discussed to illustrate the state of the industry.¹ These companies represent different operating models with different processing capacities and startup costs, which allows each company to cater to different regions and farms.

Biorefining of seaweed-based products presents a new approach to seaweed processing which is applicable to many farmed seaweed species to increase production of both high value and greenhouse gas mitigating products. We emphasize that further research and thorough environmental impact assessments are needed to support sustainable development of the industry and ensure the climate-positive benefits of seaweed farming are fully realized.

Introduction

Seaweed processing is mainly focused on extraction of high value compounds for use in the food, pharmaceutical, and cosmetics industries. A single stream production process is commonly used, resulting in large amounts of unused biomass and other residues, which are typically discarded. When large amounts of chemicals and solvents are used for extraction, it may result in degradation of non-target compounds, limiting uses for the unused biomass. By using greener extraction methods, sequential extraction of compounds and utilization of the remaining biomass becomes feasible. This type of industrial process is called a cascading biorefinery. Businesses based on such biorefineries seek to maximize profit by valorizing a greater portion of the seaweed biomass, resulting in a substantial reduction in waste and production of a portfolio of products. By doing so, there is potential for seaweed to become a feedstock for a greener bioeconomy. What would normally be discarded is instead processed into new products or used for the extraction of valuable compounds. While a cascading biorefinery does not explicitly focus on eco-friendly production, the minimization of waste coupled with a more limited use of chemicals aligns well with the creation of a more environmentally friendly production process.

EDF has previously identified several products ([link](#)) which it believes have potential to mitigate greenhouse gases in the atmosphere through long-term storage of the carbon in seaweed, replacement of conventional products with high GHG and ecological footprints, or through methane suppression pathways. These include biostimulants, bioplastics, methane suppressants, construction materials, and biofuels. LCAs are needed to accurately quantify the climate mitigation potential of each product. Parts of the production, transport, and use processes result in GHG emissions while other parts may result in GHG avoidance or suppression. Except for biostimulants, seaweed products with climate mitigation potential tend to have a low sale price and markets that are still being developed. This makes them less appealing to manufacturers than the high value compounds which they typically produce. By coupling the production of GHG mitigating products with higher value compounds and products, a biorefinery may be profitable and have a positive environmental impact.

When selling seaweed into conventional supply chains, seaweed farmers are generally price takers who sell fresh seaweed or dried biomass to aggregators for a low price. In many areas, seaweed farmers take on large amounts of debt each year to enable the purchase of necessary farming inputs such as propagules and equipment. Farmers are often forced to sell their harvest at a discount to their financiers, making it hard for them to cover their debts from the previous farming cycle. During poor harvest years, they may remain in debt even after the harvest. Lack of access to farming inputs and predatory loan practices like these perpetuate a cycle of poverty for seaweed farmers in many coastal communities (Bureau of Fisheries and Aquatic Resources, 2022).

EDF hopes to enhance livelihood opportunities in these areas by enabling the manufacture and sale of value-added seaweed products. Future work will discuss the manufacture and sale of value-added seaweed products at the community level in areas with less access to capital, investment, and technical knowledge. This report focuses on biorefinery concepts which operate at a larger scale than these cottage level industries, however, it does note opportunities for farmers and coastal communities to benefit from these initiatives through ownership and operation of micro biorefineries. This can potentially allow communities to capture the value-add of seaweed processing. Several companies have begun to develop portable biorefinery concepts which can fit into several shipping containers (or fewer) and would cost significantly less to purchase than a large scale centralized biorefinery.

Energy used during processing is a key economic and environmental consideration. Seaweed is often dried immediately post-harvest to preserve bioactive and other valuable compounds and make it easier to transport. Unless sun-dried, this is a costly and energy intensive process. Even sun drying seaweed is dependent on consistently good weather and large amounts of space to be feasible. Processing freshly harvested seaweed is preferable, however this requires the biorefinery to be located close to where the seaweed is harvested to reduce transportation costs and enable immediate processing of the seaweed, before valuable compounds begin to degrade. Considering these factors, it is generally preferable to locate a biorefinery on or near coastal areas with a sufficiently large supply of seaweed. One process proposed in this paper details a concept which can produce some combination of hydrocolloids, lipids, pigments, protein, a mineral-rich liquid extract (biostimulant), and cellulose from fresh seaweed biomass. This model may be profitable and could have a positive environmental impact through the co-production of high-value compounds along with those which contribute to GHG mitigation. We anticipate GHG mitigation will be maximized when the liquid extract is sold as a biostimulant, the hydrocolloids are processed into bioplastic, and the cellulose is used as a feedstock for biofuel, as a filler or reinforcing agent in bioplastics, and in construction materials.

While we are not aware of any seaweed biorefinery companies currently operating at full commercial scale, several companies have plans to scale up their operations in the coming years. Four such companies are detailed in this paper. A strong proof of concept by these companies may increase interest and investment seaweed biorefineries and aid in the development of markets for seaweed products with GHG mitigating potential.

Types of Seaweed

Seaweed can be classified into three major types: green, red, and brown. The different natural pigments present in each type determine their color. In 2019, 35.8 million tons of seaweed were produced globally. 34.7 million tons (97%) were farmed and 1.1 million tons (3%) were wild harvested (Cai et al., 2021). 52% of farmed seaweed was red, 47% was brown, while only .04 % was green (FAO, 2021; Saji et al., 2022).

Brown Seaweeds

Saccharina japonica and *Undaria pinnatifida* (both are sometimes known as kelp) are the most commonly farmed brown seaweeds. *Saccharina japonica* is primarily used for alginate production, human food (kombu), and aquaculture feed. *Undaria pinnatifida* is used for human consumption (wakame) and as aquaculture feed (Hatch Innovation Services, n.d.). Brown seaweed is highly valued for alginate production, a hydrocolloid used as a gelling and texturizing agent in food and cosmetics. Alginophytic seaweeds constitute about 10–30% alginate by dry weight, with the remaining fraction of seaweed generally being discarded as a waste effluent (Baghel et al., 2020). A variety of side stream products, including liquid sap (biostimulant), minerals, protein, and cellulose have been identified as suitable products that can be extracted from remaining biomass following alginate extraction (Baghel et al., 2020).

Red Seaweeds

The most commonly produced red seaweeds belong to the *Eucheumatoid*, *Pryopia*, and *Gracilaria* groups. *Eucheumatoid*, are mainly produced in Indonesia, Malaysia, and the Philippines and are primarily utilized for carrageenan production. *Euchema denticulatum* and *Kappaphycus alvarezii* are two commonly farms *Euchemaoids*. *Kappaphycus* is more highly valued for its higher quality carrageenan (Tahiluddin et al., 2023). *Pyropia* (nori) are mainly produced in China, South Korea, and Japan and are consumed as a food source in the form of nori sheets and in other food products. *Gracilaria* species are mainly produced in China and Indonesia. While it is highly valued for agar production, it is also popular in aquaculture as abalone feed, and for human consumption (Hatch Innovation Services, n.d.).

Green Seaweeds

Green seaweed is the least commercially utilized type of seaweed. It is abundant in the ocean, particularly in intertidal zones (Xu et al., 2023). Green seaweed is made up of amino acids, fatty acids, and dietary fibers, polysaccharides, polyphenols, pigments, and other bioactive active substances. These bioactive compounds have been shown to have antioxidant activity, immunoregulation, anti-hypertension, anti-cancer, and anti-inflammatory properties. This gives green seaweeds pharmaceutical application in addition to use in cosmetics, food, feed, bisotimulants, and biofertilizers (Xu et al., 2023). Ulvan, a polysaccharide which makes up about 9-36% of dried green seaweed (notably *Ulvan*) has been shown to have anticancer, antioxidant, antihyperlipidemic, anti-influenza, and anticoagulant activities, making it a desirable compound (Xu et al., 2023). Ulvan is also film forming, allowing it to be used for bioplastic production in

combination with cellulose and/or non-seaweed polymers. *Ulva* in particular is useful in bioplastic production as it is high in cellulose and contains the film forming polysaccharide ulvan (Lim et al., 2021). The green seaweeds *Ulva spp* and *Enteromorpha spp* often bloom in nearshore waters receiving excessive nutrient input from anthropogenic factors such as farm runoff, atmospheric nitrogen deposition, or sewage inputs.

Seaweed Products

As of 2022, direct consumption of seaweed as food (77.6%) and hydrocolloid production (11.4%) accounted for most of global seaweed production (Sugumaran et al., 2022). The World Bank lists hydrocolloids, human food, and aquaculture feed as the current established seaweed markets and estimates the likelihood of new market development (see figure 1) (World Bank, 2023). Short term (before 2025) markets with a high potential of successful development include biostimulants, pet foods, and animal feed additives. Animal feed for methane suppression is considered possible in the short term, however, faces considerable technical and regulatory uncertainties. Medium term seaweed product markets (2024-2028) include nutraceuticals (nutritional supplements), alternative proteins, fabrics, and bioplastics. Nutraceuticals are considered likely to develop, while markets for fabrics and bioplastics face considerably more uncertainty. Long term markets include pharmaceuticals and construction materials. Pharmaceutical applications are generally high value, however, face significant regulatory uncertainty. Construction materials are considered a lower value application (World Bank, 2023).

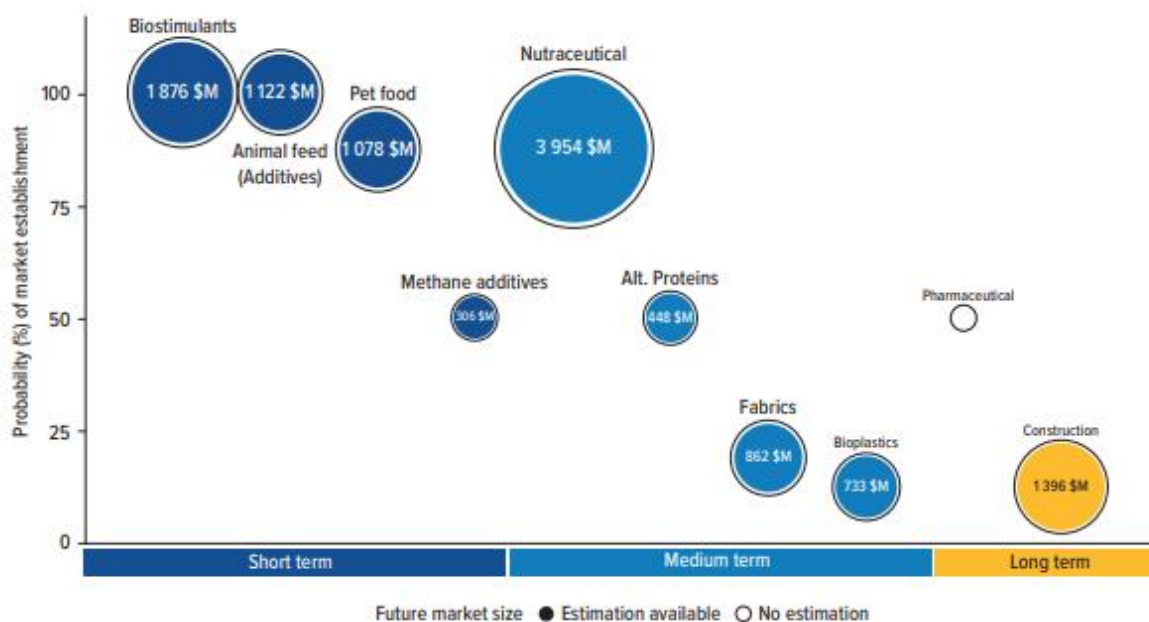


Figure 1: Emerging markets for seaweed products. Organized by estimated timescale of market establishment on the x axis, chance of successful establishment on the y-axis. Predicted market size in 2030 is indicated by the size of the bubble (and the number inside) (World Bank, 2023).

With a degree of uncertainty remaining around the net carbon impact of seaweed farming, there exists the potential to mitigate greenhouse gases in the atmosphere through the manufacture of certain seaweed products. The three ways for seaweed products to have a net GHG reduction impact are by converting seaweed into products which store carbon long term (>100 years), replacing greenhouse gas intensive products, or directly suppressing GHG (methane) emissions (Fujita et al., 2023). Hydrocolloids do not replace GHG intensive products

or store carbon long term (their carbon is generally released when the products they are in are used), however given their high commercial value and large-scale production they are discussed in detail below. In a present biorefinery setting, hydrocolloid production may be necessary to make production of lower value GHG mitigating products economically viable. Figure 2 shows some of the compounds found in seaweed and their potential commercial applications.

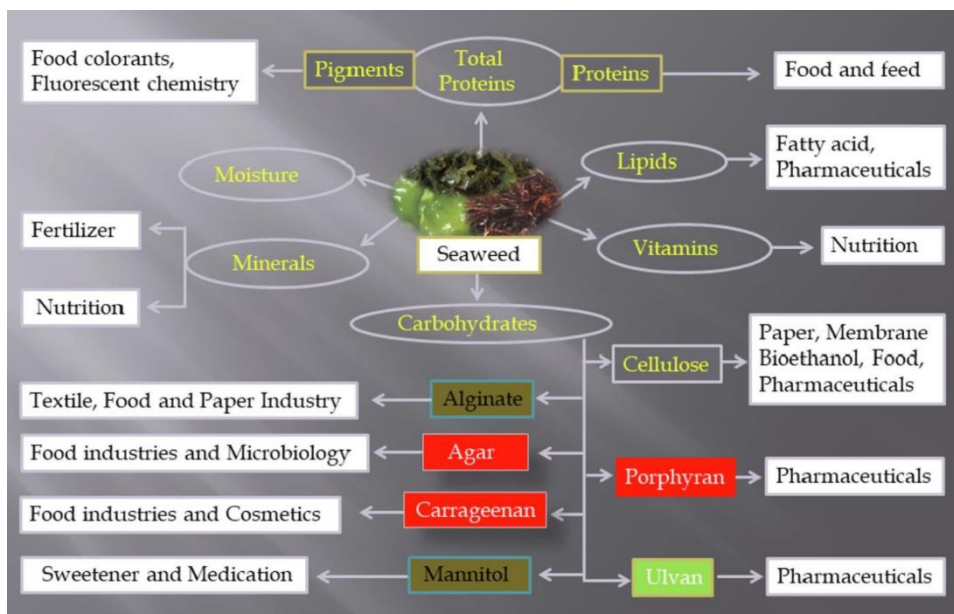


Figure 2: Seaweed components and their major applications (Baghel, 2023)

Hydrocolloids

Hydrocolloids are long chain polymers made up of polysaccharides and proteins, which are typically used as thickening and gelling agents. When dispersed in liquids they increase gelling and viscosity (Saha & Bhattacharya, 2010). The term phycocolloids is sometimes used to refer to the three seaweed derived hydrocolloids: alginate, agar, and carrageenan. Of the three, agar typically has the highest sale price. In 2009, the sale prices were found to be 18 USD/kg for agar, 12 USD/kg for alginate, and 10.4 USD/kg for carrageenan. Production volumes were 10,600 tons/yr for agar, 30,000 tons/yr for alginate, and 60,000 tons/yr for carrageenan. Total market values were 191 million USD/yr for agar, 339 million USD/yr for alginates, and 626 million USD/yr for carrageenan (Bixler & Porse, 2011).

Conventional hydrocolloid production uses only 15–30% of the total dry seaweed biomass. The remaining 70–85% is often degraded during the extraction processes and discarded as waste. If undamaged, this residue is rich in valuable compounds including natural pigments, proteins, lipids, minerals and cellulose which can be extracted from the waste in a biorefinery setting (Ingle et al. 2011; Baghel et al. 2016).

Alginate

Alginate is sourced from brown seaweeds and is widely used in the pharmaceutical, food and textile industries (Saji et al, 2022). The main seaweed species used for alginate extraction are "*Ascophyllum* and *Laminaria* (Europe), *Lessonia* (South America), *Ecklonia* (South Africa), *Durvillaea* (Australia and Chile) and *Macrocystis* (California and Baja California) (McHugh, 2002). Species of *Sargassum* and *Turbinaria* are harvested from warmer waters but usually provide low yields of lower quality alginate. "*Laminaria*, *Macrocystis* and *Ascophyllum* are the only three types of brown seaweed that are deemed to be sufficient in abundance or suitable for commercial use for alginate extraction," with other species such as *Sargassum* only being used when there is a supply shortage of these seaweeds (Saji et al., 2022)

The conventional alginate extraction process consists of soaking milled seaweed in a 2% (w/v) solution of formaldehyde overnight with a solid loading ratio of 1:10–20 (dry weight biomass to solution). The solid is then collected for acid pre-treatment with HCl at a concentration of 0.2–2% (w/v) at 40–60 °C with a 1:10–30 solid loading ratio for 2–4 hours. Next, the solid residue from the acid pre-treatment is extracted using Na₂CO₃ at a concentration of 2–4% (w/v) at 40–60 °C for 2–3 h with a 1:10–30 solid loading ratio. The liquid portion is then precipitated by ethanol (95%+) with a ratio of 1:1 (v/v). Finally, the solid output is dried in oven at 50–60 °C (Saji et al., 2022). New, greener extraction technologies such as ultrasound-assisted extraction, microwave-assisted extraction, enzyme-assisted extraction, and extrusion-assisted extraction have been found to improve alginate extraction yield and quality, but at a higher cost. (Saji et al., 2022).

Commercial seaweeds tend to be around 20% alginate by dry weight (McHugh, 2020). Conventional alginate extraction from *Sargassum terrenimum* (a seaweed less desirable for alginate extraction), results in 15% alginate by dry weight of *Sargassum*, with the other 85% being classified as waste (Baghel et al., 2020). A seaweed biorefinery process which combined a biostimulant extraction in the first step with alginate extraction in the second had a comparable yield of alginic acid to single stream processing of fresh seaweed. The biomass remaining post biostimulant extraction was more highly concentrated (24.6% alginate by dry weight). In addition to biostimulant and alginate extraction, protein, salt and cellulose were also extracted from the *Sargassum* biomass, with only 7% biomass being unused (Baghel et al., 2020).

Agar

Agar is present in red seaweeds and is typically sourced from *Gelidium* (wild harvested) and *Gracilaria*. *Pterocladia* and *Gelidiella* are also used for agar production, albeit less frequently (McHugh, 2002). *Gelidium* is considered to produce a higher quality agar, however it is difficult to cultivate.

Agar is commonly used as a gelling agent in processed foods, cosmetics, and pharmaceutical products and is also used in medicine and biotechnology applications. Agar is highly valued since it typically has a higher melting point than other gelling agents. The commercial price of

agar can vary depending on its quality, which is determined by factors such as gel strength, gelling temperature, and chemical properties (Marinho-Soriano, & Bourret, 2005).

The conventional method of agar extraction consists of an alkaline pretreatment to increase syneresis (expulsion of liquid from the gel), heating at high pressure and temperature, high heat filtration, and rounds of freezing and thawing to remove water (Dhandapani et al., 2022). Alkaline pretreatment was found to increase the agar extraction purity; however, it partially degraded the agar, leading to a decrease in the strength of the agar gel (Martínez-Sanz et al., 2020). Agar can be extracted at home or in cottage level settings by using heat only, extraction with heat and sun bleaching, or extraction with heat, NaOH, and sun bleaching (De Valicourt, 2015).

Carrageenan

Like agar, carrageenan is found in red seaweed. It is typically sourced from *Kappaphycus* and *Eucheuma*. It is traditionally used as a gelling and thickening agent in food, pharmaceutical, and biotechnological applications (Tarman et al., 2020). At the beginning of the century, *Kappaphycus alvarezii* and *Eucheuma denticulatum* accounted for about 85% of global carrageenan production and were typically cultivated in warm water countries with low labor costs such as the Philippines, Indonesia, and Zanzibar (with cultivation being promoted in India, Africa and the Pacific islands). *Gigartina* (Chile, Morocco and Mexico) was responsible for 10% of carrageenan extraction and *Chondrus crispus* (Canada, France Spain, Portugal, Republic of Korea), accounted for about 5% (McHugh, 2002). Similarly, a 2017 report estimated *Kappaphycus* and *Eucheuma* to make up about 90% of global carrageenan production, with a cold-water species harvested in South America (not specified) and a small amount of *Chondrus crispus* comprising the remaining portion (Campbell & Hotchkiss, 2017).

There are 6 different forms of carrageenan. The commercially produced forms are typically Kappa (κ)-carrageenan (from *Kappaphycus alvarezii*), Iota (ι)-carrageenan (*Eucheuma spinosum*), and Lambda (λ)-carrageenan (*Gigartina* and *Chondrus*). These three types are differentiated by one, two, and three sulphate ester groups. κ - and ι -carrageenan are generally used as gel-forming agents, while λ -carrageenan is used primarily as a thickening agent (Campo et al., 2009).

Processed carrageenan can be identified as either refined carrageenan (RC) or semi-refined carrageenan (SRC), depending on its purity (Tarman et al., 2020). In both cases, it is recommended that the seaweed is dried quickly after harvest to prevent degradation (Tarman et al., 2020). The conventional method of SRC production consists of cleaned and rinsed seaweed being heated in a hot alkali solution for several hours. “The process causes protein, lipid, salt and pigment to be extracted in the alkali solution...after the seaweed has been heated in the alkali solution, the seaweed is washed and chopped” (Tarman et al., 2020). The chopped seaweed may then be bleached to whiten and kill bacteria, resulting in semi-refined carrageenan. To produce refined carrageenan, the hydrocolloid is then extracted and separated

from the seaweed biomass. The conventional method of refined carrageenan extraction consists of dried seaweed being rinsed then soaked in water for 12 hours. The seaweed is then heated in an alkali solution for up to 4 hours (Al-alawi et al., 2011; Tarman et al., 2020). Carrageenan can also be extracted using only a hot water solution. This results in a higher yield than the alkali solution, however the resulting carrageenan has a lower gel strength due to greater sulphate content than in the alkali extracted carrageenan (Vázquez-Delfín et al., 2013; Tarman et al., 2020). In each case, the extract is then filtered, and the carrageenan is removed and concentrated using vacuum distillation. The carrageenan is then further concentrated, in one of two ways. One way is to mix the carrageenan with salts such as potassium chloride then freeze and thaw it, removing excess water from the gel each time it thaws. Another way is to mix the carrageenan with a concentrated alcohol such as isopropanol and precipitate it (Tarman et al., 2020). The precipitate is then separated using a centrifuge or fine sieve, pressed to remove the solvent and washed with more alcohol to further dehydrate it. It is then dried and milled to a particle size of 80 mesh or finer (McHugh, 2003).

Ulvan

Ulvan is often not included in mentions of seaweed hydrocolloids. It is unclear if this is due to its chemical makeup or simply that processing of green seaweed is less common. Like other hydrocolloids, it is a sulphated polysaccharide with gelling properties. It is found in green seaweeds, primarily those of the *Ulva* genus. In addition to being a gelling agent, it is noted to have a range of biological activity which may give it the potential to fight diseases (Kidgell et al., 2019). Notably, ulvan has been shown to have anticancer, antioxidant, antihyperlipidemic, anti-influenza, and anticoagulant activities, giving it an application in pharmaceuticals (Xu et al., 2023). Since it is a gelling agent, ulvan is film forming, making it desirable for bioplastic production. It is commonly mixed with cellulose or non-seaweed polymers to add strength and rigidity (Lim et al., 2021).

One method of ulvan extraction from seaweed powder consists of suspending the powder in a solution of hydrochloric acid (HCl) and heating it at 60°C for 2 hours. The liquid solution is then kept, while the residue is separated out using a 100 µm nylon filter. The solid undergoes another round of heating in an HCl solution for 1 hour and once again the liquid is separated and kept. The liquids are then combined and centrifuged to remove suspended particles. Ulvan is then precipitated using ethanol and isolated through centrifugation. Next, ethanol is used to wash the isolated ulvan and a rotary evaporator is used to evaporate the ethanol. Deionized water is added to dissolve the ulvan, the solution is neutralized using sodium hydroxide (NaOH), frozen, and lyophilized (freeze dried).

GHG Mitigating Products

EDF has done [prior work](#) to identify products which can be made from seaweed and may contribute to GHG mitigation. These products include construction materials (long-term

storage), biofuels, biostimulants, biofertilizers, bioplastics, and textiles (replace GHG intensive products), animal feed supplements and manure additives (GHG mitigation through methane suppression) (Fujita et al., 2023; Albright, 2023). These products are discussed below. Detailed life cycle analysis should be performed with each product to estimate its true impact.

Biostimulants

Seaweed based biostimulants are the most established of these products, with the global market for biostimulants estimated to be worth \$2,556 million USD in 2021 and growing with a 10% CAGR (Bullion, 2022). Brown seaweed, particularly *Ascophyllum nodosum* is commonly used in commercial biostimulant production, however biostimulants from red and green seaweed are sold commercially as well. *Fucus serratus* and *Enteromorpha intestinalis* are other commonly used brown seaweeds, while *Ulva lactuca* and *Kappaphycus alvarezii* are green and red seaweeds that have been used (Craigie, 2011).

A biostimulant can be described as, “a substance or microorganism applied to plants with the aim to enhance nutrition efficiency, abiotic stress tolerance and/or crop quality traits, regardless of its nutrient content” (du Jardin, 2015). “Biofertilizers are considered a subcategory of biostimulants which focus on increasing nutrient availability and nutrient use by plants (du Jardin, 2015). Conventional fertilizers typically focus on exogenously supplying plants with essential nutrients. While biofertilizers may do this they are also intended to “increase nutrient use efficiency and open new routes of nutrients acquisition by plants” (du Jardin, 2015). Therefore, both biofertilizers and biostimulants seek to improve plant health and crop yield, however it is important to consider the mechanism in which each product acts in order to properly classify it. Under this definition, a biofertilizer may have a lower nutrient concentration than a conventional fertilizer. However, Merfield and Johnson, 2016 provide a contrasting definition. They define biofertilizers as “materials of biological origin...that contain sufficient levels of plant nutrients (nitrogen, phosphorus, potassium, calcium, magnesium, etc.). They differentiate biofertilizers from biostimulants by the higher nutrient concentration in biofertilizers. They do not indicate a specific concentration at which this cutoff occurs.

Biostimulants are composed of a variety of bioactive compounds which produce a range of effects in the plant and in soils, including increased yields and greater tolerances to abiotic stresses including drought, increased salinity in water and soils, high and low temperatures, and nutritional deficiencies (Franzoni et al., 2022; Goñi, Quille, & O'Connell, 2018; Campobenedetto et al., 2018; De Saeger et al., 2020; Rouphael et al., 2020). Extraction methods significantly influence the yield of these bioactive compounds. This means that the ideal extraction method changes based on the targeted crop, desired physiological effect, and the seasonal variation of the composition of macroalgae (El Boukhari et al, 2020). Further complicating matters, these bioactive compounds act synergistically, making it very difficult to determine if it is a single compound or a group of compounds which are responsible for a desired agricultural effect (Ertani et al., 2018). Manufacturers tend to develop their own, proprietary extraction methods

which they rely on to differentiate their product. Water based extraction, alkaline hydrolysis, and acid hydrolysis are the conventional production methods (Shukla et al., 2019). Craigie, 2011 reports the most common extraction process to involve heating the seaweed in alkaline sodium or potassium solutions. The digestate from anaerobic digestion of seaweed biomass for biogas production is rich in minerals and can be used as a biofertilizer product (Soleymani and Rosentrater, 2017). The biomass remaining following fermentation for bioethanol production is also suitable as a biofertilizer (Johnston et al., 2023).

A water extraction done on *Ulva fasciata* yielded carbon, nitrogen, sulphur and minerals. Figure 3 shows the amount of each of these elements found in 80mL of the liquid extract (Trivedi et al., 2016).

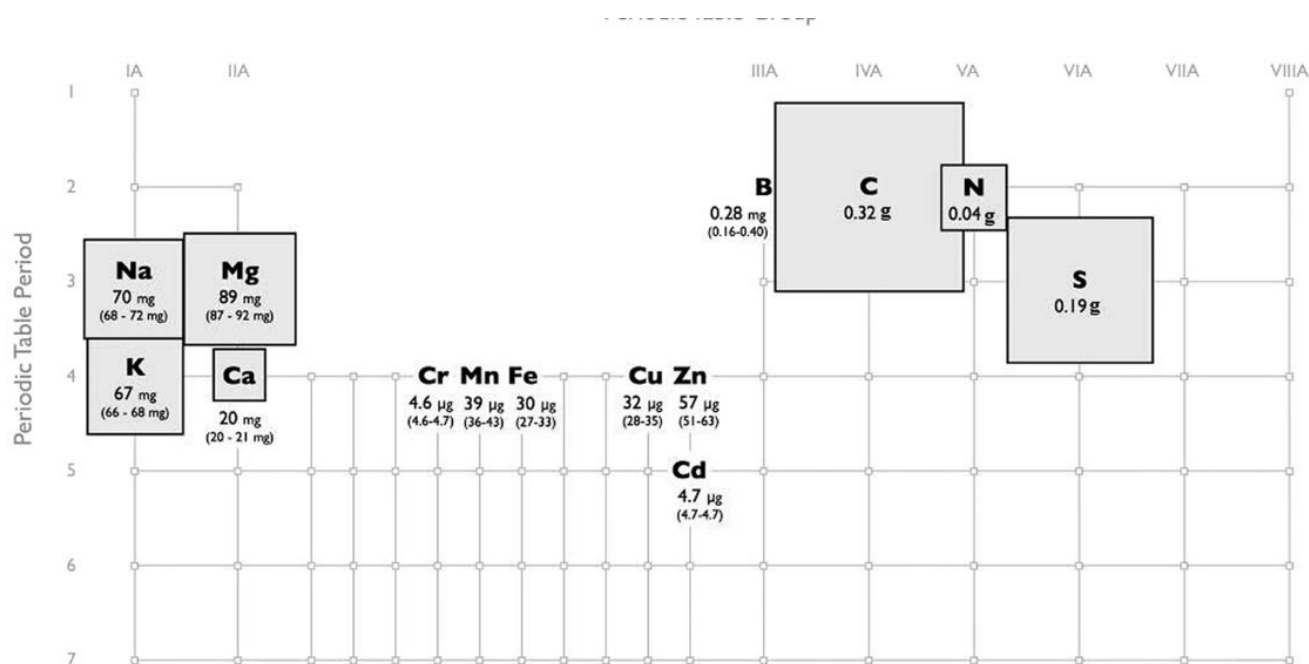


Figure 3: Carbon, nitrogen, sulphur, and mineral content found in 80mL of liquid extract from *Ulva fasciata* (obtained from 50 g of *Ulva* biomass and 100 mL water) (Trivedi et al., 2016).

While Baghel et al., 2023 lists high seaweed ash content as a concern for thermochemical processing, one potential solution is to extract the sap, which is rich in minerals, from seaweed, prior to thermochemical processing. The sap extraction results in a liquid extract and a granular biomass residue. The sap is rich in minerals and bioactive compounds and has applications as a biostimulant. This process also removes a significant amount of moisture, so that the remaining biomass can be dried using less energy and contains a higher concentration of hydrocolloids and other desirable compounds.

Ultrasound-assisted extraction (UAE), enzyme-assisted extraction (EAE), supercritical fluid extraction (SFU), microwave-assisted extraction (MAE), and pressurized liquid extraction (PLE)

are extraction methods which do not affect the activity of bioactive compounds. Additionally, they result in a higher extraction yield, shorter extraction time, and are considered more environmentally friendly than the conventional solid-liquid and liquid-liquid extraction methods, which often use large amounts of toxic solvents (Michalak and Chojnacka, 2015). Eswaran et al., 2005 and Reddy et al., 2018, have both patented a process which produces a biostimulant in a biorefinery setting through aqueous extraction from fresh seaweed biomass, prior to extraction of other compounds. Eswaran et al., 2005 uses only water as the extraction medium, while Reddy et al., 2018 uses water with a phosphate buffer.

Bioplastics

Conventional plastic use remains widespread, with a total of 12,000 Mt of plastic projected to accumulate in the environment by 2050 based on current use trends (Geyer et al., 2017). "Fossil fuel-based plastics do not biodegrade, instead breaking down into microplastics that are increasingly being recognized as a threat to human and environmental health" (Gries et al., 2023; di Bartolo et al., 2021; Shahul Hamid et al., 2018). Bioplastics, which are made from organic material, are seen as a more sustainable alternative. Seaweed and land-based crops are both suitable bioplastic feedstocks, but unlike land-based, large-scale use of seaweed for bioplastic production is not considered a threat to food security as seaweed can be grown without land, freshwater or nutrient inputs.

Many different types of conventional plastic exist. They differ significantly in terms of their properties and applications. The two main categories are thermoplastics and thermosetting plastics. Thermoplastics may be reheated and remolded and are commonly used for plastic films, fibers and packaging. Thermosetting plastics are more rigid and cannot be remolded once cooled and hardened. Common applications include appliances, adhesives, and car parts (Singh, 2019).

Global bioplastic production was 1.79 million tons in 2023 (EUBIO_Admin, n.d.). Typically, the polysaccharide, protein, and lipid components of plants are used to make bioplastics (Lim et al., 2021). Like conventional plastics, several different types of bioplastics exist (see figure 4), not all of which are biodegradable. Some are simply bio-based but do not break down rapidly enough to be considered fully biodegradable. "Drop-in" bioplastics use the same technical equipment as conventional plastic production but replace the petroleum-based resin pellets with a plant-based resin (Albright, 2023).

Comparison of bio plastics and their limitations				
Biopolymer	Feedstock	Raw Material	Properties	Substitute for
Starch Based	Corn, potato, wheat, tapioca	Starch	Low water vapor barrier poor mechanical properties bad processability brittleness	Polystyrene (PS)
Cellulose based	Wood pulp	Cellulose	Low water vapor barrier poor mechanical properties bad processability brittleness	Polypropylene (PP)
Polyhydroxyalkanoates (PHA) and (PHB)	Corn, potatoes, maize, tapioca, vegetable oils	Starch	PHA ranges from stiff, brittle to semi rubber-like PHB has better oxygen barrier properties than both PP and PET, better water vapor barrier properties than PP, and fat and odor barrier properties that are sufficient for use in food packaging	Polypropylene (PP) Polyethylene (PE)
Polylactic acid (PLA)	Corn, sugar beet, potatoes, wheat, maize, tapioca	Lactic acid	High tensile strength and modulus. However, its brittleness and low crystallinity lead to low thermal stability and limited applications	Low density and high density polyethylene (LDPE and HDPE) polystyrene (PS) Polyethylene terephthalate (PET) Polypropylene (PP)

Figure 4: Different types of bioplastics and their properties, terrestrial feedstocks, compounds from which they are manufactured, and the type of conventional plastic for which they substitute (Albright, 2023).

Agar, alginate, carrageenan, and ulvan have film forming properties which are highly conducive to the manufacturing of bioplastic films and cellulose is often included as a filler and to provide rigidity. However, these bioplastics tend to be very expensive compared to conventional plastic. Opportunity costs are high, given the other high value applications of hydrocolloids in food, cosmetics and pharmaceuticals (Lim et al., 2021; Abdul Khalil et al., 2016). On their own, hydrocolloids tend to form weak plastics, so reinforcing fillers such as cellulose are generally incorporated (Ayala et al., 2023). A 10% cellulose concentration has been observed to create the highest bioplastic strength (Baghel et al., 2021). Plastic films made solely from seaweed are generally not water repellant (Lime et al., 2021). Glycerin is often added to increase water repellency and decrease brittleness (Ayala et al., 2023; Albright, 2023).

Polysaccharides vary between green, red, and brown seaweeds. Red seaweed is commonly used for bioplastic production due to their carrageenan and agar content, two film forming polysaccharides. Cellulose, floridean, starch, xylan, mannan, and porphyran are other polysaccharides commonly found in red seaweeds (Goyanes & D'Accorso, 2017). Green seaweed tends to be high in cellulose. *Ulva* in particular is commonly used in bioplastic production as it is high in cellulose and contains the film forming polysaccharide ulvan. During

bioplastic production, ulvan is often mixed with non-seaweed polymers (Lim et al., 2021). Brown seaweeds typically contain the polyssacharides laminarin, fucoidan, and alginate, with small amounts of cellulose, mannitol, and sargassan (Saepudin et al., 2018). Of these, alginate, fucoidan, and cellulose are relevant for bioplastic production (Lim et al., 2021).

Extraction methods which use minimal solvents or eliminate the need for them completely should be prioritized to make bioplastics a truly green material. These methods include enzyme-assisted extraction (EAE), microwave-assisted extraction (MAE), photo-bleaching extraction (PBE), reactive extrusion (REX), pressurized solvent extraction (PSE), supercritical fluid extraction (SFE), and ultrasound-assisted extraction (UAE). In addition to being more eco-friendly, these methods have been observed to increase strength and quality of bioplastics. They can be more economically favorable than conventional methods, by eliminating the need for large amounts of water, chemicals, and waste management (Lim et al., 2021).

One potential method for manufacture of a compostable bioplastic involves mixing alginate with glycerin and cellulose to increase strength and water repellency. The mix is then cast on a flat mold, sprayed with a solution of calcium chloride to increase homogeneity, water resistance, and flexibility, and left to dry (Ayala et al., 2023).

Methane Suppressants

The interest in seaweed-based methane suppressants greatly increased following a study which found the seaweeds *Dictyota* and *Asparagopsis* inhibited methane production by ruminants by 92.2% and 98.9% respectively (compared to decorticated cottonseed meal) over a 72-hour period (Machado et al., 2014). The study was done in vitro and involved fermenting the seaweed with rumen fluid for 72 hours and measuring methane emissions against a control. In total, 20 tropical macroalgae species were tested. Each seaweed was rinsed, centrifuged, freeze-dried, milled and stored frozen prior to the experiment. All seaweed species were observed to decrease methane production. *Ulva* and *Sargassum*, two seaweeds commonly associated with algal blooms were found to decrease methane production by 50.3% and 34.3% respectively compared to decorticated cottonseed meal (Machado et al., 2014). Since then, in vivo studies have been performed with high levels of variability. In one study it was found that inclusion of 0.20% *Asparagopsis taxiformis* in ruminant feed over a 90-day period reduced enteric methane emissions by 98% (Kinley et al., 2020). Application of these seaweeds to rice paddies and manure pits (other significant agricultural sources of methane) have also been discussed but there are few studies that evaluate these use cases.

The presence of halogenic compounds in seaweed, particularly bromoform, has been observed to be correlated with methane inhibition. Bromoform is believed to be the compound most responsible for the reduction in enteric methane emissions from ruminants (Min et al., 2021). Bromoform is toxic to humans and there is significant concern around feeding high levels of

bromoform to cattle, however it has not been observed in the tissues or milk of animals fed diets with high levels of bromoform. Long-term studies are needed to reduce uncertainty about the impacts of seaweed feed supplements on animal and human health (Albright, 2023).

Freeze drying seaweed immediately post-harvest is the most common way to preserve bromoform content. The seaweed is then milled or chopped and incorporated into the standard cattle feed. Oil emulsion is an alternative to freeze drying. It has been found to preserve a higher level of bromoform than freeze drying and use significantly less energy. Oil emulsion preserves bromoform content for at least 12 weeks. In this method, the freshly harvested seaweed is blotted dry and homogenized in vegetable oil (Albright et al., 2023).

Both methods discussed above utilize the entire seaweed biomass, resulting in a single stream processing technique which does not produce biomass waste. Unless bromoform and halocarbons are extracted from the seaweed, methane suppressants are not suitable for manufacturing in biorefineries settings since they do not typically produce waste.

Textiles and Clothing

Seaweed-based textiles are predominantly made from sodium alginate, which is derived from brown seaweed. The typical method of obtaining sodium alginate involves soaking ground seaweed in an acidic solution to remove fucoidans, laminarins, proteins and polyphenols and produce alginic acid (Albright, 2023). The alginic acid is then soaked in a sodium carbonate solution to convert it into sodium alginate (Jayasinghe, 2022). The sodium alginate may then be mixed with other additives (typically this is company specific proprietary information) and spun into fibers and yarn, which is often interwoven with conventional fibers to make a final product. Additives and incorporation of conventional fibers results in significant variation in seaweed content of the final product. SmartFiber's SeaCell fiber contains 19% seaweed by volume, while Keel Labs reports their Kelsun fiber is over 75% seaweed (Albright, 2023; Kelsun, 2023).

In addition to fabrics, seaweed can also be made into plant-based leather. The process is similar, but to make leather, sodium alginate and additives are poured into a mold, heated and pressed into sheets, rather than spun into yarn. A backing (often fabric) is then added to the sheets (Albright, 2023).

The market for seaweed-based leather and textiles is not currently large, however the total plant-based leather market was estimated to be \$67.6 million in 2022 and cellulose fiber markets were worth \$18 billion in 2022, indicating that there is a market demand for these products (Research and Markets Ltd, 2023; Markets and Markets, 2023).

Construction Materials

Seaweed has several applications in construction materials. Most commonly cellulose, alginate, or ash from seaweed is used as a fiber fill or binding agent (Albright, 2023). *Sargassum* (a brown seaweed), has been found to be a suitable feedstock for making paneling (medium density fiberboard and particleboards), polymer composites (fibers), portland cement composites (ash, fibers, and additives), pavement (fibers and additives), adobe (fibers and additives), and roof and facade (whole seaweed). Due to large-scale algal blooms, *Sargassum* is widely available in the Caribbean as a cheap feedstock (Rossignolo et al., 2022).

Posidonia oceanica (seagrass) and *Kappaphycus alvarezii* (red seaweed) are the most cited species used in construction materials, however as most of the compounds used for construction materials are not species specific, there are a wide variety of seaweeds and mentioned in the literature (Rossignolo et al., 2022). Due to the relatively low value of construction materials, wild harvested seaweed is most often used. Use of *Sargassum* and other seaweeds which experience large blooms are also common. *Sargassum* blooms in the Caribbean are known to cause ecological concerns and adversely impact tourism so much so that there are opportunities there to be paid to collect it from beaches or the near shore. Several companies have explored using biomass which they have been paid to collect as a feedstock for construction materials (Albright, 2023).

Panels are made with algae-based fiber, primarily cellulose, instead of wood fibers. The fiber is mixed with sawdust (from wood) and an adhesive. Algae fibers can also be added to polymer composites as a filler and reinforcing material (Rossignolo et al., 2022).

Ash or fiber from algae may be added to portland cement composite. The ash is produced by the burning of seaweed, which may occur during bioenergy production (Rossignolo et al., 2022). Addition of ash to portland cement composite at concentrations of .5% and 2% ash by weight have both been found to increase strength of the cement (Azim et al., 2016; Gupta et al., 2022). Raw kelp powder mixed with Portland cement at 20% concentration was found to increase thermal performance and decrease its carbon footprint (Lorentzen et al., 2021). Algae nanofibers with a high concentration of cellulose were found to increase the bending stress tolerance of concrete by 2.7 times when added at a rate of 5% by weight (Cengiz and Kaya, 2017). Seaweed powder added at a rate of 20% by weight was found to increase compressive and tensile strength (Majid et al., 2019). Alginate from brown seaweed is also seen as a suitable additive to Portland cement (Rossignolo et al., 2022).

Other construction applications include dried algae powder mixed with dirt to create seaweed-based Adobe bricks, alginate mixed with biomaterial and waste construction materials, and the use of dried and shredded *Posidonia oceanica* as an insulation material (Albright, 2023). Recently, floating bricks made from kelp and pelagic sea clay have also been developed, with applications for floating platforms, structures, and ships. The bricks can be recycled or reused

when the original structure reaches the end of its life (Seabrick, 2022). At \$360 per ton, it is significantly cheaper than floating concrete, aluminum, and steel structures (Fiorenza, 2023). Pelagic sediments are in areas of the open ocean floor protected from terrestrial influence, such as deposition of detritus. Pelagic clays are very low in organic matter and are relatively free of any reactive organic carbon (Hesse and Schacht, 2011). Red clay covers roughly 40% of the floor of the Pacific Ocean, however it accumulates at a very low deposition rate of only a few meters or less over the course of a million years (Yamazaki et al., 2020; Opdyke and Foster, 1970). This indicates it is an abundant marine resource, but care must be taken to ensure it will not be harvested at a harmful or unsustainable rate. Little information is available on how the clay is harvested and research should be done to ensure that harvesting methods themselves do not damage ecosystems or result in large amounts of GHG emissions.

Since cellulose and other fibers are often discarded in waste streams, a biorefinery setting would enable these to be used as a feedstock for construction materials. These markets are not anticipated to develop in the short term as it may take time for manufacturers to conduct strength and safety tests with these products, before bringing them to market.

Biofuels

Biofuel production from seaweed has garnered extensive interest but has yet to be shown to be economically viable. Both wet and dried seaweed are suitable for biofuel production, however, the processing methods differ depending on which are used. Dried seaweed biomass can be turned into energy through direct combustion, pyrolysis, gasification, or biodiesel production. Wet seaweed biomass is converted to energy through hydrothermal treatment, fermentation into bioethanol or biobutanol, or anaerobic digestion into biogas. Of these methods, only biodiesel, bioethanol, and biobutanol production do not use the entire biomass (Milledge et al., 2014). Solar drying is less energy intensive than other drying methods, making it preferable for bioenergy production, however this may restrict the amount of biomass available depending on the weather and space for drying. Bioenergy production is often viewed as one of the final steps in a biorefinery concept, where the remaining “waste” is used as a feedstock. Carbohydrates are generally used for biofuel production, with brown seaweed typically having the highest carbohydrate content (Dave et al., 2013). Lipids may also be a suitable feedstock for biofuel production (Monlau et al., 2021), however most seaweed have a lipid content below 5%, which is considered insufficient for large scale biofuel production (McDermid & Stuerke, 2013).

Conversion of cellulose to bioethanol is the most common conversion pathway (Wadi et al., 2019). Other polysaccharides and sugar alcohols such as laminarin, mannitol, and alginate are also suitable feedstocks, however these compounds have other high value commercial applications (Soleymani & Rosentrater, 2017; Roesijadi et al., 2010). Cellulose can be converted into bioethanol through enzymatic hydrolysis and fermentation of the resulting hydrolysate. Minerals, lipids, and ulvan can be extracted from the seaweed prior to this process (Baghel et al., 2016). The final step of bioethanol production is distillation, in which the bioethanol is

further isolated and distilled water is obtained (Johnston et al., 2023). Anaerobic digestion is used to produce biogas using either polysaccharides or a slurry of chopped seaweed biomass as feedstock (Dave et al., 2013). Bioethanol and biogas may be co-produced. In this case, the biomass first undergoes fermentation to produce bioethanol and the remaining biomass is put in an anaerobic digester to produce biogas (Soleymani & Rosentrater, 2017).

Seaweed biofuels are considered preferable to conventional land-based biofuels as they contain low amounts of lignin and do not compete for land use, thus minimizing concerns over creating food security (Uju et al, 2015; Jung et al., 2013). Lignin is a polymer found in plant cell walls which gives them rigidity but is difficult to process into biofuels.

The Sustainable Aviation Fuel Grand Challenge is an initiative by the US government to generate production of at least 3 billion gallons of sustainable aviation fuels by 2030 and 35 billion gallons by 2050 (equivalent to annual US aviation fuel demand). A variety of grants and initiatives have been created to support this goal (US Department of Energy et al., 2022). High density liquid fuels are considered the most promising way to decarbonize air travel, since electric batteries are too heavy to feasibly power aircraft. The federal aviation administration is giving out grants of up to \$50 million to promote development of sustainable aviation fuels. To reach the 2030 target, the short-term focus is on established methods of biofuel production (using land-based crops). Reaching the 2050 goal “requires a continuing focus on supporting ongoing innovation, including research, development, and demonstration (RD&D) of new feedstock and conversion technologies with potential for exponential growth in production capacity, greater emissions reductions, and reductions in cost of production and carbon intensity (CI) after 2030” (US Department of Energy et al, 2022).

Seaweed-based biofuels are not currently seen as economically viable (Soleymani & Rosentrater, 2017), however research and development grants, private sector investments, and co-production of biofuels alongside higher value products may change this in the future.

Other notable compounds

Pigments

The three main classes of natural pigments found in macroalgae are chlorophylls, carotenoids and phycobiliproteins. The color of seaweed is determined by the pigments they contain. Green seaweed contains chlorophyll a and b as primary pigments. Red seaweed predominantly contains phycobiliproteins. Brown seaweed gets its color from fucoxanthin (Baghel et al., 2021). Natural pigments have been observed to have many positive health effects, making them suitable for inclusion in pharmaceuticals and food products. The beneficial effects include, but are not limited to “antioxidant, anticancer, anti-inflammatory, anti-obesity, anti-angiogenic and neuroprotective activities” (figure 5) (Pangestuti and Kim, 2011). They are of high value to the pharmaceutical industry.

Table 1 – Marine algae-derived natural pigments and potential health benefit effects.			
Natural pigments	Health benefit effects	Sources	References
Chlorophyll <i>a</i>	Antioxidant	<i>Enteromorpha prolifera</i> , <i>Fucus vesiculosus</i>	Le Tutour et al. (1998)
Pheophytin <i>a</i>	Antimutagenic Neuroprotective	<i>Porphyra tenera</i> <i>Sargassum fulvellum</i>	Okai et al. (1996) Ina et al. (2007) and Ina and Kamei (2006)
	Antimutagenic	<i>Enteromorpha prolifera</i>	Hiqashi Okai et al. (1999) and Okai and Hiqashi Okai (1997)
	Anti-inflammatory	<i>Enteromorpha prolifera</i>	Okai and Hiqashi Okai (1997)
Pheophorbide <i>a</i>	Antioxidant	<i>Enteromorpha prolifera</i>	Cho et al. (2011)
Pyropheophytin <i>a</i>	Antioxidant	<i>Eisenia bicyclis</i>	Cahyana et al. (1992)
Phycoerythrobilin	Antioxidant	<i>Porphyra</i> sp.	Yabuta et al. (2010)
Lutein	Antimutagenic	<i>Porphyra tenera</i>	Okai et al. (1996)
β-Carotene	Antimutagenic	<i>Porphyra tenera</i>	Okai et al. (1996)
Fucoxanthin	Antioxidant	<i>Hijikia fusiformis</i> , <i>Undaria pinnatifida</i> , <i>Fucus serratus</i> , <i>Padina tetrastrum</i>	Nomura et al. (1997), Yan et al. (1999) and Sasaki et al. (2008)
	Anticancer	<i>Undaria pinnatifida</i>	Hosokawa et al. (1999) and Kotake Nara, Terasaki, et al. (2005)
	Anti-inflammatory	<i>Myagropsis myagroides</i>	Heo et al. (2010)
	Anti-obesity	<i>Undaria pinnatifida</i>	Maeda et al. (2005), Maeda, Hosokawa, Sashima, Funayama, et al. (2007), Maeda, Hosokawa, Sashima, and Miyashita (2007) and Maeda et al. (2008, chap. 32)
	Anti-angiogenic	<i>Undaria pinnatifida</i>	Sugawara et al. (2006)
	Neuroprotective	<i>Hijikia fusiformis</i>	Okuzumi et al. (1990)
	Prevent osteoporosis	<i>Laminaria japonica</i>	Das et al. (2010)
	Photoprotective	<i>Laminaria japonica</i>	Shimoda et al. (2010) and Heo and Jeon (2009)
	Anticancer	<i>Codium fragile</i>	Ganesan et al. (2011)
	Anti-angiogenic	<i>Codium fragile</i>	Ganesan et al. (2010)

Figure 5: Health benefits associated with seaweed derived pigments (Pangestuti and Kim, 2011).

Conventional techniques using organic solvents are generally favored due to their low initial investment cost and operating simplicity, however they often negatively impact subsequent extraction of other compounds (Manzoor et al., 2024; Capanoglu, Nemli, & Tomas-Barberan, 2022). A common extraction method for extraction of natural pigments from seaweed includes mixing the seaweed with solvents and precipitating the pigments with ammonium sulphate. Common solvents include ethanol and a mixture of methanol and chloroform. Centrifuges are often used to increase ease of separation (Reddy et al., 2018; Saepudin et al., 2018; and Xu et al., 2020). Recently, green extraction technologies including supercritical fluid extraction (SFE), ultrasound-assisted extraction (UAE), pressurized liquid extraction (PLE), and microwave-assisted extraction (MAE) have been used for natural pigment extraction from macroalgae (Manzoor et al., 2024).

While green extraction technologies are favorable for preserving compounds for subsequent extraction, it has been shown that other compounds may be extracted from seaweed biomass along with natural pigments. In addition to natural pigments, Reddy et al., 2018 extract a liquid biostimulant, hydrocolloids, lipids, and cellulose from seaweed biomass. In this case the natural pigments are an early-stage extraction. The biostimulant and natural pigments are first separated from the rest of the biomass, leaving a solid residue which is used for extraction of the other compounds. The natural pigments are then precipitated using ammonium sulphate, simultaneously yielding a liquid biostimulant.

Cellulose

Cellulose is generally considered a low value compound. It has applications for making paper, textiles, construction materials, bioplastics and biofuels. It has also been used by the pharmaceutical, cosmetic, food industries (Halib et al., 2017; Baghel et al., 2021). Seaweed derived cellulose has the same properties as cellulose derived from terrestrial plants, however its low lignin content makes it a more favorable feedstock for biofuel production. When making biofuel from terrestrial plants, the lignin must first be removed. This process uses harsh chemical treatments and can degrade the biomass (Verversis et al., 2004; Lee et al., 2014).

Cellulose remains present in the waste biomass from hydrocolloid extraction. Dried seaweed was found to contain 0.85–34% cellulose by dry weight. The waste biomass from hydrocolloid production contains 27 to 45% cellulose by dry weight. Extracting cellulose from the highly concentrated waste fraction requires less solvent and chemical usage than cellulose extraction from dried seaweed, while producing a similar yield (Baghel et al., 2021).

A conventional method of cellulose extraction from dried seaweed biomass consists of bleaching the dried seaweed biomass with sodium chlorite (NaClO_2) in an acetate buffer at 60 °C for 3–6 hours. The seaweed is then washed to a neutral pH. This is followed by an alkali treatment (0.5 M NaOH) at 60 °C for 6–12 hours and subsequent washing to obtain a neutral pH. The alkali treated material is then boiled in a solution of 5% HCl (V/V), followed by incubation at room temperature. Lastly, the remaining material is washed until it reaches a neutral pH and dried (Baghel et al., 2021).

Proteins

Seaweed proteins have applications in the pharmaceutical, nutraceutical, cosmeceutical, food and feed industries. Seaweeds are “rich in peptides, enzymes, phycobiliproteins, glycoproteins, cell wall-attached proteins, and mycosporine-like amino acids” (Pliego-Cortes et al, 2020). Protein concentration differs by species with red seaweed generally having the highest protein concentration (20-47% dw), followed by green (9-26%), while brown has the lowest concentration (3-15%) (Fleurence et al, 2018; Pliego-Cortes et al, 2020). Species, harvest

season, location, and growing conditions greatly affect protein content, making aquaculture a more predictable source of biomass for protein production than wild harvest. In vitro digestibility of protein from *Pyropia columbina*, a red seaweed, by humans was found to be 74.3%, which is lower than digestibility of animal proteins, but comparable to other sources of plant proteins. The high fiber content is seen as being a barrier to digestibility (Cian et al., 2014).

A tough polysaccharide-rich cell wall and the occurrence of phenolic compounds makes protein extractability from seaweed difficult (Gajaria et al., 2017; Pliego-Cortes et al, 2020). Proteins are often tightly bound up with other compounds such as pigments, cellulose and lectins (O'Connor et al., 2020). Seaweed proteins must be isolated from the rest of the biomass prior to extraction, requiring a pretreatment step which breaks and disrupts the cell wall polysaccharides. Methods of pretreatment include grinding, osmotic shock, alkaline treatment, freezing and thawing, and ultrasonic sonication (Echave et al, 2021).

To avoid protein degradation, freshly harvested seaweed biomass must be frozen, dried, or processed immediately (Pliego-Cortes et al, 2020). There are a variety of pretreatment and extraction options to extract seaweed proteins. These vary depending on the species and desired protein (Echave et al, 2021). Liquid extraction techniques coupled with physical methods are the conventional way to treat and extract seaweed proteins (Pliego-Cortes et al, 2020). Potential liquid extraction systems include the use of distilled water, buffers, acidic or alkaline solutions, urea, and phenol-based systems. Subcritical water extraction is a promising method of using water as a solvent for protein extraction. It can be conducted following hydrocolloid extraction and was found to successfully yield up to 96.1% of the protein content of seaweeds, while avoiding the use of solvents and chemicals (Trigueros et al., 2021; Arias, Feijoo, and Moreira et al., 2023). Osmotic shock, freezing and thawing, and grinding are methods of physical disruption. Alternative extraction methods include enzyme assisted extraction, ultrasound assisted extraction, pulsed electric field extraction, membrane filtration, microwave assisted extraction, and pressurized liquid extraction (Pliego-Cortes et al, 2020). Purification occurs following extraction to separate the protein peptides from other extracted components which can include polysaccharides, minerals, and phenolic compounds (Echave et al, 2021). Ultrafiltration, which relies on molecule size differences and ionic-exchange chromatography, which relies on charge differences are the most common methods of purification. Dialysis is also used to remove small molecules (Echave et al, 2021).

Proteins are suitable to be extracted in a biorefinery setting. One study considers the extraction of pigments, lipids, proteins, polysaccharides (specifically carrageenan), biostimulants and biogas (Arias, Feijoo, and Moreira et al., 2023). Another proposes a biorefinery which extracts proteins from *Ulva lactuca* biomass, alongside a minerals rich sap, lipids, ulvan and cellulose. In this study protein was extracted following, extract of the sap, lipids, and ulvan, with cellulose being extracted last (Gajaria et al., 2017).

The biorefinery companies Oceanium and GOA both have plans to produce a food grade protein product. Thalasso has indicated that they plan to create extraction technology to fit each of their clients' needs, leaving the door open for them to create technology targeting protein extraction. Origin by Ocean has not indicated if they are interested in protein extraction. In addition to protein, Oceanium makes a seaweed-based ink, a fiber product for human consumption, and incorporates bioactives from seaweed into their skincare and health and wellness products. In GOA's biorefinery process, protein is the first compound extracted, with subsequent production of valuable carbohydrates (such as hydrocolloids and mannitol), biogas, and minerals which can be used as biostimulants and biofertilizers.

Lipids

Most seaweed has a lipid content below 5% of dry weight, a small fraction of seaweed biomass, however there are several seaweed species (particularly of the Dictyotales order) which have lipid contents above 10% (McDermid & Stuerke, 2013; Gosch et al., 2012). Depending on the type of lipid, algal oils can be used in pharmaceuticals, nutraceuticals (due to their favorable omega 3 to omega 6 ratio) and as feedstocks for biofuels and industrial chemical replacements (Gosch et al., 2012). The polyunsaturated fats found in seaweed lipids naturally occur in a beneficial ratio to each other, giving them the highest value when sold as nutraceuticals (Kumari et al., 2013; Moreira et al., 2021). Lipids from brown seaweed often contain the pigment fucoxanthin, which has a previously noted application in pharmaceuticals (Miyashita, Mikami, & Hosokawa, 2013).

Two common methods of lipid extraction include using only direct transesterification (quicker and more efficient) and solvent extraction, followed by transesterification (traditional extraction method) (Gosch et al., 2012). Many lipid extraction methods are rather complex. A simple method of lipid extraction from seaweed can be done following the method of Bligh and Dyer, 1959. This method involves adding seaweed biomass to a solvent mixture of 1:2 chloroform to methanol (at a rate of 100 mL per ~5 g dry residual biomass) and homogenized by vortexing. The homogenous mixture is then centrifuged at 4000 rpm at 4 °C for 20 min and the supernatant is removed and stored. Centrifugation is repeated 2–3 times until the supernatant is clear. The supernatants are then pooled and filtered. The filtrate, which is a lipid solution is washed with water and centrifuged at 4000 rpm for 5 min at 4 °C. The lower layer of lipid is collected and dried (Bligh and Dyer, 1959; Trivedi et al., 2016).

Lipids are a suitable compound to be extracted in a biorefinery setting (Gajaria et al., 2017, Reddy et al., 2018, Arias, Feijoo, and Moreira et al., 2023). It appears that lipid extraction typically occurs towards the middle of a biorefinery process. In one case it is done following sap extraction, but before ulvan, protein, and cellulose extraction (Gajaria et al., 2017). In another,

it is done following sap and pigments extraction and before hydrocolloid and cellulose extraction (Reddy et al., 2018).

Vertical and Horizontal Integration of the Seaweed Industry

A variety of terms have been used to refer to processes which convert seaweed biomass into a portfolio of value-added products. The term biorefinery was initially coined to describe the conversion of biomass into energy and chemical products, analogous to a traditional petroleum-based refinery (O’Callaghan, 2016; Leufstadt and Wenall, 2023). The economics of biofuel production requires side stream product revenue to be economically viable. An important goal of this type of biorefinery is to be a cleaner alternative to a petroleum refinery. (O’Callaghan, 2016).

This definition has evolved over time and now the term biorefinery is commonly used to refer to a facility which produces several products, using greener technologies and minimizing waste (Rise, 2020; Leufstadt and Wenall, 2023). This contrasts with traditional single-stream seaweed processing. Single stream processing describes the conversion of seaweed into one compound or product, with unused biomass and residues typically being discarded as waste. Data on the percentage of seaweed used for single stream processing are not readily available, however currently, about 77.6% of seaweed is used for food and 11.4% is used for hydrocolloid production. During food production, the whole biomass of seaweed is generally used, thus it is not a suitable product to be incorporated into a biorefinery. However, hydrocolloid production generates a large amount of waste with up to 70-85% of the biomass being discarded. In certain situations, this waste is applied to crops or fed to animals, but that is contingent on solvents and chemicals no longer being present in the waste. (Baghel et al., 2020, Ingle et al. 2011, Baghel et al. 2016). Given the high value of hydrocolloids and the wide range of compounds present in seaweed that remain in the biomass post extraction, we believe this presents an opportunity for co-production with side stream products.

The term coastal marine biorefinery has been used to describe a seaweed biorefinery located near shore to facilitate the processing of fresh seaweed biomass (thus reducing the need for drying and transportation) and to allow for the use of seawater in processing (reducing freshwater inputs) (Johnston, 2023). It is worth noting that saltwater may not be a suitable medium for all production processes and products made through fermentation will require specific marine yeast strains.

A cascading biorefinery refers to the creation of multiple value-added products and has been defined as “a processing facility that integrates multiple biomass valorization pathways to produce value-added products, by letting biomass cascade through different extraction steps” (Leufstadt and Wenall, 2023). Harsh processing can alter the biochemical composition of the biomass, therefore careful consideration of extraction order and prioritization of early extraction of higher value products may be warranted. For this reason, mild processing techniques are generally preferred, further promoting the green nature of a cascading biorefinery (Leufstadt and Wenall, 2023).

Recently, at least two companies (GOA and Thalasso) have begun developing portable micro-biorefinery concepts. These have the advantage of being cheaper, mobile, and more easily modified than a standard biorefinery concept which is more similar to production in a factory setting. The lower cost of entry allows for the possibility of purchase or leasing by smaller producers (such as seaweed farmers and communities), and the portability of these units allows for their siting in remote coastal areas. By being easily modified, the product portfolio is flexible and can change with demand. Additionally, it allows producers to invest in new capabilities as their budgets expand. As of this writing, portable seaweed biorefineries are in the pilot testing stage.

A cascading biorefinery has potential to be a more environmentally friendly production method than single stream processing, however it does not necessarily favor the production of GHG mitigating products. That said, minimizing waste and co-producing high-value products with GHG mitigating products has the potential to make the supply chain more environmentally friendly, which may attract interest from mission-driven businesses and investors. Identifying and encouraging product streams with greater GHG mitigation potential is an important first step to maximizing the environmental benefits of a cascading biorefinery.

Vertical Integration

Vertical Integration refers to the degree to which a firm controls the supply chain. Complete vertical integration of a seaweed biorefinery entails ownership and control of the nursery, farm, transportation, production facilities, and sale of product to consumers. Complete vertical integration can be difficult to attain as it requires significant investment and in-depth knowledge of each step of the production process. The advantage of vertical integration is that it can allow for greater control of the supply chain, higher levels of efficiency, and increased profits (Hayes, 2024).

Seaweed farming and processing tend to not be vertically integrated. For example, the standard supply chain of hydrocolloids in the Philippines involves many actors (see figure 6). The farmer purchases propagules or seedlings and finances ropes and equipment from lenders. The farmers then grow, harvest, clean, and dry the seaweed, before selling to traders. The traders are middlemen who aggregate smaller seaweed harvests from the farmers and sell in large quantities to processors. They consolidate the seaweed and may further clean and dry it when necessary to ensure consistent quality. Smaller traders may sell to larger aggregators. Carrageenan production is prominent in the Philippines. Once the processors have manufactured the carrageenan it is generally sold to companies which incorporate it into their own products, before sale of the product to the consumer or supermarkets and retailers (Bureau of Fisheries and Aquatic Resources, 2022). Increased vertical integration would involve

one of these actors taking control of additional positions in the supply chain. Doing so has potential to increase the revenue and control this actor has.

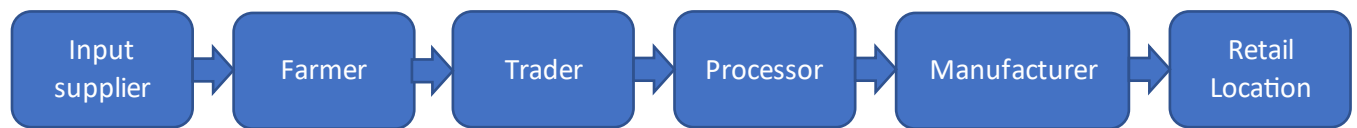


Figure 6: Sample supply chain of Hydrocolloid Products in the Philippines

It may be possible for seaweed farmers to increase their profit by controlling additional aspects of the supply chain. To do this a farmer would need technical knowledge, along with the time and capital necessary to process the seaweed, all of which can be difficult for farmers to obtain. However, if farmers can take control of more aspects of the production process, such as through the production and sale of value-added products, their margins may increase significantly.

Horizontal Integration

Horizontal Integration refers to collaboration between actors on the same level of the supply chain (Palmieri et al., 2019). It is more likely to be successful when there is a low level of competition between these actors and collaboration can lead to shared risk and reward, increased competitive advantage for all parties, and decreased transportation and logistical costs. Horizontal integration may be difficult to attain given the nature of firm competition, however it has the potential to benefit consumers by making higher value products available at a lower cost and may be more environmentally favorable if equipment, infrastructure, or transportation are shared between actors (Leufstadt and Wenall, 2023).

Horizontal integration may be another path forward for seaweed farmers to increase their profits. Farmer cooperatives are a relevant example of horizontal collaboration where farmers work together to aggregate their seaweed, increase access to knowledge and training, and invest in capital which can be shared among farmers. This may enable them to build technical skills and aggregate their seaweed to sell directly to processing facilities for a higher margin (rather than needing to sell to an aggregator). If a cooperative can invest in a small scale biorefinery or use equipment which simulates a biorefinery operation, this may allow farmers to manufacture and sell value added seaweed products and transition them from being price takers to being price setters. This is an ambitious goal and, in many areas, would likely require outside funding for capital investment and training in how to manufacture value-added products and market them for sale. Local nonprofits may be best equipped to tackle these challenges on a case-by-case basis.

Current Biorefinery Initiatives

Four biorefinery companies are discussed in this report: Origin by Ocean, OCEANIUM, Thalasso, and GOA. At the time of writing, none had begun operating at full commercial scale. We know of only one company, OCEANIUM, that has made a sale of their product, a fiber supplement, to date. While all four have plans to scale their operations and target dates to build their full biorefineries, all currently remain in the pilot phase. Thalasso and GOA build portable micro biorefineries, while Origin by Ocean and OCEANIUM plan to build more traditional production facilities.

Lack of proof of concept is considered a major challenge for biorefinery initiatives as many questions remain about product yield in a large commercial setting, along with economic feasibility. High transportation cost of fresh biomass, high ash content of seaweeds, and lack of availability of fresh biomass are other challenges facing biorefineries (Baghel et al., 2023; Leufstadt and Wenall, 2023). The transportation issue can be solved if the biorefinery is on the coast, near where the seaweed is harvested. Origin by Ocean plans to locate their initial operation on the shore of the Baltic Sea where large algal blooms lead to adequate supply, without the need for wild harvest from kelp forests. One of OCEANIUM's goals is to help expand seaweed farming in the western hemisphere, however they have also explored utilizing seaweed from algal blooms. For large scale seaweed farming to expand beyond Asia, it is believed that the biorefining of seaweed first must be proven at an industrial scale and that large-scale cultivation will follow the demand the biorefineries will create (Leufstadt and Wenall, 2023). While collecting seaweed from blooms may reduce costs relative to farming seaweed or procuring farmed seaweed, volumes and quality may be too variable to sustain a biorefinery over time.

Both the GOA and Thalasso business model revolves around the sale of easily modifiable, portable biorefineries which can produce a variety of products. This approach enables production of seaweed-based products in remote areas without nearby processing facilities and allows the owner to scale up and add new production capabilities as they deem necessary. If owned by farmers or a community, this enables them to extract more value from the seaweed they produce through the creation of value-added products.

Complexity increases significantly with the number of products made in a biorefinery system. More products entail more investment in capital, more complexity in processing, more business and technical knowledge, and more relationships to maintain with customers in a variety of industries. To reduce cost and complexity, biorefineries may wish to first optimize production of a few high revenue products to start, then add additional products and side streams as they go, to decrease complexity of operations at the outset (Leufstadt and Wenall, 2023). Others feel that cascading biorefineries are best implemented by planning all the outputs and processes in advance to reduce challenges associated with modifying or adding new processes later.

Origin by Ocean

Origin by Ocean is a Finland based company which was founded in 2019 to replace conventional, oil-based chemicals with algae-based alternatives. They have raised €9.5 million over 3 rounds of funding, which at the time of writing is equivalent to 10.2 million USD. The most recent round of funding was April 26th, 2023. Their main investors, Voima Ventures, Lifeline Ventures, and Business Finland, are all based in Finland (Crunchbase, 2023).

Their environmental value proposition is to reduce the GHG impact of the chemical industry and to clean up areas affected by eutrophication. They do this by sourcing their feedstock from invasive algae and harmful algal blooms (Origin by Ocean, 2023).

They currently use three brown seaweeds, *Sargassum*, *Fucus vesiculosus*, and Kelp (unspecified species). Blue-Green cyanobacteria harvested from harmful algal blooms in the Baltic Sea is also used. The *Sargassum* is wild harvested from the Caribbean shore. *Fucus vesiculosus* is wild harvested from the Baltic Sea and Origin by Ocean is currently working to develop farming infrastructure for it as well. The Kelp is cultivated at an unspecified location in Europe. Origin by Ocean uses floating algae harvesters which are attached to a boat to collect algae. According to their site, they plan to create a “business ecosystem” which will allow for increased side stream work and revenue for the people they work with (including seaweed farmers and producers utilizing seaweed feedstock). They will operate a centralized biorefinery in which the full production process will be done at one location (Origin by Ocean, 2023).



Image 1 (left): Sargassum in the Caribbean; Image 2 (right): Lab scale biorefining of an Origin by Ocean product (Origin by Ocean, 2024)

They use a patented biorefinery process to separate out sodium alginate, mycosporin, fucoxanthin, fucoidan, laminarin, and a seaweed residue. These products have applications in food, cosmetics, agriculture, textiles, detergents, and packaging. While they do not disclose details about their biorefinery process, they claim to further minimize waste and impact by recycling water and chemicals during production (Origin by Ocean, 2023).

Their plan is to open biorefineries in areas impacted by large algal blooms to guarantee a large source of feedstock and help clean up these blooms before they reach shore. The past few years have been dedicated to product development, trials, and proof of concept of their biorefinery and products, along with closing a pre-seed and seed funding round. In 2024 they plan to fulfill some small-scale customer orders, before establishing a biorefinery by the Baltic Sea and going fully commercial in 2025. In 2027 they hope to establish biorefineries in the Caribbean, Indonesia, and Australia to meet international demand and reach breakeven in their operations. They plan to continue to increase their production capacity by operating multiple biorefineries in Southeast Asia, the Caribbean, and the EU (Origin by Ocean, 2023). While their initial biorefinery will be capable of processing 20,000 wet tons of seaweed per year, in the future they plan to establish biorefineries capable of processing 100,000 tons per year (Leufstedt and Wenall, 2023).

OCEANIUM

OCEANIUM develops and makes innovative, functional seaweed ingredients to catalyze the seaweed industry for ocean and people's health. They have raised over \$12 million through seed rounds, various grants, and a venture round. The grants were provided by Innovate UK and the European Commission which holds funding competitions for businesses and organizations working with emerging technologies. OCEANIUM cite Builders Vision, World Wildlife Fund, Green Angel Ventures, Sustainable Finance Initiative members, Astia, Katapult Ocean and Sustainable Ocean Alliance as some of their investors (OCEANIUM, 2024b).

OCEANIUM uses proprietary clean and green processing technology to maximize the value of their seaweed and is working towards zero waste and carbon neutrality in their operations. Through their cascading biorefinery technology, they produce high-purity bioactive ingredients for health and cosmetics, including a high-purity marine bioactive which has undergone various testing for health and skincare applications. OCEANIUM has developed a range of innovative materials including a fully biodegradable, seaweed and water-based ink for luxury packaging and textiles, plus a functional, superfood ingredient for food, beverages and supplements. They have made significant progress with their product development and their high-purity marine bioactive has undergone various testing both for health and skincare applications.



Image 3 (left): OCEANIUM prototype seaweed-based material; Image 4 (right): Preparation of OCEANIUM superfood ingredient (OCEANIUM, personal communication, 2024)

OCEANIUM sells B2B (business to business) to enable companies to incorporate sustainably sourced, traceable high-quality ingredients and components into their products to meet their sustainable development targets and consumer demand. OCEANIUM's technological developments allow it to purchase and process seaweed efficiently. They work with sustainable farmers across Europe to stimulate both supply and demand, unlocking a pinch point in the emerging seaweed farming industry and contributing to six of the UN's Sustainable Development Goals. OCEANIUM's ingredients are intended to support future food security, healthy diets and a transition away from resource-intensive food and materials.

Their products are mainly produced from brown seaweeds, primarily *Saccharina latissima* (sugar kelp). In 2022, they began exploring the use of a green seaweed, *Ulva* (sea lettuce). In 2022 their seaweed was sourced from the Faroe Islands, Norway, Scotland, France and Portugal (OCEANIUM, 2022).

Kelp-EU is an OCEANIUM project co-funded by the EU, which seeks to create a sustainable EU seaweed industry by working with seaweed farmers to create a supply chain of sustainably farmed seaweed, develop high quality, sustainable seaweed products, and design a biorefinery site to scale up processing capabilities. The project ran from October 2021 to December 2023 and the remaining deliverables will be published on their website (OCEANIUM, 2024a).

OCEANIUM are fundraising to build a first of a kind seaweed biorefinery which will undertake the entire production process of their ingredient products. Their plan is to replicate and scale their facilities globally, including the potential for licensing and regional partnerships of their biorefinery technology. They envision full-scale biorefineries co-located next to seaweed farms that would process 20,000 tons of wet seaweed per year thus helping to mitigate ocean eutrophication, ensure food security and create jobs along coastal regions.

Thalasso

Thalasso is a Norwegian company with a strong presence in the Caribbean. They currently focus on harvesting sargassum blooms before they reach the shore and using them in their portable biorefinery concept to make valuable products. Thalasso has raised \$500,000 USD in grants and private investments during the pre-seed stage, and they have currently raised \$200,000 USD in the seed round. This round is ongoing, with a target of \$2 million USD. The pre-seed funding was supported by a mix of individual investors and grants, including Rumbo Ventures based in Spain, which invests in early-stage climate technology companies, and Flow Ventures based in Norway, which specializes in ocean-based industries. This funding has been used to advance Thalasso's initiatives, including the development of an automatic seaweed packing solution for their sargassum harvester and for lab research to increase yields in their biorefinery concept.

Thalasso's work began with the development of an autonomous electric harvester, which captures Sargassum in the Caribbean before it washes ashore. They have continued this work with the development of a portable micro biorefinery to create value from the harvested Sargassum (Thalasso, 2024). They have begun the construction of their first micro biorefinery and expect to soon have the components which produce a biostimulant operational. In talks with Thalasso representatives, they stated they will carry out an initial pilot in July-August 2024 with the Puerto Rico government. The focus of this pilot is obtaining biostimulants, fucoidan, and alginate from Sargassum. The biorefinery is currently limited to processing Sargassum and brown seaweed, but there are plans to expand its capabilities to include red and green seaweed as the business becomes more established.



Image 5 (left): Frame being built for Thalasso biorefinery container; Image 6 (right): Mock-up of a completed Thalasso biorefinery (Thalasso, personal communication, 2024)

Thalasso claims their biorefinery is easy to install, fits in a large shipping container, is easily modified post-installation for production of new products, and can process 3-4 tons of wet

seaweed per day. The inputs to the biorefinery are water, electricity, seaweed and some chemicals. They are working to minimize the amounts of non-seaweed inputs in their operations. The only waste produced are fibers and cellulose, which some potential buyers have expressed interest in purchasing. However, Thalasso emphasizes the importance of ensuring that partnerships with larger corporations are based on genuine sustainability efforts rather than greenwashing.

Part of Thalasso's value proposition is to enable remote farming communities to control more of the production process and extract more value from their seaweed (Thalasso, 2024). They claim it will cost less than \$500,000 per unit and are exploring the feasibility of leasing out their biorefineries to further increase accessibility for these communities and farmers (Personal Communication).

GOA

GOA Ventures is a Dutch company founded in 2017, which is backed by the Blue Forward Fund of Paris based VC company VC Seventure Partners. Seventure finances "innovative companies within Life sciences and Digital technologies" (Seventure, 2024). GOA's business model revolves around the sale of turnkey, portable biorefineries which can produce a variety of products from any type of seaweed. In addition to providing their customers with training and operations support, GOA also helps them in selling the products derived from the biorefinery (personal communication).

According to GOA, they have patented their technology for processing fresh seaweed. This technology is mobile and fits in several 20ft shipping containers. It is made to be modular and scalable to easily fit the changing production capabilities and to work with any type of species. Their bioprocessing facilities are meant to be set up near shore so that fresh seaweed can be processed without the need for preservation or drying. GOA also holds the design to do pre-processing of fresh seaweeds on their harvesting vessels.

The first step of their biorefinery process consists of food-grade functional proteins being extracted from the seaweed and sold for application in vegan protein markets. The protein depleted biomass is then converted into renewable energy (biogas) using a new and innovative technology. A portion of this biogas is used to fuel onsite operations. The surplus capacity of renewable energy can then be used to fuel regional households or community facilities. Recent developments have also opened the door to extracting valuable carbohydrates prior to biogas production. The left-over residue from the production of biogas has potential as a soil-improver, resulting in four total bioproducts from each kilo of processed seaweed (personal communication).



Image 7 (left): GOA processing of seaweed; Image 8: Seaweed liquid crude protein extract (GOA, personal communication, 2024)

In 2017, GOA began developing technical knowledge, filing its IP, performing pilot tests at over 100 kg scale and testing market interest in seaweed derived products. As of 2023, GOA has been researching their processes in its own laboratory, while simultaneously creating biorefinery designs for pilot scale and large-scale production. They have successfully tested their process and design on 15 different seaweed species (including red, green, and brown seaweeds) and plan to tailor each biorefinery to the local seaweed species and their customer's individual needs. They estimate over 10,000 tons of wet seaweed per year will need to be processed to break even. Intended volumes for an economically viable biorefinery are 25,000 tons of fresh seaweed (wet weight) per year. They have reached agreements with potential customers to purchase their technology and hope to have a facility up and running in 2025 or 2026. The interested companies hope to manufacture their products year-round, meaning their bio-processing facilities would require a large quantity of fresh seaweed input every day. Due to the high volume of seaweed required, they anticipate that in the short term their initial customers to be in Asia or the Caribbean (personal communication).

Their site lists proteins, carbohydrates, and minerals as the potential products from the biorefinery. Proteins are intended for use as a food component, while carbohydrates have more varied applications. Their site lists hydrocolloids and sugars (mannitol) as valuable carbohydrates which may be sold on their own or further processed into products such as bioethanol, biogas, and bioplastics. Their site indicates the capability of their biorefinery to

extract minerals including, but not limited to nitrogen and phosphorous, indicating biostimulants and biofertilizers as potential products (GOA Ventures, 2024).”

Cascading Biorefinery Concepts

From 2011-2022, there were fifty-nine papers published which discussed the recovery of 2-7 products from seaweed using integrated biorefining approaches. Across the papers, a total of 255 products were developed with an average of 4.32 products per species (Baghel, 2023). This body of research resulted in at least two patented processes. A method to extract a mineral rich liquid extract (liquid biostimulant) and carrageenan from *Kappaphycus alvarezii* (Eswaran et. al., 2005) and a process which can extract liquid biostimulant/fertilizer, natural pigments, lipids, hydrocolloids, and cellulose from fresh *Kappaphycus alvarezii* or *Sarconema scinaioide* (Reddy et. al., 2018). These two processes are further discussed below.

A Techno Economic Analysis (TEA) can be used to evaluate the economic feasibility of a biorefinery. The TEAs currently available for seaweed biorefinery concepts have been conducted in the context of biofuel and bioenergy production. Outside of biofuels, the literature is lacking in TEA done on seaweed-based products with GHG mitigation potential. From the analyses done on biofuels it is apparent that local energy and labor costs have the biggest impact on the breakeven price of bioenergy production (Soleymani and Rosentrater, 2017). Labor cost has the most influence as it makes up a larger share of costs and high energy prices may be partly offset by a higher sale price for the bioenergy produced and sold. In a 2017 study, the breakeven point for bioethanol was determined to be as low as \$1.55/L when biogas and fertilizer are produced as secondary products. At that time, the economically feasible sale price of bioethanol was identified to be \$.95/L, indicating that even with production of secondary products, seaweed-based biofuels are not yet cost competitive with terrestrial crops. Increasing the productivity of seaweed farms and increasing the scale of production were seen as two feasible ways to bridge the gap (Soleymani and Rosentrater, 2017). Greene et al., 2020, also cites the length of the seaweed growing season as a consideration which can greatly affect the breakeven price of biofuel. By producing nitrogen and phosphorous based fertilizers as a co-product, they find the potential for a breakeven point as low as \$1.35/L. Another TEA found that single stream production of biofuel would not be profitable unless produced in a biorefinery setting. When produced alongside mannitol, sodium alginate and protein, bioethanol was estimated to be profitable so long as the seaweed used as a feedstock was purchased at a price below \$374 US per ton of dried seaweed (Nazemi et al., 2021).

There are many potential biorefinery concepts which combine production of high value compounds with greenhouse gas mitigating products. This section describes biorefinery those which have been detailed in patents and academic literature. Additionally, it develops a proposed biorefinery concept which processes seaweed to make a mineral rich extract, pigments, lipids, hydrocolloids or ulvan, protein and cellulose. The concept differs based on the type of seaweed used and its concentration of each component. Red and green seaweeds have high concentrations of protein, so are suitable for protein extraction. Brown seaweed has low protein concentrations and therefore may be better utilized for lipid extraction. To maximize the climate change mitigation potential of the biorefinery, hydrocolloids and ulvan may be used

for bioplastic production and cellulose may be used in bioplastics, construction materials, or as a feedstock for biofuel production.

Concept 1: Mineral rich extract, lipids, ulvan, and cellulose from green seaweed (*Ulva fasciata*) (Trivedi et al., 2016)

A green seaweed biorefinery processing *Ulva fasciata* could produce a mineral rich liquid extract, lipids, ulvan, and cellulose (see figure 7) (Trivedi et al., 2016). Along with water, the mineral rich liquid extract contains carbon, nitrogen, sulphur and minerals. This extraction process was found to use 66% of *Ulva* biomass. The yields were comparable to that of the direct extraction techniques standardly used for each compound. The specific techniques used for each extraction are not discussed, however the steps involve:

- 1) A water extraction in which 100 mL of water is added to 50g of *Ulva* biomass, yielding 80mL of mineral rich liquid extract.
- 2) A lipid extraction
- 3) Ulvan extraction
- 4) Ethanol extraction which involves enzymatic hydrolysis of the cellulose rich residual biomass following ulvan extraction, followed by fermentation of the hydrolysate by the yeast *Saccharomyces cerevisiae*. Alternatively, cellulose could be extracted.

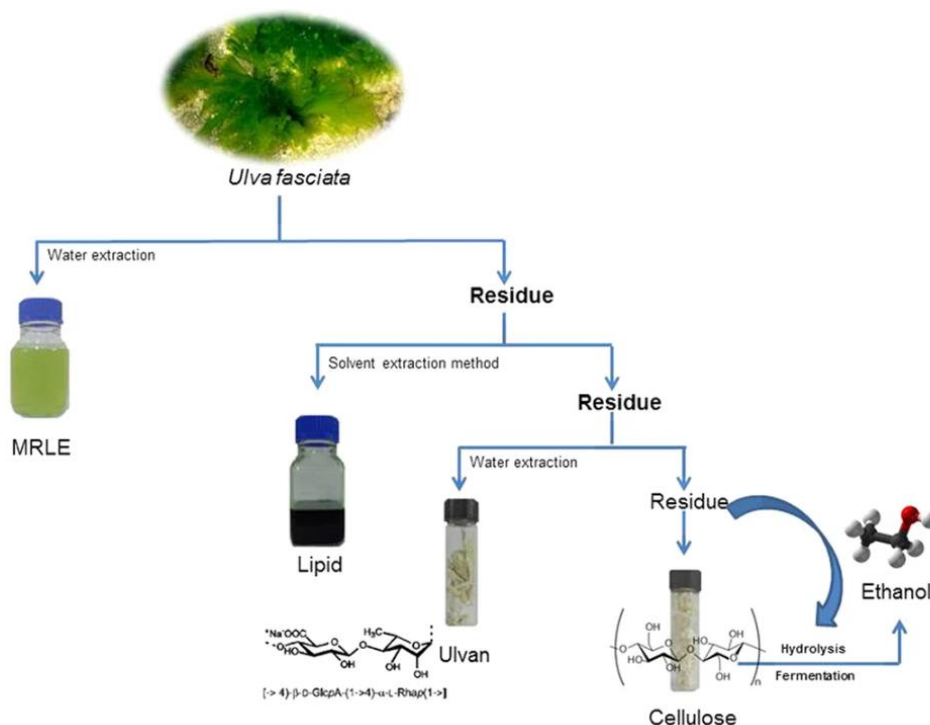


Figure 7: A sequential extraction of products from fresh *Ulva fasciata* feedstock (Trivedi et al., 2016)

Concept 2: Mineral rich extract, lipids, ulvan, cellulose, and protein production from green seaweed (*Ulva lactuca*) (Gajaria et al., 2017)

Gajaria et al., 2017 expands on concept 1 detailed above. It outlines a process to recover the same products as Trivedi et al., 2016, in the same order, with the addition of protein extraction in between ulvan and cellulose extraction (see figure 8). Four methods of obtaining a mineral rich liquid extract (sap) were compared: extraction from crushed biomass, extraction from whole biomass, extraction from whole biomass along with a heat treatment, and extraction from crushed biomass along with a heated treatment. Crushed biomass combined with the heat treatment resulted in the best yield of most elements, however an extraction from crushed biomass without the heat treatment is the recommended extraction method as it had comparable yields, did not require additional energy input, and the heat treatment was found to increase the solubility of ulvan in the liquid extract, therefore reducing ulvan yield later on (Gajalaria et al., 2017). The steps involve:

- 1) 50 g of fresh algae is combined with 100 ml of deionized water and is crushed using a kitchen mixer grinder. The mixture is then filtered using a muslin cloth followed by 0.21 μm filter paper to separate the liquid extract from the solid residue
- 2) For lipid extraction, the solid residue is then mixed with chloroform and methanol in the ratio of 1:2. The mixture is kept on a magnetic stirrer for at least 3 h to ensure complete lipid solubilization, then transferred to a separating funnel along with distilled water in a 1:1 ratio. The funnel is left to stand until the two phases are separated evenly. The lower is collected and filtered through 0.21 μm filter paper and transferred to the vacuum evaporator to remove solvents. Gajalaria et al., 2017 does not specify which layer is lipid and which is the residue, however the work of Bligh and Dyer, 1959 it appears to indicate that the lower layer is the chloroform layer containing lipids, while the upper layer is the methanol layer, containing the residue.
- 3) Ulvan extraction is conducted in accordance with the work of Jaulneau et al., 2010. The residue is incubated in distilled water at 90 °C for 2 h. The mixture is then allowed to cool and filtered through muslin cloth and 0.21 μm filter paper. Iso-propanol is added to the filtered suspension and stirred vigorously for 30 min. The precipitates are recovered by muslin cloth filtration and dried in the oven
- 4) For protein extraction, the remaining biomass is then subjected to an alkaline treatment, involving the use of sodium hydroxide at 80 °C. This causes the complete dissolution of algal biomass so that proteins are more easily liberated. The mixture is allowed to cool at room temperature, filtered using 0.21 μm filter paper, then neutralized using hydrochloric acid. The suspension is then dialyzed and lyophilized (freeze-dried).
- 5) For cellulose extraction, the remaining residue was added to 36% w/w sodium hypochlorite at pH 3 and incubated overnight at 65–70 °C. The sample was washed with distilled water until neutrality then treated with 0.5 M sodium hydroxide at 60 °C

overnight. The residue is then subjected to acid digestion using 5% HCl and heated to boiling. It is then washed up to neutrality. The residue is then dried.

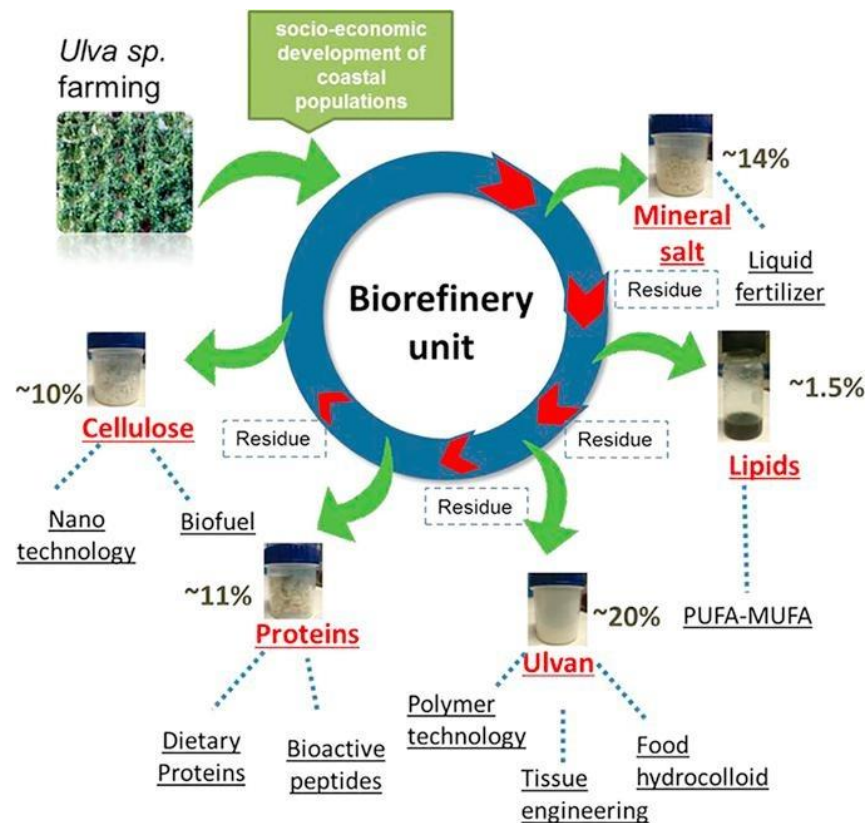


Figure 8: A green seaweed biorefinery which produces a mineral rich liquid extract, lipids, ulvan, protein, and cellulose from *Ulva lactuca* (Gajaria et al., 2017).

Concept 3: Protein, fertilizer, mannitol, alginate, and bioethanol production from brown seaweed (*Nizimuddina zanardini*) (Nazemi et al., 2021)

Nazemi et al., 2021 discusses a brown seaweed biorefinery which uses *Nizimuddina zanardini* to produce protein, fertilizer, mannitol (a sugar alcohol with applications in the food and pharmaceutical industries), sodium alginate, and bioethanol (See figure 9). A techno-economic analysis of the system concluded that it would be profitable at any dried seaweed sale price of 374 \$/tonne_{dw} or less. Conversely, single stream production of biofuel was determined to be unprofitable if the dried seaweed sale price is -64 \$/tonne_{dw} or higher. This indicates that a biorefinery is needed to make biofuel production from macro-algae feasible (Nazemi et al., 2021).

The steps of the process include:

- 1) The seaweed is ground into a slurry and diluted with hot water and pumped into a pretreatment reactor for 1h at 120°C. The slurry is then sent to a vacuum belt filter to separate liquids and solids
- 2) The solid filtered out is diluted and undergoes hydrolysis and fermentation. Enzymatic hydrolysis is done using the enzyme cellulase. The portion of the solid rich in alginate is then separated from the hydrolysate.
- 3) The hydrolysate, which is rich in glucose, is sent to the fermentation reactor where the microorganism *Zymomonas mobilis* converts sugars into ethanol. Ethanol is then purified through distillation and molecular adsorption
- 4) Sodium alginate extraction is a complex process. First, the alginate rich solid is soaked in formalin to prevent discoloration. Next is an acid treatment process where calcium, magnesium, and potassium salts of alginate are converted into alginic acid by ion-exchange reactions. Alginic acid is then converted into sodium alginate through an ion exchange reaction with sodium carbonate. The sodium alginate solution is converted into calcium alginate through an ion exchange reaction with calcium chloride, bleached, then converted back into alginic acid through an ion exchange reaction with hydrochloric acid. The alginic acid is dewatered using a hydraulic press and converted back into sodium alginate (in the form of a paste) through an ion exchange reaction with sodium carbonate and dried. It is not clarified why conversion into calcium alginate and alginic acid occur following the first solution of sodium alginate being obtained. It appears that this is done because calcium carbonate is more resistant to bleaching (which improves color and odor of the final product) and alginic acid is more easily dewatered than sodium alginate.
- 5) Next, the liquid portion separated in the vacuum belt filter in step 1 is processed to recover protein, mannitol, and minerals for fertilizer use.
- 6) An ultrafiltration system is used to separate the protein from compounds of lower molecular weight and dried to produce a powdered protein
- 7) The filtrate is concentrated at 80°C (to avoid mannitol degradation) in an evaporation chamber then pumped into an ion exchange membrane for demineralization. The minerals are collected for use as a fertilizer, while the remaining solution is sent through a crystallization unit which includes an evaporator, a crystallizer, and a centrifuge. The recovered mannitol is then dried
- 8) Throughout the process, wastewater streams from all units are collected. Depending on the chemical oxygen demand of the wastewater, it is either processed for biogas production soluble mineral recovery

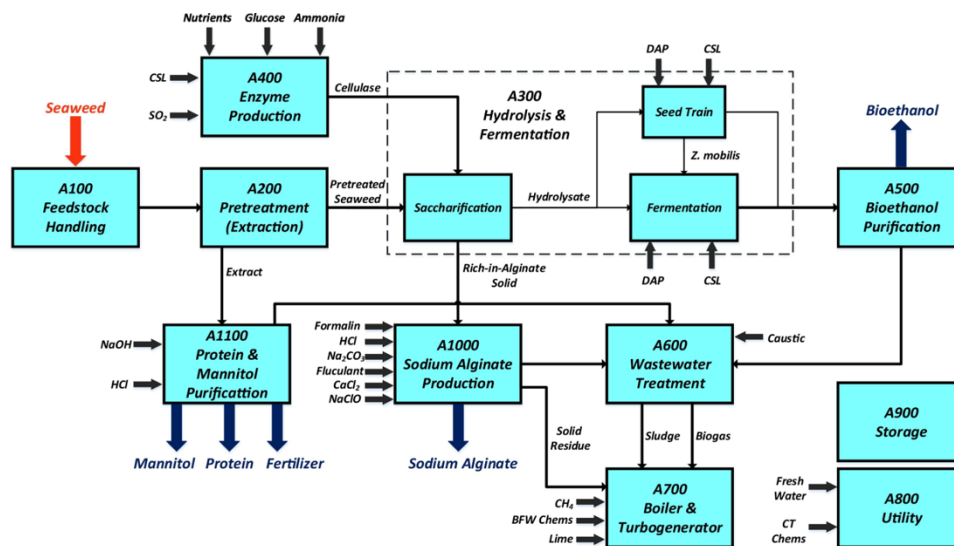


Figure 9: A brown seaweed biorefinery which produces mannitol, protein, fertilizer, sodium alginate and bioethanol from *Nizimuddinina zanardini* in Iran (Nazemi et al., 2021)

Concept 4: Sap (biostimulant), alginic acid, protein, cellulose and salt from brown seaweed (*Sargassum muticum*) (Baghel et al., 2020)

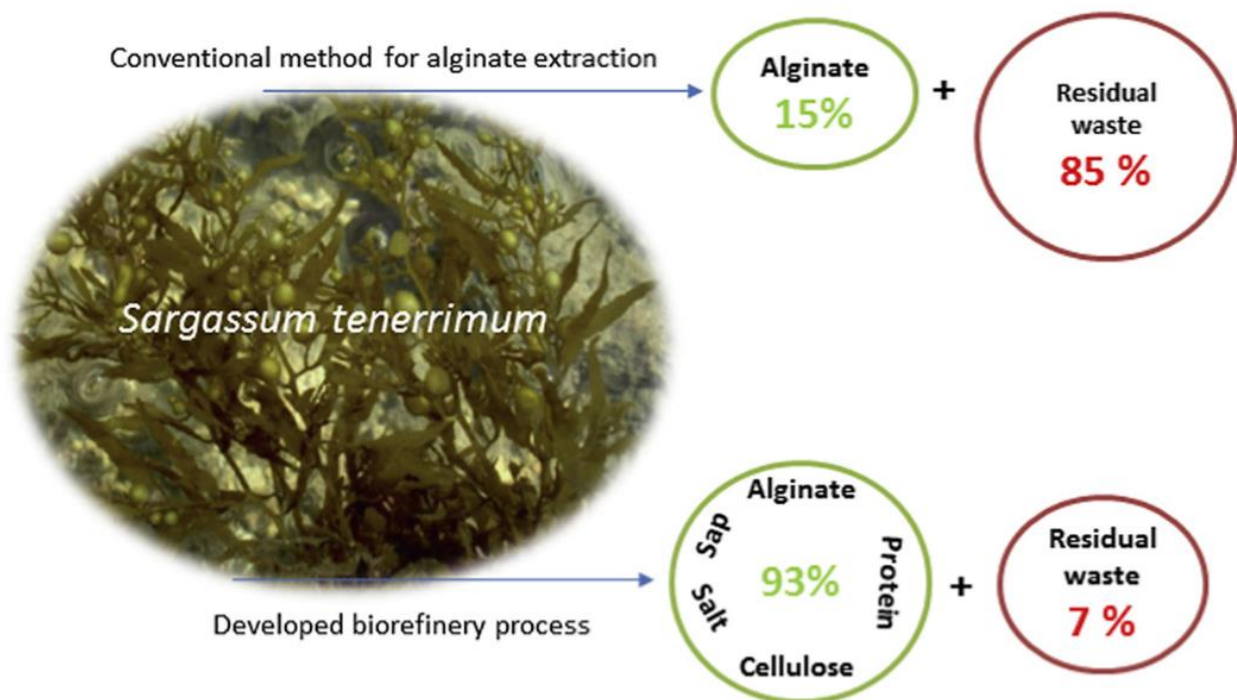
This process outlines a biorefinery which uses *Sargassum* as a feedstock to produce a biostimulant, alginic acid, protein, cellulose and salt (figure 10). 1kg of biomass was found to yield 541.33 ± 5.50 mL sap, 32 ± 1.5 g alginic acid, 3.8 ± 0.2 g protein concentrate, 10 ± 0.5 g and 115 ± 5 g salt. 93% of biomass is utilized, with only 7% residual waste. This is a notable improvement to conventional single stream processing of alginate which yields 15% alginate with 85% waste (Baghel et al., 2020).

The steps of the process include:

- 1) Biomass is crushed using a mixer grinder and the sap is squeezed out of the biomass using a muslin cloth. The sap may be used as a biostimulant
- 2) The residual biomass is then bleached in a sodium hypochlorite solution (NaClO_2) at 65°C for 6h then separated from the solution using a muslin cloth. The filtrate is kept for recovery of salts, while the solid is rinsed with tap water, dried then hydrolyzed in a sodium carbonate solution (Na_2CO_3) at room temperature while stirring for 2 hours. This is again filtered through a muslin cloth. The solid residue is kept for extraction of additional compounds. Alginic acid is precipitated from the filtrate using hydrochloric acid (HCl), separated through filtration with a muslin cloth (filtrate is kept for recovery of salt), dried at 65°C and powdered.
- 3) The solid residue is hydrolyzed in a sodium hydroxide (NaOH) solution at 65°C for 3h then filtered through a muslin cloth to separate the filtrate containing protein with the cellulose rich solid residue. Protein is then recovered from the filtrate by using HCl to

lower the pH of the solution to 2, filtering the solution (filtrate is kept for salt recovery), and washing and drying the solid to obtain protein

- 4) The cellulose rich residue is suspended in a solution of HCl and heated to boiling. The slurry is then kept at room temperature overnight, washed, and dried at 65°C for 12h to yield cellulose.
- 5) The filtrates collected throughout the process are now mixed and made to reach a neutral pH through addition of NaOH. This is then left to evaporate in tray to obtain the salt



Seaweed biorefinery: A sustainable process for valorising the biomass of brown seaweed

Figure 10: A brown seaweed biorefinery which produces a biostimulant, alginic acid, protein, cellulose, and salt from *Sargassum* biomass (Baghel et al., 2020).

Concept 5: Biostimulant and hydrocolloid production from red and brown seaweeds

(*Kappaphycus alvarezii*, *Sargassum wightii* and *Sargassum tenerrium*) (Eswaran et al., 2005)

Eswaran et al., 2005 details a patented process through which a seaweed mineral rich liquid extract (biostimulant) and a hydrocolloid (K-carrageenan) are extracted from fresh *Kappaphycus alvarezii*, *Sargassum wightii* and *Sargassum tenerrium* biomass (figure 11).

Typically, seaweed is dried at the location of harvest and shipped to the processing facility. In this process, the first step is to extract a mineral rich liquid from the freshly harvested seaweed

and then dry the remaining solid fraction. This produces a biostimulants and makes the remaining fraction of biomass easier to dry, transport, and store, potentially resulting in significant energy and cost savings. The remaining biomass is more highly concentrated with hydrocolloids, containing 1.5-2 times the carrageenan by weight as fresh seaweed biomass (Eswaran et al., 2005).

The steps involve:

- 1) Freshly harvested seaweed is rinsed, crushed/ground into a slurry. The liquid fraction (sap) is separated using a muslin cloth, filter, and/or centrifugation resulting in a mineral rich liquid extract and a semi-solid residue
- 2) The sap can be diluted with water and sold as a liquid biostimulant (preservatives may be added if desired).
- 3) The remaining residue is a semi-solid wet granule. It is then dried prior to hydrocolloid extraction. Hydrocolloid extraction is not detailed in this process; however, they can be extracted in the same methods as from fresh seaweed biomass, resulting in hydrocolloids and a waste residue.

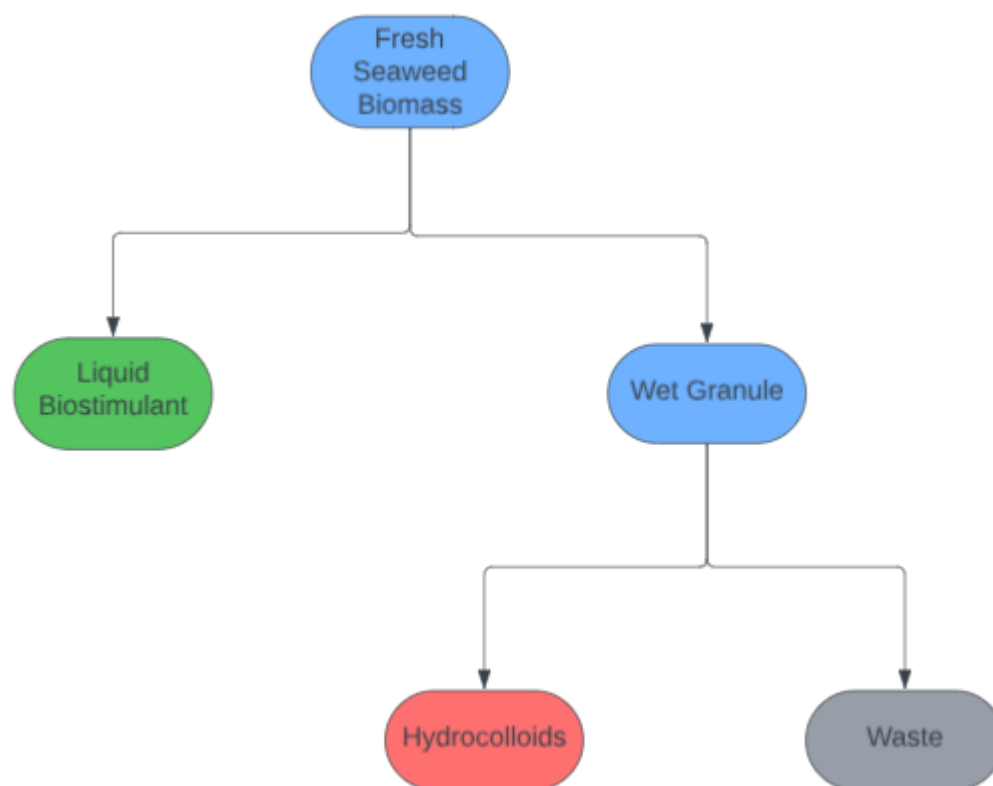


Figure 11: Patented process which produces a liquid biostimulant and hydrocolloids. (Eswaran et al., 2005). Blue boxes indicate intermediary steps, green boxes indicate GHG mitigating products, red boxes indicate other extracted compounds, and gray boxes indicate discarded materials.

Concept 6: Biostimulant, hydrocolloid, pigment, lipid, and cellulose production from red seaweed (*Gracilaria dura*, *Gelidium pusillum*, *Kappaphycus alvarezii* and *Sarconema scinaoides* (Reddy et al., 2018)

Reddy et al., 2018, further refines this process detailed in concept 5 to eliminate the waste fraction by producing pigments, lipids, and cellulose in addition to hydrocolloids and the biostimulant (figure 12). In this case hydrocolloids, pigments, lipids, and biostimulant are medium-high value products, while the cellulose is considered lower value. This approach is patented and is aimed at minimizing biomass waste, chemical usage, and solvent use (the solvents used in lipid extraction can be reused for 2-3 cycles without affecting product quality). The process was tested with five red seaweeds, *Gracilaria dura*, *Gracilaria acerosa*, *Gelidium pusillum*, *Kappaphycus alvarezii* and *Sarconema scinaioide*. The method is patented in the US with an adjusted expiration date of 2035, however the extraction processes detailed within the patent are highly specific and alternative processes exist. EDF counsel has advised that this cascading biorefinery process could be used by entrepreneurs with some modifications without infringing upon this patent. Modifications may be as simple as using different pH, temperature, time, centrifuge speed, centrifuge time, and centrifuge temperature than those specified in the patent. Alternative extraction techniques or addition or subtraction of the compounds produced would also avoid patent infringement.

Hydrocolloids such as agar, alginates, and carrageenan have applications in food, pharmaceuticals, and cosmetics (Pereira et al, 2020). Macroalgae lipids have been found to have polyunsaturated fatty acids in a nutritionally beneficial ratio and thus have applications as a supplement (nutraceutical) or in foods (Kumari et al, 2013). Macroalgae derived natural pigments have applications in foods and pharmaceuticals and have exhibited “various beneficial biological activities such as antioxidant, anticancer, anti-inflammatory, anti-obesity, anti-angiogenic and neuroprotective activities” (Pangestuti and Kim 2011). Cellulose can be used to produce bioethanol (Wadi et al, 2019). Seaweed liquid extracts are used as an agricultural input and are typically characterized as biostimulants (El Boukhari et al, 2020). Figure 12 below depicts the discussed patented biorefinery process. The yield of products obtained through this biorefinery approach was slightly lower than through single stream methods, but the quality was comparable. The quality of agar was found to be higher than through single stream processing (Reddy et al, 2018).

The steps include:

- 1) Freshly harvested seaweed is homogenized and chilled in a .1M phosphate buffer using a grinder. It is incubated for 12 hours and centrifuged several times. The supernatant and solid residue are separated
- 2) Pigments are precipitated from the supernatant using ammonium sulphate
- 3) Following pigment precipitation, the remaining supernatant is a mineral rich liquid extract, which can be diluted with water and applied as a liquid biostimulant

- 4) The solid residue remaining after centrifugation then undergoes lipid extraction using a 1:2 ratio of chloroform to methanol. The liquid residues are collected, filtered, washed with water, and dried to yield a lipid fraction. Solvents used for lipid extraction may be reused 2-3 times without adversely affecting lipid yield
- 5) The solid fraction remaining following lipid extraction is heated at 65 °C for one hour to remove remaining solvents and is used for hydrocolloid extraction
- 6) If the seaweed used is an agarophyte, distilled water is added to the solid fraction, heated at 120 ° for 1.5 hours, homogenized, and centrifuged. The supernatant is left at room temperature to gel, then is frozen, thawed, and dried after thawing to yield agar
- 7) If the seaweed is a carragenophyte, the solid fraction is treated with potassium hydroxide (KOH), cooked at 72 °C for 2 hours, then filtered through muslin cloth. The unfiltered material is washed until neutral, mixed with distilled water, cooked at 78 °C for 45 minutes, homogenized, and centrifuged. The supernatant is collected and precipitated with iso-propanol and dried to yield carrageenan
- 8) Cellulose extraction is then conducted on the remaining solid fraction. The solids are soaked in an acetate buffer containing 36% NaClO₂ which acts as a bleach. The biomass is washed with water until neutral, dried at room temperature, added to a 5% solution of hydrochloric acid, heated to boiling, and kept at room temperature overnight. The slurry is once again washed with water till neutral and dried to obtain cellulose
- 9) Also mentioned in the patent is the opportunity to produce bioethanol through cellulose fermentation. In this case, cellulose is hydrolyzed with the enzyme cellulase in a sodium acetate buffer at a pH of 4.8 for 36 hours at 45 °C. The hydrolysate is enriched with peptone and yeast extract, steam sterilized in an autoclave, inoculated with *Saccharomyces cerevisiae* (a yeast strain), and incubated for 12 hours at 28 °C on an orbital shaker to obtain ethanol



Figure 12: Patented process which produces a liquid biostimulant, natural pigments, hydrocolloids, lipids, and cellulose (Reddy et al., 2018). Blue boxes indicate intermediary steps, green boxes indicate products with GHG mitigating potential, and red boxes indicate other extracted compounds and final products.

Concept 7: Bioethanol, biogas, and biofertilizer production from seaweed (no specific type or species of seaweed is specified) (Soleymani and Rosentrater, 2017)

Soleymani and Rosentrater, 2017 detail the co-production of bioethanol, biogas, and biofertilizer from seaweed biomass. The paper does not indicate any specific species or type of seaweed. All macroalgae contain some amount of minerals (which can be used in a biofertilizer) and carbohydrates (which can be used in biofuel production), this approach may be applicable to many seaweeds, however the carbohydrate and mineral content would have a large impact on the yield of each product. In this process (see figure 13), the biomass was first fermented to produce bioethanol. The residuals from fermentation were placed in an anaerobic digester to produce biogas, resulting in biogas and digestate, which is mineral rich and suitable as a fertilizer. Biogas could be burned as an onsite source of energy or sold. However, if this process is used in addition to the previously discussed biorefinery concept, it is unclear if the digestate would still be a biofertilizer, as the cellulose was previously separated from the minerals in the seaweed.

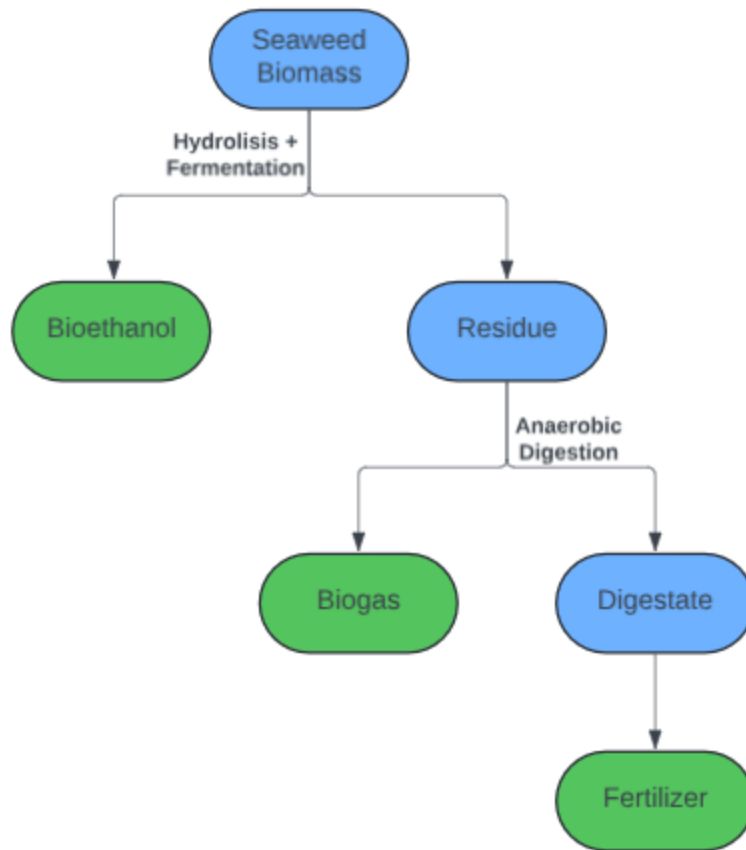


Figure 13: Production of bioethanol, biogas, and biofertilizer from seaweed biomass (Soleymani and Rosentrater, 2017)

Proposed Concept: A biorefinery which produces a biostimulant, pigments, proteins (or lipids), hydrocolloids (or ulvan) and cellulose

Building on the concepts previously discussed, this section highlights a new concept which includes the production of high value products alongside products with GHG mitigating potential. A general concept is presented which can be tweaked to better fit different kinds and species of seaweed. The number of compounds extracted is kept at 5 to reduce complexity. Compounds with existing markets, high value, or the potential to mitigate greenhouse gases in the atmosphere are prioritized.

Two reports are referenced for insight into markets for seaweed products; the “Global Seaweed: New and Emerging Markets Report 2023” from the World Bank (see Figure 1) and “Analysis of farmed seaweed carbon crediting and novel markets to help decarbonize supply chains” published by Bain and the Nature Conservancy. The World Bank report examines all seaweed markets, while the Bain and Nature Conservancy report focuses on those with potential to mitigate greenhouse gases in the atmosphere. In the second report, biostimulants

and bioplastics are determined to be the seaweed products with GHG mitigation potential best poised to develop markets (Bain & Company and The Nature Conservancy, 2023). In particular, the production of a biostimulant is an important component of the biorefinery as their markets are already fairly established and growing. To achieve greater mitigation impact, it is encouraged that hydrocolloids (or ulvan) and cellulose are used for bioplastic production. Hydrocolloids and ulvan serve as film forming agents, while cellulose can be used as a filler or reinforcing agent to add rigidity. Other green uses of cellulose include biofuel production and incorporation into construction materials; however, these applications have less developed markets.

The proposal consists of production of a biostimulant, pigments, hydrocolloids (or ulvan), proteins (or lipids for brown seaweed) and cellulose. The type of hydrocolloid extracted depends on the seaweed. Certain red seaweed contains carrageenan, while others contain agar. Brown seaweed contains alginate. Certain green seaweeds contain ulvan. While ulvan is generally not classified as a hydrocolloid in most literature, it is a sulphated polysaccharide with gelling and film forming properties (in addition to its observed bioactive properties) (Kidgell et al., 2019).

Seaweeds which are high in protein, such as red seaweeds (20-47% by dry weight) and certain green seaweeds (9-26% protein by dry weight) can produce a significant amount of plant based protein. Brown seaweed, which is generally low in protein (3-15% protein by dry weight) may instead be better utilized for lipid production (Fleurence et al, 2018; Pliego-Cortes et al, 2020). Seaweed tends to have a low lipid concentration; however, their lipids may be suitable for nutraceutical products given that they often contain omega 3 fatty acids (Miyashita, Mikami, & Hosokawa, 2013).

Factors which affect the concentration of compounds include species of the seaweed, season of harvest, maturity of the seaweed at time of harvest, and other environmental factors.

Process steps:

- 1) Separation and Extraction of Pigment and Minerals
 - a. Freshly harvested seaweed is homogenized and chilled in a .1M phosphate buffer using a grinder. It is incubated overnight and centrifuged several times to separate the supernatant and solid residue (Reddy et al., 2018).
 - b. Pigment precipitation: Pigments are then precipitated from the supernatant using ammonium sulphate (Reddy et al., 2018).
 - c. Mineral Rich Liquid Extract: Following pigment precipitation, the remaining supernatant is a mineral rich liquid extract, which can be diluted with water and applied as a liquid biostimulant (Reddy et al., 2018).
- 2) Lipid Extraction (only for brown seaweeds)

- a. The solid residue remaining after centrifugation undergoes a lipid extraction using a solution with a 1:2 ratio of chloroform to methanol. The liquid residues are collected, filtered, washed with water, and dried to yield a lipid fraction (Reddy et al., 2018).
- 3) Hydrocolloid/Ulvan extraction
 - a. If the seaweed is a red seaweed and an agarophyte, distilled water is added to the solid fraction, heated at 120 ° for 1.5 hours, homogenized, and centrifuged. The supernatant is left at room temperature to gel, then is frozen, thawed, and dried after thawing to yield agar (Reddy et al., 2018).
 - b. If the seaweed is a red seaweed and a carragenophyte, the solid fraction is treated with potassium hydroxide (KOH), cooked at 72 °C for 2 hours, then filtered through muslin cloth. The unfiltered material is washed until neutral, mixed with distilled water, cooked at 78 °C for 45 minutes, homogenized, and centrifuged. The supernatant is collected and precipitated with iso-propanol and dried to yield carrageenan (Reddy et al., 2018).
 - c. If the seaweed is an alginophytic brown seaweed, it is bleached in a sodium hypochlorite solution (NaClO_2) at 65°C for 6h then separated from the solution using a muslin cloth. The solid is rinsed with tap water, dried, then hydrolyzed in a sodium carbonate solution (Na_2CO_3) at room temperature while stirring for 2 hours. This is again filtered through a muslin cloth. The solid residue is kept for extraction of additional compounds. Alginic acid is precipitated from the filtrate using hydrochloric acid (HCl), separated through filtration with a muslin cloth, dried at 65°C and powdered (Baghel et al., 2020).
 - d. If the seaweed is a green seaweed and contains ulvan, the residue is first incubated in distilled water at 90 °C for 2 h. The mixture is then allowed to cool and filtered through muslin cloth and 0.21 µm filter paper. Isopropanol is added to the filtered suspension and stirred vigorously for 30 min. The precipitates are recovered by muslin cloth filtration and dried in the oven (Jaulneau et al., 2010; Gajaria et al., 2017).
- 4) Protein Extraction (red and green seaweeds)
 - a. The residual biomass following hydrocolloid extraction is subjected to alkaline treatment for protein extraction. This is done using sodium hydroxide (NaOH) at 80 °C. The mixture is cooled at room temperature and filtered using a 0.21 µm filter, followed by neutralization with hydrochloric acid. The suspension is then dialyzed, and the protein is freeze dried (Gajaria et al., 2017).
- 5) Cellulose extraction
 - a. The remaining solids are soaked in an acetate buffer containing 36% NaClO_2 which acts as a bleach. The biomass is washed with water until neutral, dried at room temperature, added to a 5% solution of hydrochloric acid, heated to boiling, and kept at room temperature overnight. The slurry is once again washed with water till neutral and dried to obtain cellulose (Reddy et al., 2018).



Figure 14: Proposed concept for the extraction of a liquid biostimulant, pigments, hydrocolloids/ulvan, protein, and cellulose from green or red seaweed. Blue boxes indicate intermediary steps. Green boxes indicate final products with GHG mitigating potential. Red boxes indicate other extracted compounds. The production of bioplastics, bioenergy, and construction materials are not detailed in this concept, but are suitable uses for hydrocolloids/ulvan and cellulose.

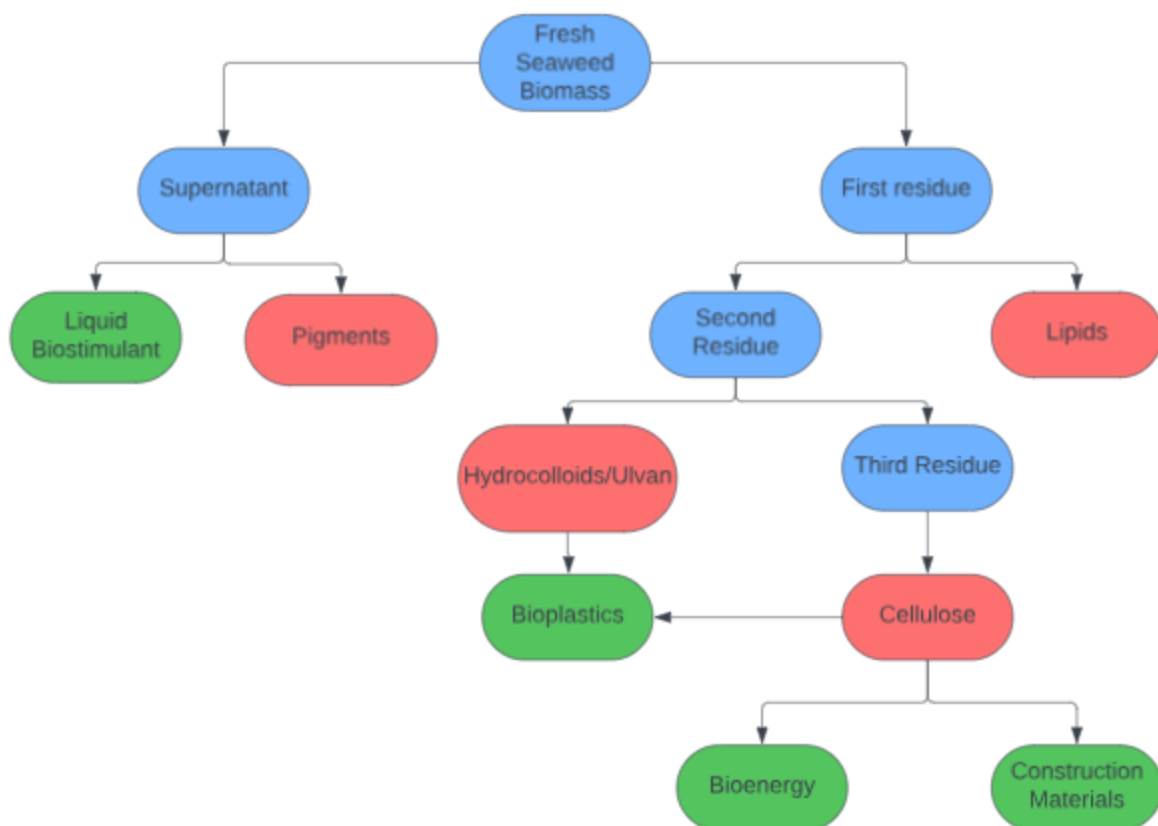


Figure 15: Proposed concept for the extraction of a liquid biostimulant, pigments, lipids, hydrocolloids/ulvan, and cellulose from brown seaweed. Blue boxes indicate intermediary steps. Green boxes indicate final products with GHG mitigating potential. Red boxes indicate other extracted compounds and final products. The production of bioplastics, bioenergy, and construction materials are not detailed in this concept, but are suitable uses for hydrocolloids/ulvan and cellulose.

Conclusion and Recommendations

Biorefineries have the potential to solve several pressing problems in the seaweed industry and contribute to climate change mitigation, all while making a profit. They can reduce waste, create increased value of seaweed biomass, increase the demand for farmed seaweed, and encourage a reduction in harsh chemical usage during processing. Given that biorefinery companies are still in their infancy, there currently exists the potential to identify and establish a set of best practices which the industry can build around. We're hopeful that in the coming years, the establishment of biorefinery operations will provide proof of viability and will further increase interest and investment in biorefining and seaweed farming.

Minimizing the usage of harsh chemicals in a biorefinery is advantageous as it avoids degradation of sequentially extracted compounds and reduces pollution, however recently green extraction methods have gained attention as more eco-friendly techniques. Green extraction methods referenced in this report include ultrasound-assisted extraction (UAE), enzyme-assisted extraction (EAE), microwave-assisted extraction (MAE), photo-bleaching extraction (PBE), reactive extrusion (REX), pressurized solvent extraction (PSE), supercritical fluid extraction (SFE), and pressurized liquid extraction (PLE) (Michalak and Chojnacka, 2015; Lim et al., 2021). Many of these methods require investment in high-tech equipment. While they minimize chemical and solvent usage, energy input is still required. This report encourages Life Cycle Analysis (LCA) and Techno Economic Analysis (TEA) which compare these methods with conventional solvent based extraction methods to be conducted. This will lead to a better understanding of how these novel methods compare to traditional extraction techniques in terms of environmental and economic impact. Simple extractions using only water also prevent degradation and pollution but may result in lower yields.

In many areas seaweed farmers are price takers who sell whole seaweed biomass at a low price. Depending on the harvest, they may not be able to repay their loans at the end of the season and fall into a cycle of borrowing and debt. We hope that a biorefinery would enable a higher sale price of seaweed since it creates more value from biomass than single stream processing. This results in better margins for producers, but efforts should also be made to ensure that the benefits of creating additional value from seaweed biomass are passed on to seaweed farmers too.

Opportunities to establish value-added product industries run by local communities and farmer cooperatives should be identified and trainings should be made available at the local level to enable seaweed farmers to manufacture and sell these products on their own. Future work will attempt to better understand this challenge in the context of Cabalian Bay in the Philippines. A new generation of small-scale biorefineries may be suitable for deployment in remote coastal communities lacking infrastructure. If seaweed farmers and their local communities have access to these facilities and are trained to operate them, this may allow for the manufacture and sale

of a portfolio of products, with a much greater share of the value-addition being captured by the farmers themselves. Currently, biostimulants appear to be a viable option due to the ease of extraction and relatively high market value. EDF is also working to conduct an experiment to test that a seaweed biostimulant that is made from simple kitchen equipment can have a positive impact on agricultural crops.

Literature Cited

Abdul Khalil, H. P. S., Tye, Y. Y., Saurabh, C. K., Leh, C. P., Lai, T. K., Chong, E. W. N., & Syakir, M. I. (2017). Biodegradable polymer films from seaweed polysaccharides: a review on cellulose as a reinforcement material. *Express Polymer Letters*, 11(4), 244-265.

https://www.researchgate.net/publication/313259525_Biodegradable_polymer_films_from_seaweed_polysaccharides_A_review_on_cellulose_as_a_reinforcement_material

Adhya, T., Kollah, B., Mohanty, S. R., & Wassmann, R. (2001). Methane emission from rice fields at Cuttack, India. *Methane Emissions from Major Rice Ecosystems in Asia* 58, 95–105. Kluwer Academic Publishers.

https://www.researchgate.net/publication/256438725_Methane_emission_from_rice_fields_at_Cuttack_India/citations

Al-Alawi, A. A., Al-Marhubi, I. M., Al-Belushi, M. S., & Soussi, B. (2011). Characterization of carrageenan extracted from *Hypnea bryoides* in Oman. *Marine Biotechnology*, 13(5), 893–899.

<https://doi.org/10.1007/s10126-010-9350-7>

Albright, G. (2023). Seaweed Product Analysis. *Environmental Defense Fund*.

Álvarez-Viñas, M., Flórez-Fernández, N., González-Muñoz, M. J., & Domínguez, H. (2019a). Influence of molecular weight on the properties of *Sargassum muticum* fucoidan. *Algal Research*, 38, 101393. <https://doi.org/10.1016/j.algal.2018.101393>

Álvarez-Viñas, M., Flórez-Fernández, N., Torres, M. D., & Domínguez, H. (2019b). Successful approaches for a red seaweed biorefinery. *Marine Drugs*, 17(11), 620.

<https://doi.org/10.3390/md17110620>

Angus, J.F. (2012). Fertilizer Science and Technology. In R.A. Meyers (Ed.), *Encyclopedia of Sustainability Science and Technology*. Springer, New York, NY. https://doi.org/10.1007/978-1-4419-0851-3_193

Arias, A., Feijoo, G., & Moreira, M. T. (2023). Macroalgae biorefineries as a sustainable resource in the extraction of value-added compounds. *Algal Research*, 69, 102954.

<https://doi.org/10.1016/j.algal.2022.102954>.

Ayala, M., Thomsen, M., & Pizzol, M. (2023). Life Cycle Assessment of pilot scale production of seaweed-based bioplastic. *Algal Research*, 71, <https://doi.org/10.1016/j.algal.2023.103036>.

Azim, M., Bin, F., & Muis, A. (2016). Potential application of biocomposite from seaweed as a green construction material. *Universiti Teknologi Petronas*.

<https://utpedia.utp.edu.my/id/eprint/17856/>

Baghel, R. S., Reddy, C. R. K., & Singh, R. P. (2021). Seaweed-based cellulose: Applications, and future perspectives. *Carbohydrate Polymers*, 267, 118241. <https://doi.org/10.1016/j.carbpol.2021.118241>.

Baghel, R. S., Suthar, P., Gajaria, T. K., Bhattacharya, S., Anil, A., & Reddy, C. R. K. (2020). Seaweed biorefinery: A sustainable process for valorizing the biomass of brown seaweed. *Journal of Cleaner Production*, 263, 121359. <https://doi.org/10.1016/j.jclepro.2020.121359>

Baghel, R. S., Trivedi, N., & Reddy, C. R. K. (2016). A simple process for recovery of a stream of products from marine macroalgal biomass. *Bioresource Technology*, 203, 160–165. <https://doi.org/10.1016/j.biortech.2015.12.051>.

Baghel, R.S. (2023). Developments in seaweed biorefinery research: A comprehensive review. *Chemical Engineering Journal*, 454(2). <https://doi.org/10.1016/j.cej.2022.140177>.

Bain & Company and The Nature Conservancy. (2023). Analysis of farmed seaweed carbon crediting and novel markets to help decarbonize supply chains. Bain & Company and The Nature Conservancy. <https://www.nature.org/content/dam/tnc/nature/en/documents/SeaweedMarketsAnalysis.pdf>

Balina, K., Romagnoli, F., & Blumberga, D. (2017). Seaweed biorefinery concept for sustainable use of marine resources. *Energy Procedia*, 128, 504-511. <https://doi.org/10.1016/j.egypro.2017.09.067>

Barrett, L., Theuerkauf, S., Rose, J., Alleway, H., Bricker, S., Parker, M., Petrolia, D., Jones, R., (2022). Sustainable growth of non-fed aquaculture can generate valuable ecosystem benefits, *Ecosystem Services*, 53, <https://doi.org/10.1016/j.ecoser.2021.101396>.

Bixler, H. J., & Porse, H. (2011). A decade of change in the seaweed hydrocolloids industry. *Journal of Applied Phycology*, 23, 321-335. <https://doi.org/10.1007/s10811-010-9529-3>

Bligh, E. G., & Dyer, W. J. (1959). A rapid method of total lipid extraction and purification. *Canadian Journal of Biochemistry and Physiology*, 37, 911–917.

Bullion, A. (202, December 1). Biostimulants Market Growing Strongly at 10% per Annum. *S&P Global*. <https://www.spglobal.com/commodityinsights/en/ci/research-analysis/biostimulants-market-growing-strongly-at-10-per-annum.html>

Bureau of Fisheries and Aquatic Resources. (2022). The Philippine Seaweed Industry Roadmap (2022-2026). <https://www.pcaf.da.gov.ph/wp-content/uploads/2022/06/Philippine-Seaweed-Industry-Roadmap-2022-2026.pdf>

Cai, J., Lovatelli, A., Garrido Gamarro, E., Geehan, J., Lucente, D., Mair, G., Miao, W., Reantaso, M., Roubach, R., Yuan, X., Aguilar-Manjarrez, J., Cornish, L., Dabbadie, L., Desrochers, A., Diffey,

S., Tauati, M., Hurtado, A., Potin, P., & Przybyla, C. (2021). Seaweeds and Microalgae: An Overview for Unlocking Their Potential in Global Aquaculture Development. *FAO Fisheries and Aquaculture Circular*. <https://www.fao.org/3/cb5670en/cb5670en.pdf>

Calumpong, H. P., Maypa, A. P., & Magbanua, M. (1999). Population and alginate yield and quality assessment of four *Sargassum* species in Negros Island, central Philippines. *Hydrobiologia*, 398/399, 211–215. <https://doi.org/10.1023/A:1017015824822>

Campbell, R., & Hotchkiss, S. (2017). Carrageenan Industry Market Overview. In A. Hurtado, A. Critchley, & I. Neish (Eds.), *Tropical Seaweed Farming: Trends, Problems and Opportunities*. Developments in Applied Phycology, vol 9. Springer, Cham. https://doi.org/10.1007/978-3-319-63498-2_13

Campobenedetto, C., Mannino, G., Beekwilder, J., Contartese, V., Karlova, R., & Berteà, C. M. (2021). The application of a biostimulant based on tannins affects root architecture and improves tolerance to salinity in tomato plants. *Scientific Reports*, 11, Article 354. <https://doi.org/10.1038/s41598-020-79770-5>

Campo, V. L., Kawano, D. F., da Silva, D. B., & Carvalho, I. (2009). Carrageenans: Biological properties, chemical modifications and structural analysis – A review. *Carbohydrate Polymers*, 77(2), 167–180. <https://doi.org/10.1016/j.carbpol.2009.01.020>

Capanoglu, E., Nemli, E., & Tomas-Barberan, F. (2022). Novel approaches in the valorization of agricultural wastes and their applications. *Journal of Agricultural and Food Chemistry*, 70(23), 6787–6804.

Cebrián-Lloret, V., Metz, M., Martínez-Abad, A., Knutsen, S. H., Ballance, S., López-Rubio, A., & Martínez-Sanz, M. (2022). Valorization of alginate-extracted seaweed biomass for the development of cellulose-based packaging films. *Algal Research*, 61, 102576. <https://doi.org/10.1016/j.algal.2021.102576>

Cengiz, A., Kaya, M., & Bayramgil, N. P. (2017). Flexural stress enhancement of concrete by incorporation of algal cellulose nanofibers. *Construction Building Material*, 149, 289–295. <https://doi.org/10.1016/j.conbuildmat.2017.05.104>

Cian, R. E., Fajardo, M. A., Alaiz, M., Vioque, J., Gonzalez, R. J., & Drago, S. R. (2014). Chemical composition, nutritional and antioxidant properties of the red edible seaweed *Porphyra columbina*. *International Journal of Food Science & Nutrition*, 65, 299–305. <https://doi.org/10.3109/09637486.2013.854746>

Craigie, J. S. (2011). Seaweed extract stimuli in plant science and agriculture. *Journal of Applied Phycology*, 23, 371–393. <https://doi.org/10.1007/s10811-010-9560-4>

Crunchbase. (2023). *Origin by Ocean*. <https://www.crunchbase.com/organization/origin-by-ocean>.

Crunchbase. (2024a). Oceanium. https://www.crunchbase.com/organization/oceanium/company_financials

Crunchbase. (2024b). Thalasso. https://www.crunchbase.com/organization/thalasso/company_financials

Dasgupta, D., Kumar, K., Miglani, R., Mishra, R., Panda, A. K., & Bisht, S. S. (2021). Microbial biofertilizers: Recent trends and future outlook. In S. De Mandal & A. K. Passari (Eds.), *Recent Advancement in Microbial Biotechnology*, 1-26. <https://doi.org/10.1016/B978-0-12-822098-6.00001-X>

Dave, A., Huang, Y., Rezvani, S., McIlveen-Wright, D., Novaes, M., & Hewitt, N. (2013). Techno-economic assessment of biofuel development by anaerobic digestion of European marine cold-water seaweeds. *Bioresource Technology*, 135, 120–127. <https://doi.org/10.1016/j.biortech.2013.01.005>

De Saeger, J., Van Praet, S., Vereecke, D., Park, J., Jacques, S., Han, T., & Depuydt, S. (2020). Toward the molecular understanding of the action mechanism of *Ascophyllum nodosum* extracts on plants. *Journal of Applied Phycology*, 32(573-597). <https://doi.org/10.1007/s10811-019-01903-9>

de Valicourt. (2015, September 2). DIY Agar. Project: Agar extraction from Gracilariaceae spp. Nordic Food Lab. [https://nordicfoodlab.org/blog/2015/09/diy-agar/#:~:text=Extraction%20using%20heat%2C%20NaOH%20\(lye,hours%20at%2085%C2%B0C](https://nordicfoodlab.org/blog/2015/09/diy-agar/#:~:text=Extraction%20using%20heat%2C%20NaOH%20(lye,hours%20at%2085%C2%B0C).

Dhandapani, R., Elangovan, M. P., Subbarayalu, R., Khalifa, A. Y. Z., Paramasivam, R., Sankaranarayanan, S., Thangavelu, S., & Selvakumar, V. (2022). Small, Large-Scale Production and Cost-Benefit Analysis and Marketing of Agar from Gelidium. In Amaresan, N., Dharumadurai, D., Cundell, D.R. (Eds.), *Industrial Microbiology Based Entrepreneurship* (pp. 127–145). Springer. https://doi.org/10.1007/978-981-19-6664-4_10

Di Bartolo, A., Infurna, G., & Dintcheva, N. T. (2021). A Review of Bioplastics and Their Adoption in the Circular Economy. *Polymers*, 13(8). <https://doi.org/10.3390/polym13081229>.

du Jardin, P. (2015). Plant biostimulants: Definition, concept, main categories and regulation. *Scientia Horticulturae*, 196, 3-14. <https://doi.org/10.1016/j.scienta.2015.09.021>

Echave, J., Fraga-Corral, M., Garcia-Perez, P., Popović-Djordjević, J., Avdović, E. H., Radulović, M., Xiao, J., Prieto, M. A., & Simal-Gandara, J. (2021). Seaweed Protein Hydrolysates and

Bioactive Peptides: Extraction, Purification, and Applications. *Marine Drugs*, 19(9), 500.
<https://doi.org/10.3390/md19090500>

El Boukhari, M. E. M., Barakate, M., Bouhia, Y., & Lyamlouli, K. (2020). Trends in Seaweed Extract Based Biostimulants: Manufacturing Process and Beneficial Effect on Soil-Plant Systems. *Plants (Basel, Switzerland)*, 9(3), 359. <https://doi.org/10.3390/plants9030359>

Ertani, A., Francioso, O., Tinti, A., Schiavon, M., Pizzeghello, D., & Nardi, S. (2018). Evaluation of seaweed extracts from *Laminaria* and *Ascophyllum nodosum* spp. as biostimulants in *Zea mays* L. using a combination of chemical, biochemical, and morphological approaches. *Frontiers in Plant Science* 9. <https://doi.org/10.3389/fpls.2018.00428>

Eswaran, K., Ghosh, P. K., Siddhanta, A. K., Patolia, J. S., Periyasamy, C., Mehta, A. S., ... Rajyaguru, M. R. (2005). Integrated method for production of carrageenan and liquid fertilizer from fresh seaweeds. U.S. Patent 6,893,479.
<https://patents.google.com/patent/US6893479B2/en>.

EUBIO_Admin. (n.d.). Market. European Bioplastics e.V. Blog. Retrieved July 12, 2023, from <https://www.european-bioplastics.org/market/>
FAO. (2021). *FAO Aquaculture, Capture and Global Production Databases*. F.A.O. United Nations: Roma, Italy. https://www.fao.org/fishery/statistics-query/en/aquaculture/aquaculture_quantity

Filote, C., Santos, S. C., Popa, V. I., Botelho, C. M., & Volf, I. (2021). Biorefinery of marine macroalgae into high-tech bioproducts: A review. *Environmental Chemistry Letters*, 19, 969–1000. <https://doi.org/10.1007/s10311-020-01124-4>

Fiorenza, M. (2023, February 15). SeaBrick, Better and Less Expensive than Concrete, It's Eco Restorative and Sequesters CO2. *The Seasteading Institute*.
<https://www.seasteading.org/seabrick/>

Fleurence, J., Moránçais, M., & Dumay, J. (2018). Seaweed proteins. In *Proteins in Food Processing* (Second Edition) (pp. 245–262). Woodhead Publishing.
<https://doi.org/10.1016/B978-0-08-100722-8.00010-3>

Flórez-Fernández, N., Illera, M., Sánchez, M., Lodeiro, P., Torres, M. D., López-Mosquera, M. E., Soto, M., Sastre de Vicente, M., & Domínguez, H. (2021). Integrated valorization of *Sargassum muticum* in biorefineries. *Chemical Engineering Journal*, 404, 125635.
<https://doi.org/10.1016/j.cej.2020.125635>

Franzoni, G., Cocetta, G., Prinsi, B., Ferrante, A., & Espen, L. (2022). Biostimulants on crops: Their impact under abiotic stress conditions. *Horticulturae*, 8(3), 189.
<https://doi.org/10.3390/horticulturae8030189>

Freile-Pelegrín, Y., & Madera-Santana, T. J. (2017). Biodegradable polymer blends and composites from seaweeds. *Handbook of Composites from Renewable Materials* 419-438. <https://doi.org/10.1002/9781119441632.ch98>

Fujita, R., Augyte, S., Bender, J., Brittingham, P., Buschmann, A. H., Chalfin, M., Collins, J., Davis, K. A., Gallagher, J. B., Gentry, R., Gruby, R. L., Kleisner, K., Moritsch, M., Price, N., Roberson, L., Taylor, J., & Yarish, C. (2023). Seaweed blue carbon: Ready? Or Not? *Marine Policy*, 155, 105747. <https://doi.org/10.1016/j.marpol.2023.105747>

Gajaria, T. K., Suthar, P., Baghel, R. S., Balar, N. B., Sharnagat, P., Mantri, V. A., & Reddy, C. R. K. (2017). Integration of protein extraction with a stream of byproducts from marine macroalgae: A model forms the basis for marine bioeconomy. *Bioresource Technology*, 243, 867-873. <https://doi.org/10.1016/j.biortech.2017.0.149>.

Geyer, R., Jambeck J., Law K. (2017). Production, use, and fate of all plastics ever made | *Science Advances*, 3(7). <https://www.science.org/doi/10.1126/sciadv.1700782>.

Goa Ventures. (2024, January 18). Home. <https://goa-ventures.com/>

Goñi, O., Quille, P., & O'Connell, S. (2018). Ascophyllum nodosum extract biostimulants and their role in enhancing tolerance to drought stress in tomato plants. *Plant Physiology and Biochemistry*, 126, 63-73. <https://doi.org/10.1016/j.plaphy.2018.02.024>

Gosch, B. J., Magnusson, M., Paul, N. A., & de Nys, R. (2012). Total lipid and fatty acid composition of seaweeds for the selection of species for oil-based biofuel and bioproducts. *Global Change Biology. Bioenergy*, 4, 919-930. <https://doi.org/10.1111/j.1757-1707.2012.01175.x>

Goyanes, S. N., & D'Accorso, N. B. (2017). Industrial applications of renewable biomass products. *Industrial Applications of Renewable Biomass Products: Present and Future*. <https://doi.org/10.1007/978-3-319-61288-1>

Grand View Research. (n.d.). *Alginate Market Size Worth \$1.07 Billion By 2028 | CAGR 5.0%*. Accessed 10 January, 2024. <https://www.grandviewresearch.com/industry-analysis/alginate-market>

Greene, J. M., Gulden, J., Wood, G., Huesemann, M., & Quinn, J. C. (2020). Techno-economic analysis and global warming potential of a novel offshore macroalgae biorefinery. *Algal Research*. Advance online publication. <https://doi.org/10.1016/j.algal.2020.102032>

Gries, T., Herbst de Cortina, M., Miller, J., Ngo, D., & Seif, J. (2023). Seaweed: The Solution to Pollution? A Comparative Life Cycle Assessment of LDPE and Algal Flexible Film Packaging. [Master's Group Project, Master of Environmental Science and Management]. *UC Santa*

Barbara. <https://bren.ucsb.edu/projects/sea-weed-solution-pollution-comparative-life-cycle-assessment-ldpe-and-algal-flexible-film>

Gupta, S., Palansooriya, K. N., Dissanayake, P. D., Sik, O. Y., & Kua, H. W. (2020). Carbonaceous inserts from lignocellulosic and non-lignocellulosic sources in cement mortar: preparation conditions and its effect on hydration kinetics and physical properties. *Construction and Building Materials*, 264. <https://doi.org/10.1016/j.conbuildmat.2020.120214>.

Halib, N., Perrone, F., Cemazar, M., Dapas, B., Farra, R., Abrami, M., Chiarappa, G., Forte, G., Zanconati, F., Pozzato, G., et al. (2017). Potential applications of nanocellulose-containing materials in the biomedical field. *Materials*, 10(8), 977. <https://doi.org/10.3390/ma10080977>

Harper, J. (2023, January 23). Turning problem sea algae into a replacement for plastic. BBC. <https://www.bbc.com/news/business-64317261>.

Hatch Innovation Services (n.d.). Global Production Overview. Accessed 23 January, 2024. <https://seaweedinsights.com/global-production/>

Herrera-Rodriguez, T., Parejo-Palacio, V., & González-Delgado, Á. D. (2018). Technoeconomic Sensibility Analysis of Industrial Agar Production from Red Algae. *Chemical Engineering Transactions*, 70. <https://doi.org/10.3303/CET1870339>

Hesse, R., & Schacht, U. (2011). Early diagenesis of deep-sea sediments. In H. Hüneke & T. Mulder (Eds.), *Developments in Sedimentology* (Vol. 63, pp. 557-713). Elsevier. <https://doi.org/10.1016/B978-0-444-53000-4.00009-3>

Hayes, A. (2024, January 12). Vertical Integration Explained: How It Works, With Types and Examples. Investopedia. <https://www.investopedia.com/terms/v/verticalintegration.asp>

Hernández-Carmona, G., McHugh, D. J., Arvizu-Higuera, D. L., & Rodríguez-Montesinos, Y. E. (1998). Pilot plant scale extraction of alginate from *Macrocystis pyrifera*. 1. Effect of pre-extraction treatments on yield and quality of alginate. *Journal of Applied Phycology*, 10(6), 507-513. <https://doi.org/10.1023/A:1008024129894>

Hurtado, A. Q., Neish, I. C., & Critchley, A. T. (2019). Phyconomy: the extensive cultivation of seaweeds, their sustainability and economic value, with particular reference to important lessons to be learned and transferred from the practice of eucheumatoid farming. *Phycologia*, 58(5), 472-483. <https://doi.org/10.1080/00318884.2019.1625632>

Ingle, K., Vitkin, E., Robin, A., Yakhini, Z., Mishori, D., & Golberg, A. (2018). Macroalgae Biorefinery from *Kappaphycus alvarezii*: Conversion Modeling and Performance Prediction for India and Philippines as Examples. *BioEnergy Research*, 11(1), 22–32. <https://www.semanticscholar.org/paper/Macroalgae-Biorefinery-from-Kappaphycus-alvarezii%3A-Ingle-Vitkin/991f111cc023245ae491852560101467bbee1a90>

Jaulneau, V., Lafitte, C., Jacquet, C., Fournier, S., Salamagne, S., Briand, X., Esquerré-Tugayé, M. T., & Dumas, B. (2010). Ulvan, a sulfated polysaccharide from green algae, activates plant immunity through the jasmonic acid signaling pathway. *Journal of Biomedicine and Biotechnology*, 2010, 1-11. <https://doi.org/10.1155/2010/525291>

Jayasinghe, G.D.T.M., Jinadasa, B.K.K.K., & Sadaruwan, N.A.G. (2022). Pathway of sodium alginate synthesis from marine brown algae, *Sargassum wightii* from Sri Lanka. *Discovery Food*, 2(2), 2. <https://doi.org/10.1007/s44187-021-00001-5>

Johnston, K. G., Abomohra, A., French, C. E., & Zaky, A. S. 2023. Recent Advances in Seaweed Biorefineries and Assessment of Their Potential for Carbon Capture and Storage. *Sustainability*. 15(17).; <https://doi.org/10.3390/su151713193>

Jung K.A., Lim S.R., Kim Y., Park J.M. Potentials of macroalgae as feedstocks for biorefinery. (2013). *Bioresources Technology*. 135 pp. 182–190. <https://doi.org/10.1016/j.biortech.2012.10.025>

Kelsun. (2024, February 6). At the helm of material innovation. *Keel Labs*. <https://www.keellabs.com/kelsun>

Kidgell, J. T., Magnusson, M., de Nys, R., & Glasson, C. R. K. (2019). Ulvan: A systematic review of extraction, composition and function. *Algal Research*, Volume, 101422. <https://doi.org/10.1016/j.algal.2019.101422>.

Kinley, R. D., Martinez-Fernandez, G., Matthews, M. K., de Nys, R., Magnusson, M., & Tomkins, N. W. (2020). Mitigating the carbon footprint and improving productivity of ruminant livestock agriculture using a red seaweed. *Journal of Cleaner Production*, 259, 120836. <https://doi.org/10.1016/j.jclepro.2020.120836>.

Kumar, L. R. G., Paul, P. T., Anas, K. K., Tejpal, C. S., Chatterjee, N. S., Anupama, T. K., Mathew, S., & Ravishankar, C. N. (2022). Phlorotannins-bioactivity and extraction perspectives. *Journal of Applied Phycology*, 34(4), 2173-2185. <https://doi.org/10.1007/s10811-022-02749-4>

Kumari, P., Bijo, A.J., Mantri, V. A., Reddy, C.R.K., & Jha, B. (2013). Fatty acid profiling of tropical marine macroalgae: An analysis from chemotaxonomic and nutritional perspectives. *Phytochemistry*, 86, 44-56. <https://doi.org/10.1016/j.phytochem.2012.10.015>

Lakshmi, D. S., Trivedi, N., & Reddy, C. R. K. (2017). Synthesis and characterization of seaweed cellulose derived carboxymethyl cellulose. *Carbohydrate polymers*, 157, 1604–1610. <https://doi.org/10.1016/j.carbpol.2016.11.042>

- Lee, H. V., Hamid, S. B. A., & Zain, S. K. (2014). Conversion of lignocellulosic biomass to nanocellulose: Structure and chemical process. *The Scientific World Journal*, 2014, 631013. <https://doi.org/10.1155/2014/631013>
- Lee, W. K., Lim, Y. Y., Leow, A. T. C., et al. (2017). Factors affecting yield and gelling properties of agar. *Journal of Applied Phycology*, 29, 1527–1540. <https://doi.org/10.1007/s10811-016-1009-y>
- Leufstedt, A., Wenall, T. (2023). Navigating the Emerging Seaweed Biorefinery Value Chain. Implications for a Seaweed Farmer. Chalmers University of Technology. <https://odr.chalmers.se/server/api/core/bitstreams/ae04dbba-7a68-4f29-bd4d-ef198a9bf226/content>
- Lim, C., Yusoff, S., Ng, C. G., Lim, P. E., & Ching, Y. C. (2021). Bioplastic made from seaweed polysaccharides with green production methods. *Journal of Environmental Chemical Engineering*, 9(5). <https://doi.org/10.1016/j.jece.2021.105895>.
- Liu, Y., An, D., Xiao, Q., Chen, F., Zhang, Y., Weng, H., & Xiao, A. (2022). A novel κ-carrageenan extracting process with calcium hydroxide and carbon dioxide. *Food Hydrocolloids*, 127. <https://doi.org/10.1016/j.foodhyd.2022.107507>
- Lorentzen, K., Smith, C., Huante, R., & Ruiz, J. (2021, March 6). KelpCrete - Using Kelp as an Additive in Concrete to Lower Carbon Emissions by Improving Thermal Resistance and Embodied Energy Costs. *California State Polytechnic University Pomona*. <http://hdl.handle.net/20.500.12680/12579z28p>
- Machado, L., Magnusson, M., Paul, N. A., de Nys, R., & Tomkins, N. (2014). Effects of marine and freshwater macroalgae on in vitro total gas and methane production. *PLoS ONE*, 9(1), <https://doi.org/10.1371/journal.pone.0085289>.
- Majid, N. B., Ibrahim, I. S. B., Sarbini, N. N. B., Zakaria, Z. A. B., & Osman, M. H. B. (2019). The chemical properties of seaweed for modify concrete. *IOP Conference Series Earth Environmental Science*, 220(1). <https://doi.org/10.1088/1755-1315/220/1/012026>
- Manzoor, M. F., Afraz, M. T., Yilmaz, B. B., Adil, M., Arshad, N., Goksen, G., Ali, M., & Zeng, X.-A. (2024). Recent progress in natural seaweed pigments: Green extraction, health-promoting activities, techno-functional properties and role in intelligent food packaging. *Journal of Agriculture and Food Research*, 15. <https://doi.org/10.1016/j.jafr.2024.100991>
- Marinho-Soriano, E., & Bourret, E. (2005). Polysaccharides from the red seaweed *Gracilaria dura* (Gracilariales, Rhodophyta). *Bioresource Technology*, 96(3), 379-382. <https://doi.org/10.1016/j.biortech.2004.04.012>

Markets and Markets. (2023). Bio-Based Leather Market Size | Global Industry Forecast. <https://www.marketsandmarkets.com/Market-Reports/bio-based-leather-market-206086810.html>

Martínez-Sanz, M., Ström, A., Lopez-Sanchez, P., Knutsen, S. H., Ballance, S., Zobel, H. K., Sokolova, A., Gilbert, E. P., & López-Rubio, A. (2020). Advanced structural characterisation of agar-based hydrogels: Rheological and small angle scattering studies. *Carbohydrate Polymers*, 236, 115655. <https://doi.org/10.1016/j.carbpol.2019.115655>

McDermid, K. J., & Stuercke, B. (2003). Nutritional composition of edible Hawaiian seaweeds. *Journal of Applied Phycology*, 15, 513-524. <https://doi.org/10.1023/B:JAPH.0000004345.31686.7f>

McHugh, D. J. (2002). Prospects for seaweed production in developing countries. Food and Agriculture Organization of the United Nations. <https://www.fao.org/3/y3550e/Y3550E00.htm>

McHugh, D.J. (2003) A Guide to the Seaweed Industry, FAO Fisheries Technical Paper. Food and Agricultural Organization of the United Nations. <https://www.fao.org/3/y4765e/y4765e0a.htm#bm10.1.1>

Merfield, C. N., & Johnson, M. (2016). Understanding Biostimulants, Biofertilisers and On-Farm Trials (Report No. 1-2016). *The BHU Future Farming Centre*. <https://www.bhu.org.nz/future-farming-centre/information/bulletin/2016-v1/understanding-biostimulants-and-biofertilisers/#:~:text=The%20main%20difference%20therefore%20is,that%20is%20biological%20in%20origin.>

Michalak, I., & Chojnacka, K. (2015). Algae as production systems of bioactive compounds. *Engineering in Life Sciences*, 15, 160–176. <https://doi.org/10.1002/elsc.201400191>

Milledge, J. J., Smith, B., Dyer, P. W., & Harvey, P. (2014). Macroalgae-Derived Biofuel: A Review of Methods of Energy Extraction from Seaweed Biomass. *Energies*, 7(11), 7194–7222. <https://doi.org/10.3390/en7117194>

Min, B. R., Parker, D., Brauer, D., Waldrip, H., Lockard, C., Hales, K., Akbay, A., & Augyte, S. (2021). The role of seaweed as a potential dietary supplementation for enteric methane mitigation in ruminants: Challenges and opportunities. *Animal Nutrition*, 7(4), 1371-1387. <https://doi.org/10.1016/j.aninu.2021.10.003>.

Miyashita, K., Mikami, N., & Hosokawa, M. (2013). Chemical and nutritional characteristics of brown seaweed lipids: A review. *Journal of Functional Foods*, 5(4), 1507-1517. <https://doi.org/10.1016/j.jff.2013.09.019>

Monlau, F., Suarez-Alvarez, S., Lallement, A., Vaca-Medina, G., Giacinti, G., Munarriz, M., Urreta, I., Raynaud, C., Ferrer, C., Castañón, S. (2021). A cascade biorefinery for the valorization

of microalgal biomass: biodiesel, biogas, fertilizers and high valuable compounds. *Algal Research*, 59, 102433. <https://doi.org/10.1016/j.algal.2021.102433>.

Moreira, A. S. P., da Costa, E., Melo, T., Lopes, D., Pais, A. C. S., Santos, S. A. O., Pitarma, B., Mendes, M., Abreu, M. H., Collén, P. N., Domingues, P., & Domingues, M. R. (2021). Polar lipids of commercial *Ulva* spp. of different origins: Profiling and relevance for seaweed valorization. *Foods*, 10(5), 914. <https://doi.org/10.3390/foods10050914>

Nazemi, F., Karimi, K., Denayer, J. F. M., & Shafiei, M. (2021). Techno-economic aspects of different process approaches based on brown macroalgae feedstock: A step toward commercialization of seaweed-based biorefineries. *Algal Research*, 58, 102366. <https://doi.org/10.1016/j.algal.2021.102366>

O’Callaghan, K. (2016). Technologies for the utilisation of biogenic waste in the bioeconomy. *Food Chemistry*, 198, 2-11. <https://doi.org/10.1016/j.foodchem.2015.11.030>.

O'Connor, J., Meaney, S., Williams, G. A., & Hayes, M. (2020). Extraction of Protein from Four Different Seaweeds Using Three Different Physical Pre-Treatment Strategies. *Molecules*, 25(8). <https://doi.org/10.3390/molecules25082005>

Oceanium. (2022). 2022 Impact Report. <https://oceanium.world/wp-content/uploads/2023/02/OCEANIUM-2022-impact-report-1.pdf>

Oceanium. (2024a, January 16). Kelp-EU. <https://oceanium.world/kelp-eu/>

Oceanium. (2024b, January 16). Oceanium. <https://oceanium.world/>

Ohta, J., Yasukawa, K., Nozaki, T., Takaya, Y., Mimura, K., Fujinaga, K., Nakamura, K., Usui, Y., Kimura, J.-I., Chang, Q., & Kato, Y. (2020). Fish proliferation and rare-earth deposition by topographically induced upwelling at the late Eocene cooling event. *Scientific Reports*, 10, 9896. <https://doi.org/10.1038/s41598-020-66835-8>

Origin by Ocean. (2024, January 16). Washing the Oceans. Retrieved from <https://www.originbyocean.com/>

Palmieri, A., Pomponi, F., & Russo, A. (2019). A triple-win scenario for horizontal collaboration in logistics: Determining enabling and key success factors. 28(6), 1166–1178. <https://doi.org/10.1002/bse.2309>

Pangestuti, R., & Kim, S.-K. (2011). Biological activities and health benefit effects of natural pigments derived from marine algae. *Journal of Functional Foods*, 3(4), 255-266. <https://doi.org/10.1016/j.jff.2011.07.001>

Peñuela, A., Robledo, D., Bourgougnon, N., Bedoux, G., Hernández-Núñez, E., & Freile-Pelegrín, Y. (2018). Environmentally Friendly Valorization of *Solieria filiformis* (Gigartinales, Rhodophyta) from IMTA Using a Biorefinery Concept. *Mar. Drugs*, 16(2), <https://doi.org/10.3390/md16120487>

Pereira, L. (2020). Colloid Producing Seaweeds. In Encyclopedia of Marine Biotechnology, S.-K. Kim (Ed.). <https://doi.org/10.1002/9781119143802.ch8>

Pliego-Cortés, H., Wijesekara, I., Lang, M., Bourgougnon, N., & Bedoux, G. (2020). Current knowledge and challenges in extraction, characterization and bioactivity of seaweed protein and seaweed-derived proteins. In *Advances in Botanical Research*, Volume 95 (pp. 289–326). Elsevier. <https://doi.org/10.1016/bs.abr.2019.11.008>

Reddy, C.R.K., Baghel, R.S., Trivedi, N., Kumari, P., Gupta, V., Prasad, K., Meena, R. (2018). Integrated process to recover a spectrum of bioproducts from fresh seaweeds, Council of Scientific and Industrial Research CSIR, U.S. Patent 10,000,579. <https://patents.google.com/patent/US10000579B2/en>

Research and Markets Ltd. (2023). Global Regenerated Cellulose Market by Type (Fibers [Viscose, Lyocell, Modal], Films), Manufacturing Process, Source, End-User Industry (Fabrics, Automotive, Agriculture, Packaging) and Region (North America, Europe, APAC, Rest of the World) - Forecast to 2027. <https://www.researchandmarkets.com/reports/5660071/global-regenerated-cellulosemarket-by-type>

RISE. N.d. What is a biorefinery? Accessed 11 December, 2023. <https://www.ri.se/en/our-stories/what-is-a-biorefinery#:~:text=Using%20biomass%20as%20a%20raw,and%20food%20industries%2C%20for%20example.>

Roesijadi, G., Jones, S. B., Snowden-Swan, L. J., & Zhu, Y. (2010). Macroalgae as a Biomass Feedstock: A Preliminary Analysis (PNNL Report No. 19944). *Pacific Northwest National Laboratory*. <https://www.osti.gov/biblio/1006310>

Rohani-Ghadikolaei, K., Abdulalian, E., & Ng, W. K. (2012). Evaluation of the proximate, fatty acid and mineral composition of representative green, brown and red seaweeds from the Persian Gulf of Iran as potential food and feed resources. *Journal of Food Science and Technology*, 49(6), 774-780. <https://doi.org/10.1007/s13197-010-0220-0>

Roleda, M.Y., Hurd, C.L., (2019). Seaweed Nutrient Physiology: Application of Concepts to Aquaculture and Bioremediation, *Phycologia*, 58 (5), 552-562. <https://www.tandfonline.com/doi/epdf/10.1080/00318884.2019.1622920?src=getftr>

Rossignolo, J. A., Duran, A. J. F. P., Bueno, C., Martinelli Filho, J. E., Savastano Junior, H., & Tonin, F. G. (2022). Algae application in civil construction: A review with focus on the potential

uses of the pelagic *Sargassum* spp. biomass. *Journal of Environmental Management*, 303, 114258. <https://doi.org/10.1016/j.jenvman.2021.114258>

Rouphael, Y., Lucini, L., Miras-Moreno, B., Colla, G., Bonini, P., & Cardarelli, M. (2020). Metabolomic responses of maize shoots and roots elicited by combinatorial seed treatments with microbial and non-microbial biostimulants. *Frontiers in Microbiology*, 11. <https://doi.org/10.3389/fmicb.2020.00664>

Rupert, R., Rodrigues, K. F., Thien, V. Y., & Yong, W. T. L. (2022). Carrageenan From *Kappaphycus alvarezii* (Rhodophyta, Solieriaceae): Metabolism, Structure, Production, and Application. *Frontiers in Plant Science*, 13. <https://doi.org/10.3389/fpls.2022.859635>

Saepudin, E., Sinurat, E., & Suryabrata, I. A. (2018). Depigmentation and Characterization of Fucoidan from Brown Seaweed *Sargassum binderi* Sonder. *IOP Conference Series: Materials Science and Engineering*, 299(1), 79–87. <https://doi.org/10.1088/1757-899X/299/1/012027>

Saha, D., & Bhattacharya, S. (2010). Hydrocolloids as thickening and gelling agents in food: a critical review. *Journal of Food Science and Technology*, 47(6), 587–597. <https://doi.org/10.1007/s13197-010-0162-6>

Saji, S., Hebden, A., Goswami, P., & Du, C. (2022). A Brief Review on the Development of Alginate Extraction Process and Its Sustainability. *Sustainability*, 14(9), 5181. <https://doi.org/10.3390/su14095181>

Sasuga, K., Yamanashi, T., Nakayama, S., & Ono, S. (2018). Discolored red seaweed *Pyropia yezoensis* with low commercial value is a novel resource for production of agar polysaccharides. *Marine Biotechnology*, 20, 520–530. <https://doi.org/10.1007/s10126-018-9823-7>

Seabrick. Accessed 21 February, 2024. <https://seabrick.ca/>
Seaweed offers new sustainable building approach. (2022, July 26). *The Victorian Connection*. <https://connection.vic.gov.au/seaweed-offers-new-sustainable-building-approach>

Seventure. (2024, January 18). Our Expertise. <https://www.seventure.fr/en/our-expertise/>

Shahul Hamid, F., Bhatti, M. S., Anuar, N., Anuar, N., Mohan, P., & Periathamby, A. (2018). Worldwide distribution and abundance of microplastic: How dire is the situation? *Waste Management & Research*, 36(10), 873–897. <https://doi.org/10.1177/0734242X18785730>

Shukla, P. S., Mantin, E. G., Adil, M., Bajpai, S., Critchley, A. T., & Prithiviraj, B. (2019). Ascophyllum nodosum-Based Biostimulants: Sustainable Applications in Agriculture for the Stimulation of Plant Growth, Stress Tolerance, and Disease Management. *Frontiers in Plant Science*, 10, 655. <https://doi.org/10.3389/fpls.2019.00655>

Singh, S. (2019, September 30). Different Types of Plastic, Their Applications & Recycle Codes. *Rajras*. <https://rajras.in/types-of-plastic/>

Soleymani, M., & Rosentrater, K. A. (2017). Techno-economic analysis of biofuel production from macroalgae (seaweed). *Bioengineering*, 4(4), 92.

<https://doi.org/10.3390/bioengineering4040092>

Sugumaran, R., Padam, B. S., Yong, W. T. L., Saallah, S., Ahmed, K., & Yusof, N. A. (2022). A Retrospective Review of Global Commercial Seaweed Production—Current Challenges, Biosecurity and Mitigation Measures and Prospects. *International Journal of Environmental Research and Public Health*, 19(12), 7087. <https://doi.org/10.3390/ijerph19127087>

Tahiluddin, A. B., Imbuk, E. S., Sarri, J. H., Mohammad, H. S., Ensano, F. N. T., Maddan, M. M., & Cabilin, B. S. (2023). Eucheumatoid seaweed farming in the southern Philippines. *Aquatic Botany*, 189, 103697. <https://doi.org/10.1016/j.aquabot.2023.103697>

Tarman, K., Kustiariyah, Sadi, U., Santoso, J., Hardjito, L., & Kim, S.K. (2020). Carrageenan and its Enzymatic Extraction. 147-159. <https://doi.org/10.1002/9781119143802.ch7>

Thalasso. (2024, January 18th). Unlocking the Value of Seaweed.

<https://www.thalassoocean.com/>

Thongchul, N., Charoensuppanimit, P., Anantpinijwatna, A., Gani, R., & Assabumrungrat, S. (2022). Overview of biorefinery. *A-Z of Biorefinery*. 3–32. <https://doi.org/10.1016/B978-0-12-819248-1.00020-8>

Trigueros, E., Alonso-Riaño, P., Ramos, C., Diop, C. I. K., Beltrán, S., & Sanz, M. T. (2021). Kinetic study of the semi-continuous extraction/hydrolysis of the protein and polysaccharide fraction of the industrial solid residue from red macroalgae by subcritical water. *Journal of Environmental Chemical Engineering*, 9(6). <https://doi.org/10.1016/j.jece.2021.106768>.

Trivedi, N., Baghel, R., Bothwell, J., & Gupta, V. (2016). An integrated process for the extraction of fuel and chemicals from marine macroalgal biomass. *Scientific Reports*, 6, 30728. <https://doi.org/10.1038/srep30728>

Uju, Wijayanta, A.T., Goto, M. & Kamiya. N. (2015). Great potency of seaweed waste biomass from the carrageenan industry for bioethanol production by peracetic acid–ionic liquid pretreatment. *Biomass and Bioenergy*, 81, 63-69.

<https://doi.org/10.1016/j.biombioe.2015.05.023>

U.S. Department of Energy, U.S. Department of Transportation, U.S. Department of Agriculture, & U.S. Environmental Protection Agency. (2022). *SAF Grand Challenge Roadmap Flight Plan for Sustainable Aviation Fuel*. <https://www.energy.gov/sites/default/files/2022-09/beto-saf-gc-roadmap-report-sept-2022.pdf>

- Ververis, C., Georghiou, K., Christodoulakis, N., Santas, P., & Santas, R. (2004). Fiber dimensions, lignin and cellulose content of various plant materials and their suitability for paper production. *Industrial Crops and Products*, 19(3), 245-254. <https://doi.org/10.1016/j.indcrop.2003.10.006>
- van Hal, J. W., Huijgen, W.J.J., & López-Contreras, A.M. (2014). Opportunities and challenges for seaweed in the biobased economy. *Trends in Biotechnology*, 32(5), 231-233. <https://doi.org/10.1016/j.tibtech.2014.02.007>
- Vázquez-Delfín, E., Robledo, D., & Freile-Pelegrin, Y. (2013). Microwave-assisted extraction of the Carrageenan from *Hypnea musciformis* (Cystocloniaceae, Rhodophyta). *Journal of Applied Phycology*, 26(2), <https://doi.org/10.1007/s10811-013-0090-8>
- Wadi, A., Ahmad, A., Tompo, M., Hasyim, H., Tuwo, A., Nakajima, M., & Karim, H. (2019). Production of Bioethanol from Seaweed, *Gracilaria verrucosa* and *Eucheuma cottonii*, by Simultaneous Saccharification and Fermentation Methods. *Journal of Physics: Conference Series*, 1341(3), 032031. <https://doi.org/10.1088/1742-6596/1341/3/032031>
- World Bank. (2023). *Global Seaweed: New and Emerging Markets Report, 2023*. World Bank. <http://hdl.handle.net/10986/40187>.
- Xiao, X., Agusti, S., Lin, F., Li, K., Pan, Y., Yu, Y., Zheng, Y., Wu, J., (2017). Nutrient removal from Chinese coastal waters by large-scale seaweed aquaculture. *Sci Rep* 7, 46613 <https://doi.org/10.1038/srep46613>
- Xu, J., Liao, W., Liu, Y., Guo, Y., Jiang, S., & Zhao, C. (2023). An overview of the nutritional and bioactive components of green seaweeds. *Food Production, Processing and Nutrition*, 5, 18. <https://doi.org/10.1186/s43014-023-00132-5>
- Xu, Y., Wang, Q., & Hou, Y. (2020). Efficient purification of R-phycoerythrin from marine algae (*Porphyra yezoensis*) based on a deep eutectic solvents aqueous two-phase system. *Marine Drugs*, 18(12), 618. <https://doi.org/10.3390/md18120618>
- Yamazaki, T., Fu, W., Shimono, T., & others. (2020). Unmixing biogenic and terrigenous magnetic mineral components in red clay of the Pacific Ocean using principal component analyses of first-order reversal curve diagrams and paleoenvironmental implications. *Earth, Planets and Space*, 72, 120. <https://doi.org/10.1186/s40623-020-01248-5>
- Yun, J-H., Archer, S.D., & Price, N.N. (2023). Valorization of waste materials from seaweed industry: An industry survey based biorefinery approach. *Reviews in Aquaculture*, 15(3), 1020-1027. <https://doi.org/10.1111/raq.12748>

Zakić, N., Vukotić, S., & Cvijanović, D. (2014). Organizational models in agriculture with special reference to small farmers. *Economics of Agriculture*, 225–237.
<https://doi.org/005.51:631.115.11>

Zollmann, M., Robin, A., Prabhu, M., Polikovsky, M., Gillis, A., Greiserman, S., & Golberg, A. (2019). Green technology in green macroalgal biorefineries. *Phycologia*, 58(5), 516-534.
<https://doi.org/10.1080/00318884.2019.1640516>