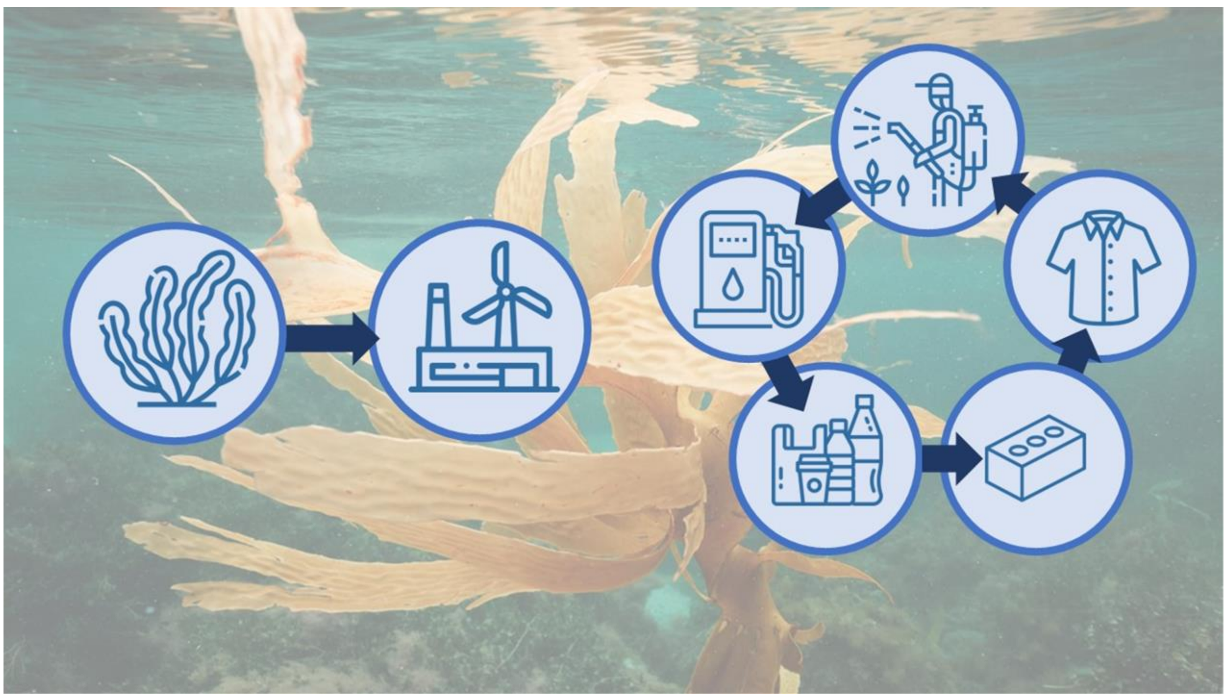
Seaweed Product Analysis

PROCESS MAPS FOR SEAWEED PRODUCTS WITH THE POTENTIAL TO MITIGATE CLIMATE CHANGE



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General Overview

About this report

There is an urgent need to reduce the concentrations of greenhouse gases (GHGs) in the atmosphere in order to avoid even more catastrophic climate change impacts. This will require both dramatic reductions in GHG emissions and active removal of GHGs from the atmosphere. This need has driven strong interest in seaweed (macroalgae) as a natural climate solution in recent years. This is based, in part, on the fact that many seaweed species absorb carbon and grow very rapidly.

However, because seaweed mostly absorbs carbon dissolved in seawater — not atmospheric carbon — oceanographic and ecological conditions have to be right for seaweed carbon absorption to result in immediate reductions in atmospheric carbon dioxide (CO_2) levels. Moreover, only a fraction of the carbon absorbed by seaweed is sequestered because some of the seaweed biomass containing the absorbed carbon is eaten by animals that convert it back to CO_2. Some of the absorbed carbon is also exuded in dissolved or mucilaginous form by the seaweed, where it is consumed by microbes, which also convert it to CO_2. A fraction of the carbon exuded by seaweed resists decomposition by microbes and can sequester carbon for some time. A fraction of seaweed biomass breaks into fragments, some of which are carried to deep water or sediments where the carbon contained in the fragments is sequestered for hundreds of years.

Because many factors influence the fraction of carbon absorbed by seaweed that is ultimately sequestered and the amount of atmospheric CO_2 that seaweed carbon absorption removes, carbon sequestration by seaweed is variable and difficult to measure. The major conventional products made from seaweed — food and colloids — also do not sequester much carbon because they have short life spans, returning carbon to the atmosphere after they are used. These products can spare the release of GHGs to the extent that they replace more GHG-intensive products.

Seaweeds can be made into a variety of products, some of which have the potential to reduce GHG concentrations in the atmosphere. However, to have a significant positive impact such products need to be produced on a much larger scale than is currently the case. This report explores the commercial feasibility of three categories of seaweed products with the potential to reduce atmospheric GHG levels: (1) products that store carbon (construction materials, textiles); (2) products that replace GHG-intensive products or spare the release of GHGs (biofuels, bioplastics, fertilizers); and (3) products that suppress GHG emissions (livestock feed supplements). This report is based largely on gray literature and direct interviews with companies making these products. Where data from commercial companies is scarce, this report supplements the gray literature with academic articles and life cycle assessments (LCAs). Each section of this report attempts to lay out a process map for each product, from at — sea production through retail phase.

Sources and species

The sources and species sections of this report describe the genus (and species, where known) of the seaweed used. Seaweed is also often categorized more simply as either red, brown or green. The chemical components of each vary widely from species to species. Seaweeds vary in their suitability as feedstocks for the manufacturing of a variety of products. For example, red seaweed is a source of agar, while brown seaweed is a source of alginate.

Cultivation and harvesting

The cultivation and harvesting sections of this report summarize the common locations and farming methods for seaweed within each product category. The most common production method worldwide is line cultivation, in which strings inoculated with seaweed spores are wound around ropes and laid out in the ocean between buoys. Farming methods and locations have implications for net GHG emissions reductions associated with seaweed products — the use of GHG-intensive construction materials or locations far from processing or manufacturing facilities can detract from these emissions reductions.

Drying and extraction

In this section, we note where the production of seaweed products requires the seaweed to be dried before use, or where certain compounds need to be extracted before processing, as these methods also have implications for net GHG emissions reductions by seaweed products.

Processing

The processing section details, as best as possible based on non-proprietary information, the method for production and equipment used. Most companies were not willing to disclose their exact methods, so processes were pieced together based on journal articles or publicly available sources.

Transportation

For industries where companies are already in the retail phase, a transportation section is included. This section lists the geographic location of the seaweed farms, the processing facilities and the primary retail market. While this is an incomplete portrait of the full supply chain and associated impacts, it does suggest industries where supply chains could be shortened, thereby potentially reducing GHG emissions. Packaging type is also noted as this has implications for net GHG emissions.

Cost

Where possible, the cost of seaweed products is compared to their conventional counterparts in this section.

Performance

The technical performance of each type of seaweed product is evaluated in this report. If relevant, it is compared to the performance of its conventional analog.

Lifespan

For products with sequestration capacity (textiles and construction materials), this report considers the lifespan of the product as this has implications for the climate mitigation potential of the product.

Opportunities and challenges

For each product category we summarize opportunities and challenges. This section considers the current roadblocks to scale that companies are facing, along with regulatory pathways that they have identified. Where there is an opportunity for synergy between multiple product streams (cascading value chains), these are noted as well.

Biostimulants

Overview

Seaweeds can be made into biostimulants that enhance plant health and crop growth. These products could spare GHG emissions associated with fertilizer production and use to the extent that farmers, golf courses, cities, homeowners or other fertilizer users reduce fertilizer use in response to these benefits. The extent of this GHG sparing effect would also depend on GHG emissions associated with the production and transport of the biostimulants.

S&P Global Commodity Insights reports that seaweed extracts make up around 40% of the total global biostimulants market, equating to around $935 million in 2021.[1] Seaweed extracts are used as biostimulants to improve plant health and crop yield or for lawn care. Seaweed extract used for agriculture can be made in a lot of ways, making it difficult to generalize the process or benefits. The companies summarized in this section are among the largest commercial producers with transparent supply chains.

Company	Product use	Development Stage
Acadian Seaplants	crops	Globally commercial
Algea	crops	Globally commercial
Olmix	crops or golf courses	Globally commercial
Carbonwave	crops	North America commercial
AgriSea	crops or lawn care	Globally commercial
The Seaweed Company	crops or lawn care	Pilot / Demonstration
Ocean Knowledge	sport turf	Globally commercial
Ocean Organics	crops or golf courses	USA commercial
Vikas Crop Care	Crops, plants, aquaculture	Globally commercial

The Food and Agriculture Organization of the United Nations (FAO) statistics suggest that China is far and away the largest producer of brown seaweed in the world.[2] There are several seaweed biostimulant companies in China; however, those manufacturers are not included in this report due to a lack of information about their production process.

Sourcing and species considerations

Most commercial biostimulants use brown seaweed, *Ascophyllum nodosum,* being the most common, although other species such as *Fucus serratus, Enteromorpha intestinalis, Ulva lactuca* and *Kappaphycus alvarezii* are used depending on the company's geographic region.[3] Companies using *A. nodosum*

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[1] "Biostimulants Market Growing Strongly at 10% per Annum | S&P Global."

[2] "FAO Fisheries and Aquaculture Department - Yearbook of Fishery and Aquaculture Statistics - Aquaculture Production."

[3] Craigie, "Seaweed Extract Stimuli in Plant Science and Agriculture."

harvest it from Maine, Nova Scotia, Scotland, Ireland and Norway. Companies using sargassum are based in India (Vikas Crop Care, The Seaweed Company) or the Caribbean (Carbonwave). AgriSea, based in New Zealand, uses a brown seaweed called spiny kelp (*Ecklonia radiata*).

Companies using green seaweed — specifically sea lettuce (*U. lactuca*) are Olmix, which sources from Brittany, France, and Pacific Bio, which grows it on land in Australia. The only red seaweed being used among the companies in this report is elkhorn sea moss (*K. alvarezii*), used by Vikas Crop Care in conjunction with *Sargassum spp*.

Cultivation and harvest

Since seaweed fertilizer is primarily produced using *A. nodosum*, most of the industry relies on wild or managed stock that is harvested mechanically or by hand. The second most common collection method appears to be washed — up seaweed collected off beaches and coastlines.

Most companies that rely on rockweed (*A. nodosum*), like Ocean Knowledge, Algea and Acadian Seaplants, are using wild stocks. They rely on mechanical harvesting or hand harvesting that cut only the top layer of seaweed, leaving the holdfast, and allowing natural regeneration over time. Standard practice is to leave at least 16 inches of holdfast. Hand harvesters collect intertidal rockweed when the tide is out, approaching the shoreline in a skiff and cutting fresh growth by hand with a knife. Mechanical harvesters are flat-bottom boats with a funnel attached to a tube. The funnel sucks in rockweed, which gets cut by a spinning auger and then passes through the tube into a net.[4]

Figure 1. Mechanical Harvesters in Maine, U.S. (Credit: Maine Seaweed Council).

Farmed stock

The Seaweed Company grows seaweed on longlines in India, Morocco and Ireland. They support 61 families who grow seaweed to supply their operations. Currently, they do not have publicly available data on the scope of those farms or operational details.

Onshore cultivation

Pacific Bio uses farmed *Ulva spp.* to create their extract. The *Ulva* is used to filter wastewater from their shrimp farm, and then the seaweed is harvested and turned into liquid fertilizer, resulting in — what they claim is — a closed-loop system.

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[4] *OCEAN ORGANICS-HD 1080p*.

Washed-up stock

A few companies rely on washed-up seaweed for their source material. Carbonwave, for example, uses sargassum that washes up on beaches in Mexico and the Caribbean, which is typically collected by heavy machinery like loaders and dump trucks. AgriSea also collects washed-up spiny kelp from New Zealand coastlines, although they do not disclose exact collection sites or methods.

Processing

The basic method for creating seaweed extract is to ferment the plants in water. As such, there is no need to dry the seaweed before fermentation, although it is likely that the seaweed needs to be rinsed before processing, to remove salt or debris. The effectiveness of seaweed extracts varies widely, depending on the nutrient value of seaweed used and the intended application. Since the extraction process is the one aspect over which companies can exert full control, no commercially active companies disclose their process in full detail. Based on literature review, the most widely used process involves hydrolysis, heating the seaweed with alkaline sodium or potassium solutions, typically under pressure. Algea uses high-pressure hydrolysis, which also raises the temperature of the reaction. Alternatively, the seaweed may be liquified at ambient pressure as in the case of the Acadian Seaplants extracts.[5] The seaweed extracts produced by Carbonwave and Ocean Knowledge are cold-pressed.[6]

Processing

After extraction, the final product may either be dried or prepared in various liquid formats generally in the pH 7-10 range. Liquid extracts are by far the most common preparation and are sold in plastic containers which range in size from quarts up to 1000-liter totes. Dry preparations typically come in paper or plastic bags up to 55 pounds, shipped on pallets also wrapped in plastic.

Figure 2. 1000-liter fertilizer tote (Credit: Appropedia).

[5] Craigie, “Seaweed Extract Stimuli in Plant Science and Agriculture.”
[6] McGonagill, Meeting with Allen from Carbonwave.

Figure 2. Olmix dry fertilizer in packaging (Credit: Olmix Group).

Application

Biostimulants are applied to crop leaves via foliar spray, or directly into the soil as drip irrigation. Both liquid and dry biostimulants are applied this way (dry biostimulants are water soluble).

Farm spraying equipment is typically a tank with multiple spraying nozzles attached that is towed behind a tractor. Drip irrigation systems are typically a series of pipes laid out among the crop rows that drips water slowly into the soil.

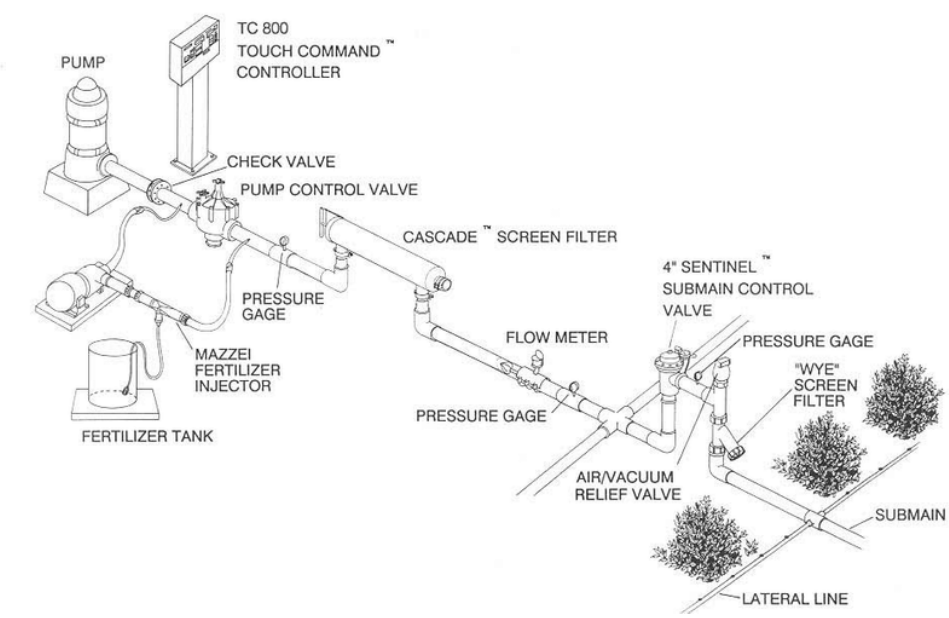

Figure 3. Drip irrigation system (Credit: ResearchGate).

Transportation

Most of the companies summarized in this report have processing plants close to the shoreline in their country of harvest. Although the distance between the shore and the harvest site is uncertain for all of the companies reviewed, the dominant species in the extract industry, *A. nosodum*, grows in the intertidal and mid-littoral zone, close to the shore. Nearly all the companies reviewed in this section operate globally, usually by shipping their products to retailers in other countries. Olmix, notably, operates factories in other countries and simply ships the raw or processed *Ulva spp.* directly to those factories for further processing and packaging.

	Source	Processing	Primary Market
Acadian Seaplants	Ireland, Scotland, Maine (USA), Canada	Ireland, Scotland, Canada	USA, Canada
Algea	Norway	Norway	Europe, Asia, USA
Olmix	France	Unclear – Research and development is based in France, but has global factories	Europe, Brazil, Southeast Asia, Canada, China, Mexico, Russia, USA, Egypt, UAE
Carbonwave	Mexico, Caribbean	Mexico	USA, Canada, Mexico
AgriSea	New Zealand	New Zealand	New Zealand, Australia, Italy
The Seaweed Company	Morocco, Ireland, India	Belgium	Still in testing (Belgium)
Ocean Knowledge	Ireland	Ireland	USA, Canada, Spain, U.K., Germany, Belgium, Finland, Sweden, China
Ocean Organics	Maine (USA)	Maine (USA)	Unclear
Vikas Crop Care	India	India	India

Cost

As of the beginning of 2023, monoammonium phosphate (MAP) had an average price of $879 per ton, potash was at $752 per ton, urea averaged $739 per ton, and diammonium phosphate (DAP) had an average price of $876 per ton.[7] It should be noted that this cost is almost triple what it was at the beginning of 2020[8], due to the conflict in Ukraine.

This report assumes the combined average of $811 per ton for traditional fertilizers in January 2023. It also assumes that farmers on average use 192kg of fertilizer per hectare, based on a World Bank/FAO report from 2018.[9] This writing, therefore, assumes a cost of $171 per hectare in traditional fertilizer use globally. While seaweed biostimulants are not intended to replace fertilizer, they can boost plant health enough to allow farmers to reduce their fertilizer use, in theory saving money and sparing GHG emissions associated with fertilizer production and use.

[7] "All Retail Fertilizer Prices Lower at Start of 2023, With Half Down Significantly."
[8] "Fertilizer Prices Expected to Remain Higher for Longer."
[9] "Igo_14nov22_e.Pdf."

Acadian Plant Health recently completed a trial where they reduced traditional fertilizer use by 30% while using their biostimulant and saw no loss in crop yield.[10]

Figure 4. Acadian's purported economic benefit of fertilizer drawdown with biostimulant (Credit: Acadian Plant Health).

Performance

Not all seaweed is the same; therefore, not all extracts are the same, and the effect they provide is highly variable depending on the recipe, dilution, method of application and time of application. Therefore, the benefits cannot be easily quantified, although seaweed extract is universally agreed to be beneficial for plants and soil, and some biostimulants have been shown to work as pesticides.[11]

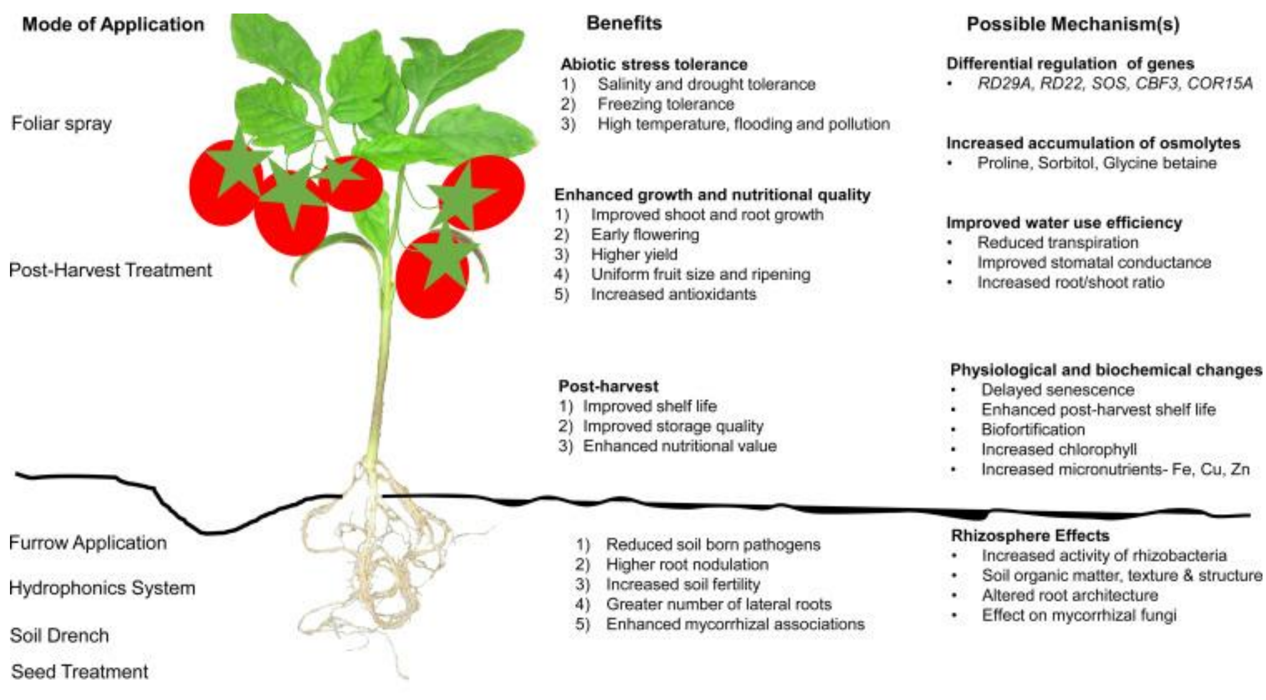

Figure 5. Possible mechanisms of seaweed extract benefits.[12]

[10] Health, "Trust Us, It Works. Why Biostimulant Companies Can No Longer Say This | Acadian Plant Health."
[11] Ali, Ramsubhag, and Jayaraman, "Biostimulant Properties of Seaweed Extracts in Plants."
[12] Battacharyya, Dhriti, Mahbobeh Zamani Babgohari, Pramod Rathor, and Balakrishnan Prithiviraj. "Seaweed Extracts as Biostimulants in Horticulture." *Scientia Horticulturae*, Biostimulants in Horticulture, 196 (November 30, 2015): 39–48. https://doi.org/10.1016/j.scienta.2015.09.012.

Effect on soil

Seaweed alginates improve moisture retention in the soil.[13] Seaweed extracts have been shown to enrich bacteria in the rhizosphere associated with plant health.[14] Notably, rhizophere bacteria assist plants with nitrogen uptake. Strengthening those bacteria reduces the need to add chemical nitrogen fertilizer.

Hussain et al. found significantly higher levels of available nitrogen in the soil for plants treated with commercially available seaweed extract.[15]

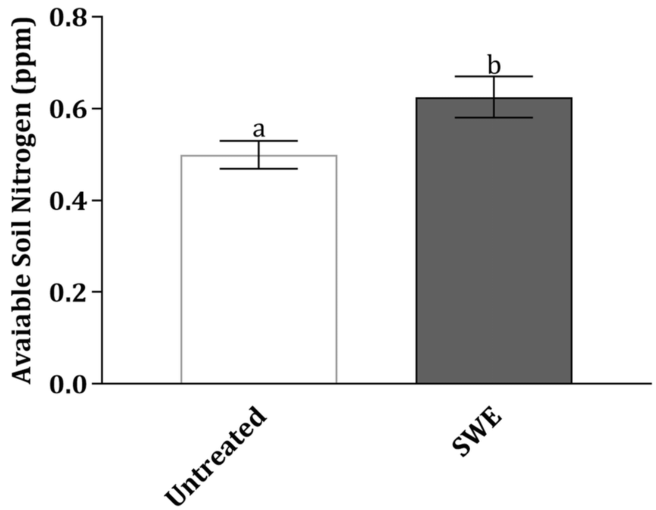

Figure 6. The effect of seaweed extracts (SWE) on available soil nitrogen (ppm) (29 DAP). The black bar indicates SWE treatment and the white bar indicates untreated control. Means followed by the same letter do not significantly differ (P =0.05,Fisher's LSD; n = 5; means with standard error bars are indicated). (Credit: Hussain et al.)

Effect on plants

Seaweed extracts can produce a wide range of benefits for plants, depending on the preparation, dosage and target crop. Seaweed extracts are generally associated with higher crop yield, more flowering and better stress tolerance. Most of the manufacturers summarized in this report offer field trial results on their websites. A quick review of the range of documented benefits includes improved germination, root development, leaf quality, flower set and fruit production.

Effect on diseases and pests

There is a mix of evidence as to the effect of biostimulants on diseases and pests. It likely depends on the brand of biostimulant and the target crop. Seaweed extracts can bolster plants' natural defense responses against fungi and bacteria. For instance, *A. nodosum* extract has been shown to upregulate antifungal compounds in alfalfa and defense responses in tobacco. Ali et al. cite several studies in which seaweed extract reduced infestations of common pests like nematodes, aphids, bollworm and borers. This reduction in infestation could be due to antifeedant effects and cytotoxicity on ovarian tissue cells of the pests.[16]

Lifespan

Acadian Plant Health reports that their products are formulated to have a shelf life of up to three years, allowing their product to be sold through retailers.[17] After use, any sequestered carbon that remains in the seaweed after biostimulant formulation will be released.

Opportunities and challenges

Incorporating seaweed extract into a traditional fertilization regiment can reduce the need for traditional fertilizer. The improved water retention, nitrogen uptake and stimulated natural defense

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[13] Ali, Ramsubhag, and Jayaraman.

[14] Chen et al., "Effect of Seaweed Extract Supplement on Rice Rhizosphere Bacterial Community in Tillering and Heading Stages."

[15] Hussain, Kasinadhuni, and Arioli, "The Effect of Seaweed Extract on Tomato Plant Growth, Productivity and Soil."

[16] Ali, Ramsubhag, and Jayaraman, "Biostimulant Properties of Seaweed Extracts in Plants."

[17] Wentz and Little, Interview with Acadian Plant Health.

response of the plants means that farmers incorporating biostimulants into their fertilization and irrigation could fertilize and water their crops less frequently and less intensely. While sales representatives and product engineers frequently make this argument, only Acadian Plant Health had quantified a reduction in traditional fertilizer; however, it was a controlled study, not a case study. Isolated case studies of customers using AgriSea products illustrate that in some instances it is possible to completely replace fertilizer use with seaweed extract[18], but more commonly the seaweed extracts are only applied — four to six times per season to supplement a conventional fertilization regiment. According to Carbonwave, the fear of under fertilizing is so high among commercial farmers that seaweed extracts are typically used in addition to other fertilizers and not as a replacement.[19]

Rhodomaxx, a small-scale Malaysian producer of biostimulant, points out that the industry is dominated by a small handful of global companies, making it difficult to scale operations without the right certifications, connections and finances.[20] Even with those factors in place, it is hard to be competitive with such well-established companies already on the market. Even among the large global suppliers, the cost of seaweed extracts is still high, making seaweed fertilizers and biostimulants a niche market. The field trials all indicate improved crop yield and soil health implying a reduction in the need for traditional fertilizer, but a generalized cost-benefit analysis does not yet exist. Some countries are beginning to institute quotas or limits on NPK, like Canada's suggestion to reduce absolute levels of GHG emissions arising from fertilizer application by 30% below 2020 levels by 2030[21], or the European Green Deal goal to reduce synthetic chemicals by 50% and fertilizers by 20% by 2030. California Agricultural Order 4.0 also limits fertilizer use in irrigation to minimize runoff pollution.[22] Regulations like this make California (USA), Europe and Canada optimal markets for biostimulant producers. Increased fertilizer prices may also create an opportunity to increase uptake of biostimulant use for the purpose of sparing fertilizer use.

[18] "Case Studies | AgriSea New Zealand | Biostimulant Nutrition Solutions."
[19] McGonagill, Meeting with Allen from Carbonwave.
[20] Chung Ngin and Faizal, Interview with Rhodomaxx.
[21] Canada, "Discussion Document."
[22] "Central Coast Regional Water Board Adopts General Waste Discharge Requirements for Discharges from Irrigated Lands."

Animal dietary supplement

Overview of product

A 2014 study by Commonwealth Scientific and Industrial Research Organisation (CSIRO) and James Cook University examined the effect of 20 different species of seaweed on reducing enteric methane emissions in ruminants. Although all the seaweed initially reduced methane emissions, *Asparagopsis taxiformis* (red), and *Dictyota bartayresii* (brown) both reduced CH_4 output by 92.2% and 98.9% respectively, after 72-hour incubation. Other species tested were unable to sustain their initial benefits within the 72-hour incubation period.

Following the publication of this study, CSIRO founded a company called FutureFeed Pty Ltd., which holds the global intellectual property (IP) rights for the use of *Asparagopsis* for livestock feed. Along with continuing to conduct research and opening regulatory pathways for this innovation, they also license other companies around the world to produce ruminant supplements using *Asparagopsis*. The companies that are currently licensed by FutureFeed are:

Company	Location	Commercial scale
CH4 Global	Australia / New Zealand	Supplement for beef cattle. Introduced in 2023. Supplements for other ruminants coming soon.
Sea Forest	Tasmania	Product available by request in Australia — all ruminants.
SeaStock	Western Australia	Not selling product — might be supplying algae to other producers.
Immersion Group	Australia	Selling *Asparagopsis* (oil and freeze-dried) in Australia and Japan. Just got funding from Japanese company (Nissui Corporation) to source their algae.
CleanEyre Global	South Australia	Working on co-growing *Asparagopsis* with shellfish. No feed supplement on market yet.
Blue Ocean Barns	Hawaii	California Department of Food and Agriculture approved Brominata in 2023, running trials in California.
Symbrosia	Hawaii	Running trials in the U.S. — mainly California.
Volta Greentech	Sweden	Pilot scale. Construction on new factory planned to start in 2023. They are growing large-scale *Asparagopsis* on land instead of in the sea.
Synergraze	Canada	Still in product development. Within three years will be commercial.

A handful of other companies are operating independently from FutureFeed to produce a product that reduces methane. These include:

Company	Location	Seaweed used	Product on market
Cascadia Seaweed	Canada	Kelp (species unknown)	Early 2024
Alga Biosciences	California	Kelp (species unknown)	Start-up — nothing yet
Greener Grazing	Vietnam / Portugal	*A.* taxiformis	Test in 2024
Acadian (Tasco/Titan)	Canada	*A. nodosum*	Since pre—2019

The halogen compound thought to be primarily responsible for inhibiting methanogens is bromoform. Bromoform is toxic to humans, so long-term studies would be required to determine whether there is bromoform content appearing in the meat or dairy of treated cows. This report also considers new research on adding seaweed to manure to reduce methane in the Performance section.

Sources and species

Most of the focus in this industry is on *A. taxiformis*, since it has performed the best so far in both *in vitro* and *in vivo* studies. CH4 Global and Sea Forest also grow *Asparagopsis armata*, which has similar methane reduction performance as *A. taxiformis* when fed at higher percentages. The companies using *A. taxiformis* and *A. armata* are growing it in Australia, New Zealand, Hawaii and Vietnam — all native habitats for the algae. Synergraze and Volta Greentech, located in Alberta and Stockholm respectively, are growing their *Asparagopsis* species via on-shore aquaculture. Cascadia uses a variety of brown kelp species, since British Colombia prohibits cultivation of non-native species.

The founder of Symbrosia mentioned that the seaweed they use is a hybrid, a cross between one strain of *Asparagopsis* that grows quickly and another strain that contains high bromoform.[23]

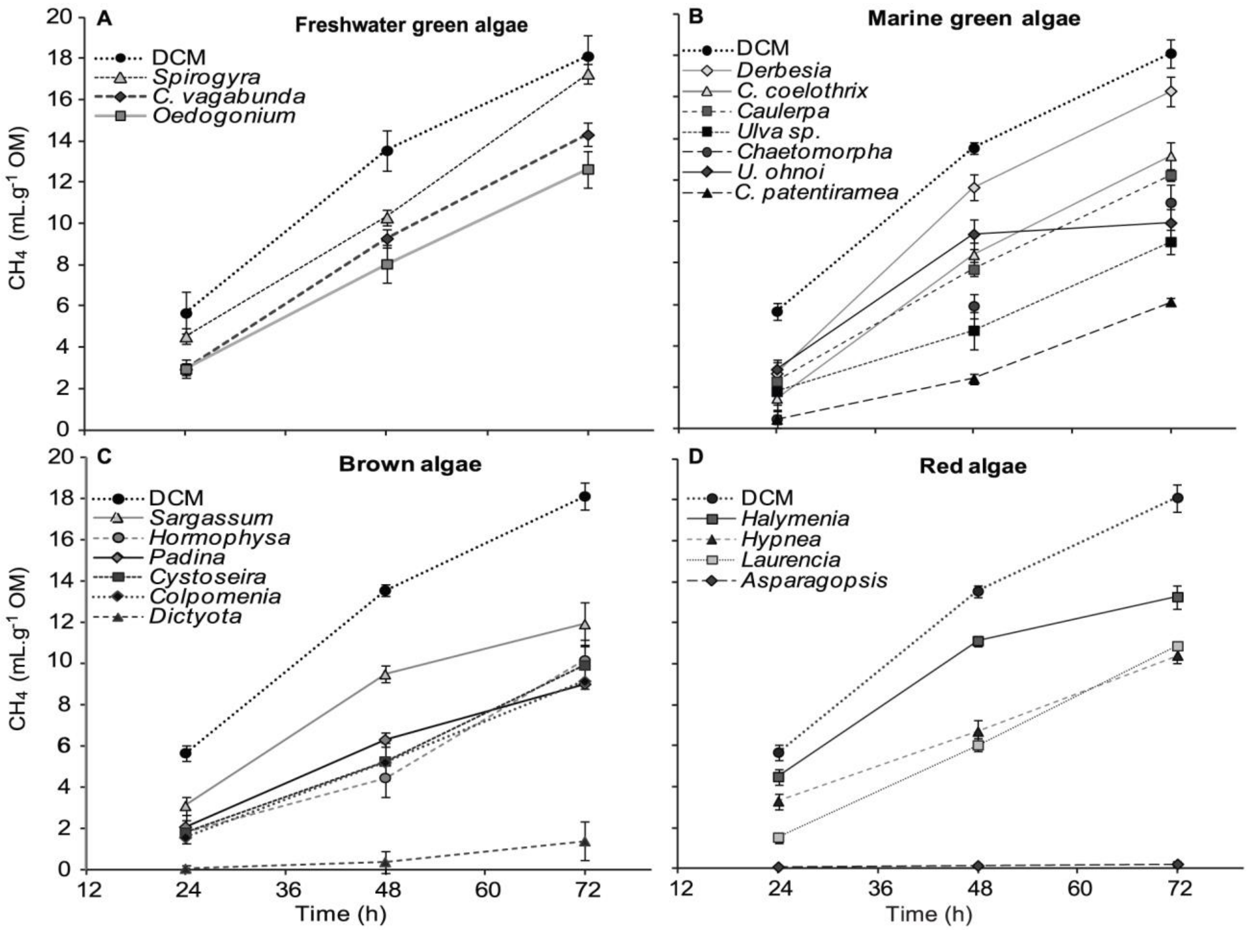

Figure 7. Comparison of methane reduction between different seaweeds over a 72-hour trial.[24]

<u>Cultivation and harvesting</u>

Most of the companies detailed in this report incubate *Asparagopsis spp.* seedstock in a lab. Typically, string is wrapped around a PVC pipe and placed into a tank of seaweed spores. The spores attach to the string and grow into sporophytes. From there, they move to seeded longlines in the ocean. Longlines are attached to anchors at either end, with buoys spaced along the line to allow it to float. The inoculated strings are unspooled from the PVC pipe and wrapped around the longline rope. During harvest, the ropes are lifted out of the ocean and farmers cut the seaweed off with a knife.

[23] "Symbrosia | Reducing Livestock Methane with Seaweed."

[24] Machado, L., Magnusson, M., Paul, N. A., and Tomkins, N. (2014). Effects of Marine and Freshwater Macroalgae on In Vitro Total Gas and Methane Production. PLOS ONE, 9(1), e85289. https://doi.org/10.1371/journal.pone.0085289

Figure 8. Asparagopsis seedstock in Volta labs (left)(Credit: Volta); Cascadia farmer checking on kelp longline (right) (Credit: Cascadia).

Some companies like Symbrosia, Volta Greentech, and Synergraze move the seedstock into tanks and continue growing it on-shore until harvest. In this scenario, the *Asparagopsis* is kept incubated in tanks with heated seawater for a few weeks, and then moved to ponds to grow to full size. Volta outlines the process on their website as using 100% renewable electricity and waste heat from surrounding factories.

Figure 9. Volta incubation tanks (above)(Credit: Volta), Symbrosia tanks (below)(Credit: Symbrosia).

CleanEyre co-cultivates their *Asparagopsis* alongside shellfish. The oyster farm infrastructure provides a suitable frame on which to grow *Asparagopsis* — the seaweed lines are strung between the same posts used to anchor the oyster bags.

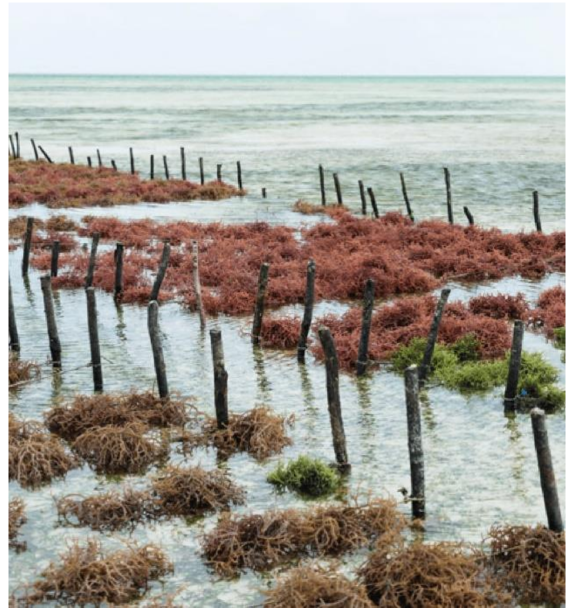

Figure 10. Asparagopsis growing alongside oysters (Credit: Clean Eyre Global).

Drying and extraction

The standard practice among the companies and researchers in this report is to freeze-dry the *Asparagopsis*.

According to researchers at CSIRO, freeze drying removes the moisture while preserving the bromoform content.[25] In that study, the freeze drying was done by a commercial food processing company (The Forager Food Company in Red Hills, Tasmania, AUS).

Processing

One process for creating total mixed rations (TMR) with *Asparagopsis* is described by Kinley et al. in a 2020 CSIRO study[26]:

- Collected biomass was frozen and stored at 15 degrees C
- Seaweed was freeze dried by a commercial food processing company to approximately 95% dry matter (DM) to retain the volatile bromoform in situ
- The freeze dried *Asparagopsis* biomass of approximately 50% organic matter was milled to 2e3 mm (Hobart D340 mixer, Troy, Ohio, U.S.) to ensure a uniform product and stored at 15 degrees C.
- The *Asparagopsis* was incorporated into a TMR containing Rhodes grass and steam rolled barley using a horizontal paddle mixer.

Figure 11. Symbrosia dried seaweed feed (Credit: Symbrosia).

In an interview with Symbrosia, they reported that they also freeze dry their *Asparagopsis*, but they do not finely mill it — they leave it in clumps.[27]

An alternative to freeze-dried *Asparagopsis* is oil emulsion. In this process, freshly collected *Asparagopsis* is homogenized in vegetable oil, which preserves nearly all the bromoform content in the seaweed for at least 12 weeks at ambient temperature. One study at James Cook University found that the bromoform

[25] Kinley et al., "Mitigating the Carbon Footprint and Improving Productivity of Ruminant Livestock Agriculture Using a Red Seaweed."
[26] Kinley et al.
[27] Hobart, Interview with Symbrosia.

content in the oil immersion was double that of freeze-dried *Asparagopsis*, which may be due to the initial loss of bromoform from the *Asparagopsis* between harvesting and freeze-drying of the biomass and/or losses during the freeze-drying process due to the volatility of bromoform.[28] The process simply involves blotting the *Asparagopsis* dry and adding it to a container of oil, which can then be homogenized. The study used an IKA ultra-turrax T-25, produced by VWR Australia.

Transportation

All the companies reviewed in this report have seeding and processing facilities near their harvesting locations. The companies that are currently commercial are producing and distributing in Australia. The companies that are pre-commercial are running trials in the U.S., predominantly in California. Symbrosia reports that their supplement is shipped to trial farmers either in plastic buckets or mylar bags.

Performance

The effect of seaweed feed supplement varies by species and inclusion rate. *Asparagopsis* has been reported to reduce methane as little as 40% and as high as 99%.[29] Studies have also documented weight gain improvement of 40-50%, and those same studies also reported no bromoform content in the subjects' meat, even after 90 days.

A 2023 study at the Swedish University of Agricultural Sciences found that methane production from the feces of cows that have previously been supplemented with *A. taxiformis* in their diet is not significantly decreased compared with the feces of cows not supplemented with it. However, the addition of *Asparagopsis* to feces showed that around 44% of CH_4 production could be reduced from the feces of dairy cows.[30] The researchers did not describe how the *Asparagopsis* was processed before adding it to the feces, nor did they describe how that process might be carried out at scale, outside of a laboratory. The brown seaweeds *Cystoseira trinodis* and *D. Bartayresii* also suppress methane production in laboratory studies.

Item	Non-AT fed cows		AT fed cows		SEM[b]	*P*-values[c]		
	CON[a]	AT added to feces	CON	AT added to feces		S	A	S×A
CH_4, L/kg DM	5.50	2.78	4.58	2.90	0.763	0.61	0.01	0.50
Total gas, L/kg DM	24.4	16.0	23.9	16.6	3.19	0.99	0.04	0.86
CH_4/total gas	0.23	0.20	0.20	0.18	0.023	0.23	0.40	0.95

[a] CON, control, without addition of AT to the feces.
[b] Standard error of mean.
[c] S represents dietary supplementation with AT, A represents the addition of AT to the feces, and S × A represents the interaction effect between dietary supplementation with AT and the addition of AT to the feces.

Figure 12. Methane emissions from cow feces treated with Asparagopsis (Credit: Ramin et al. 2023)

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[28] Magnusson et al., "Using Oil Immersion to Deliver a Naturally-Derived, Stable Bromoform Product from the Red Seaweed *Asparagopsis* Taxiformis."
[29] Kinley et al., "Mitigating the Carbon Footprint and Improving Productivity of Ruminant Livestock Agriculture Using a Red Seaweed."
[30] Ramin et al., "Reducing Methane Production from Stored Feces of Dairy Cows by *Asparagopsis* Taxiformis."

Opportunities and challenges

Aside from the freeze-drying process, the energy inputs for the processing of feed supplement are relatively low. However, *A. taxiformis* is farmed in only a handful of places around the world. To provide this species as a methane-reducer worldwide would require progress in ocean farming methods and more companies like Symbrosia and Volta who can raise *Asparagopsis* on land. This process comes with a larger set of considerations for energy use and water use.

Aside from growing capacity, Symbrosia reported that the major barrier in the U.S. is a lack of Food and Drug Administration approval. This limits the companies producing feed supplement to trials only. The dosage between producers is also inconsistent right now, with most trials still testing 0.05%, 0.1% and 0.2% inclusion rates to compare benefits and trade-offs.

Multiple long-term studies are still needed to confirm unequivocally that bromoform does not present a risk to consumers via meat or milk contamination.

Biofuel

Overview of product

Seaweed biomass can be turned into natural gas and biodiesel through a variety of processes. Any genus of seaweed can be used, either as whole biomass or as leftover waste from, say, agar extraction. This section of the report summarizes the production methods for biofuel from a variety of journal articles. It also summarizes the status of a small handful of companies working commercially in seaweed biofuel.

Commercial activity in this field is very low. The Organisation for Economic Co-operation and Development (OCED) and FAO project that the biofuel market is no longer experiencing the growth it once had.[31] Most developed countries have a mandate requiring some percentage of biofuel (typically corn ethanol) to be blended with gasoline. Blend mandates are increasingly being adopted in developing countries as well, although most countries are blending no more than 10%, and this is projected to stay consistent through 2030. The OECD and FAO report notes once exception — Indonesia's implementation of B30 (biodiesel 30% blend) is expected to increase Indonesia's domestic production and use of biodiesel to 9.7 billion liters by 2030. Since Indonesia's current main source of biodiesel is palm oil, there is a potential for seaweed biofuel to provide a more sustainable option there. This report found no Indonesian companies working on seaweed biofuel.

Overall, there is uncertainty in the future of the global biofuel market — countries are expected to adopt policies and technologies to cut GHGs over the next decade, which could spur growth. It could also lead to a decline in interest in biofuel if there is increased adoption of other technology in the energy sector, like electric vehicles.

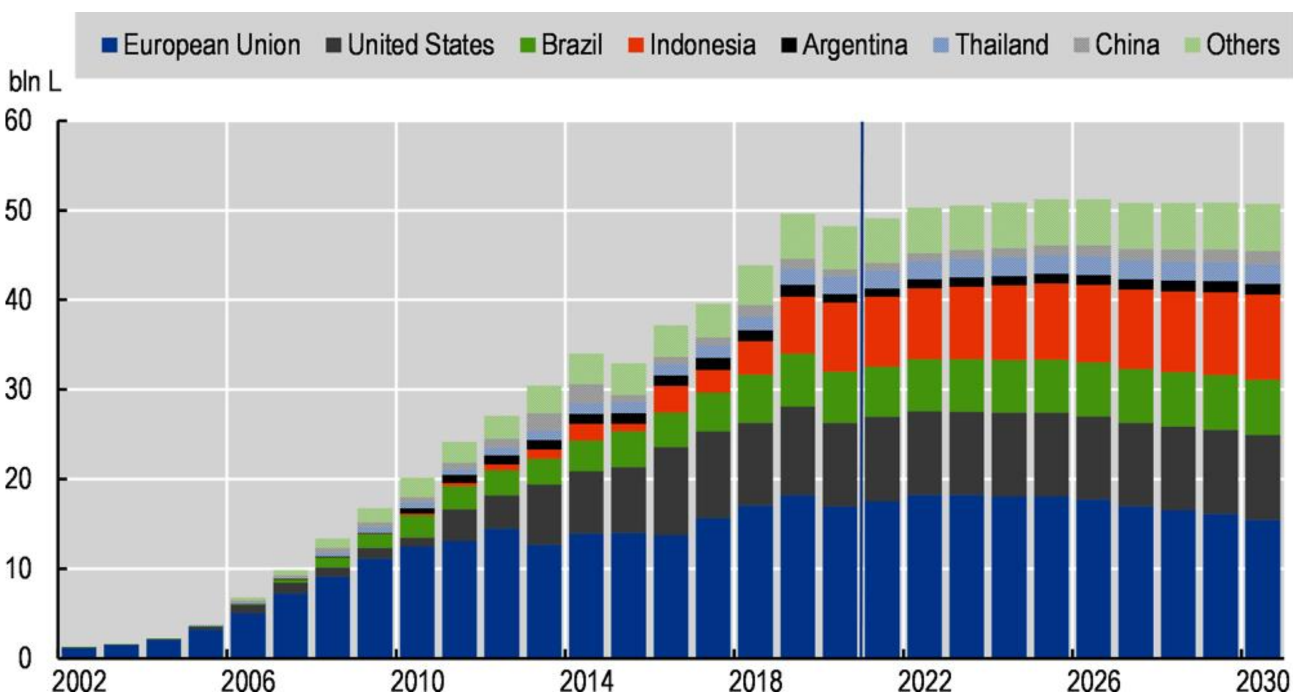

Figure 13. World biodiesel consumption (Credit: OECD/FAO [2021], "OECD-FAO Agricultural Outlook", OECD Agriculture statistics [database], http://dx.doi.org/10.1787/agr-outl-data-en).

[31] OECD and Food and Agriculture Organization of the United Nations, "Biofuels."

Sources and species

Within academic research, most of the works published on biofuel production from brown seaweed focus on *Laminaria japonica* and *Sargassum spp*., and studies using red seaweed mainly utilize species within *Gracilaria spp*., since these are the most prolific farmed and researched seaweeds in East Asia.[32] The *Gracilaria* studies often use waste left over from agar extraction rather than whole biomass. This is likely due to the high market value of agar. Among the companies summarized in this report, all are using species local to their research and development facilities, either wild harvested or farmed.

Company	Location	Seaweed used	Production scale:
SeaH4	South Africa	*Ulva* (farmed, aquaculture)	Start-up, research and development
Sea6 Energy	India	*K. alvarezii* (farmed, longline)	Research and development — only producing biostimulant and animal feed for now
Rum and Sargassum	Barbados	Sargassum (Caribbean, waste)	Pilot/demonstration
Energy Algae	Israel (unclear)	Sargassum (Caribbean, waste)	Start-up, research and development
Marine BioEnergy, Inc.	California (U.S.)	Giant Kelp — *Macrocystis pyrifera* (farmed, longline)	Research and development, funded by Advanced Research Projects Agency–Energy (ARPA-E), U.S. Department of Energy

Cultivation and harvesting

Rum and Sargassum and Energy Algae propose to use washed-up sargassum from the Caribbean. For more on those collection methods, see Cultivation and harvesting for construction materials.

SeaH4 utilizes land-based aquaculture. This allows them to use the *Ulva* as a natural filter for wastewater from fish farms or factories, create a closed-loop system and install their system anywhere in the world.[33] They do not publish details about their system.

[32] Jiang, Ingle, and Golberg, “Macroalgae (Seaweed) for Liquid Transportation Biofuel Production.”
[33] “Homepage.”

Marine BioEnergy, Inc. grows giant kelp on longlines off the coast of Catalina Island in Southern California. They use a process called depth cycling, which lowers the longlines below the local thermocline to 80 meters depth (272 feet) every night to absorb nutrients. During the day, the lines are raised back to the surface to absorb sunlight. Compared to the control, below the local thermocline to 80 meters depth (272 feet). Giant kelp grown under depth-cycling conditions had an average growth rate of 5% per day and produced four times more biomass (wet weight) than individuals grown in a kelp bed without depth-cycling. Analysis of tissue from the depth-cycled kelp showed elevated levels of protein, lower C:N ratios, and distinct elemental N and C values suggesting that the depth-cycled kelp were not nitrogen-deficient and assimilated nutrients from deep water. Depth-cycled kelp also exhibited smaller and thicker-walled pneumatocysts and larger blades.[34] The implication, according to the researchers, is that this technique could circumvent seasonal surface nutrient limitations, allowing consistent quality and quantity of seaweed to be grown year-round, facilitating large-scale production of macroalgae as feedstock for low-carbon fuels.

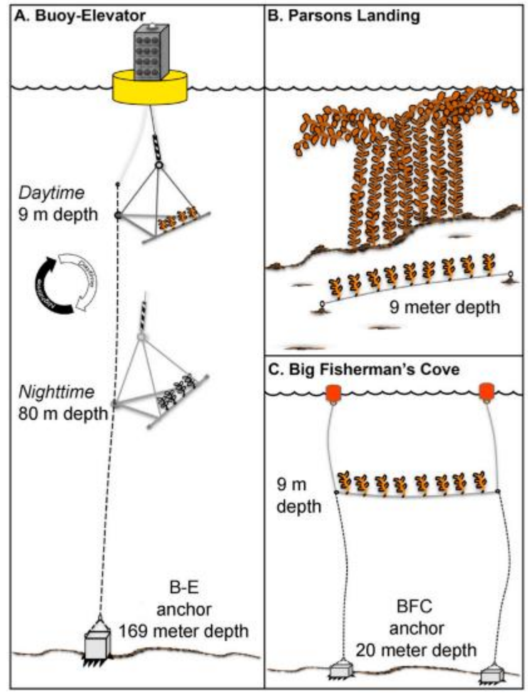

Figure 14. Solar-powered Buoy-Elevator (BE) experimental platform (Credit: Navarette et al.).

Sea6 Energy grows sargassum in tube nets on the open ocean. They have pioneered an automatic harvester, which pulls the tube nets out of the ocean, removes the seaweed and then takes a percentage of the harvest and re-fills the tube nets to place back into the ocean for further growth.[35] This process seems to be only pilot scale.

1. Tube nets pass through a crown cutter that trims the younger growth from the outside of the net. The young growth drops into a hopper.

[34] Navarrete et al., "Effects of Depth-Cycling on Nutrient Uptake and Biomass Production in the Giant Kelp Macrocystis Pyrifera."
[35] "Mechanised Ocean Farming | Sea6 Energy."

(Credit: Sea6 Energy)

2. The nets pass through a grinder, which crushes the mature growth inside the net, causing it to drop away.

3. The young growth from the hopper is stuffed back into the tube net to be re-seeded into the ocean.

Drying and extraction

Seaweed used directly for biofuel production does not need to be dried. An LCA carried out by M. Alvarado-Morales et al. rinsed the seaweed with cold water to remove sand and other debris. The wet seaweed was then milled into a slurry. The equipment used was assumed to be a circulating wet grinding attritor production mill and the energy consumption was estimated to be 38 kW h per one tonne of dry seaweed.[36]

Biofuel production using seaweed waste from agar extraction or other industries would likely already be dry, necessitating the addition of water to produce the slurry.

Processing

There are three major processes for converting seaweed into biofuel: HydroThermal Liquefaction followed by Catalytic Hydrothermal Gasification (HTL/CHG), Fermentation, and Anaerobic Digestion (AD).[37]

HTL/CHG

HTL/CHG systems process wet feedstocks into bio-oil which can be further processed by the existing refineries into needed fuels. HTL systems are produced by:

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[36] Alvarado-Morales et al., "Life Cycle Assessment of Biofuel Production from Brown Seaweed in Nordic Conditions."
[37] "Kelp To Fuel."

Company	Location	Details	Website
Genifuel	U.S.	The output of the system is biocrude oil or natural gas, or both, depending on how the system is configured. The biocrude oil and methane gas are nearly identical to the natural fossil equivalents.	genifuel.com
Steeper Energy Canada Limited	Denmark and Canada	Steeper's Calgary Canada plant was completed in November 2021 and includes units to perform full upgrading of Hydrofaction® Oil to finished fuels including marine, diesel and jet fuels.	steeperenergy.com
Circlia Nordic	Denmark	Circlia Nordic is currently working on turning sewage sludge into biocrude and making jet fuel from agricultural waste.	circlianordic.com

Fermentation

Fermentation produces alcohols such as ethanol or butanol, depending on the organisms and processes. Fermentation facilities are commonly used to process corn and other feedstocks. Organisms have been tested that efficiently digest the sugars (alginates, mannitol) found in brown kelp, although this may only be a preliminary step to increase the methane yield of seaweed during anaerobic digestion.[38]

Anerobic digestion

The most common method of biofuel production from seaweed is anaerobic digestion. Anaerobic digestion (AD) produces methane that can be injected into regional pipelines. AD technology does not need to be adapted to accept seaweed feedstock. Marine BioEnergy, Inc. has identified a few digester facilities in California, close to their Catalina growing site:

Company	Location	Details	Website
CR&R Environmental Services	Riverside County, California, U.S.	They have bench-tested kelp. The kelp performed 5% better than their normal feedstocks of lawn/garden cuttings.	crrwasteservices.com
Agromin	Oxnard/Ventura County, California, U.S.	Agromin collects local organic waste to turn into compost using AD.	agromin.com
ReSource Center	Santa Barbara County, California, U.S.	ReSource's AD turns organic material from trash collection into methane which powers the facility, and digestate, which is sun-dried for compost.	lessismore.org

[38] Herrmann et al., "Ensiling of Seaweed for a Seaweed Biofuel Industry."

A typical anaerobic digestion process is simple, although the exact details of the process may change based on the size of the facility or the feedstock used. In a standard AD system, organic waste is placed in a closed container, and heated to 100 degrees Celsius and stirred constantly for 20-30 days. During this time, it may also be sprayed with percolate (wet seaweed biomass already has enough moisture to skip this step). During digestion, bacteria break down the material, producing biogas and digestate. Biogas has high methane content and can be used to generate electricity for the grid. The leftover digestate can be sun-dried and used as compost. Many AD systems have a two-tank process; after the initial 20-30-day digestion, the digestate is moved to a second tank to allow water and solids to separate, and this second digester can capture any remaining biogas that is produced.

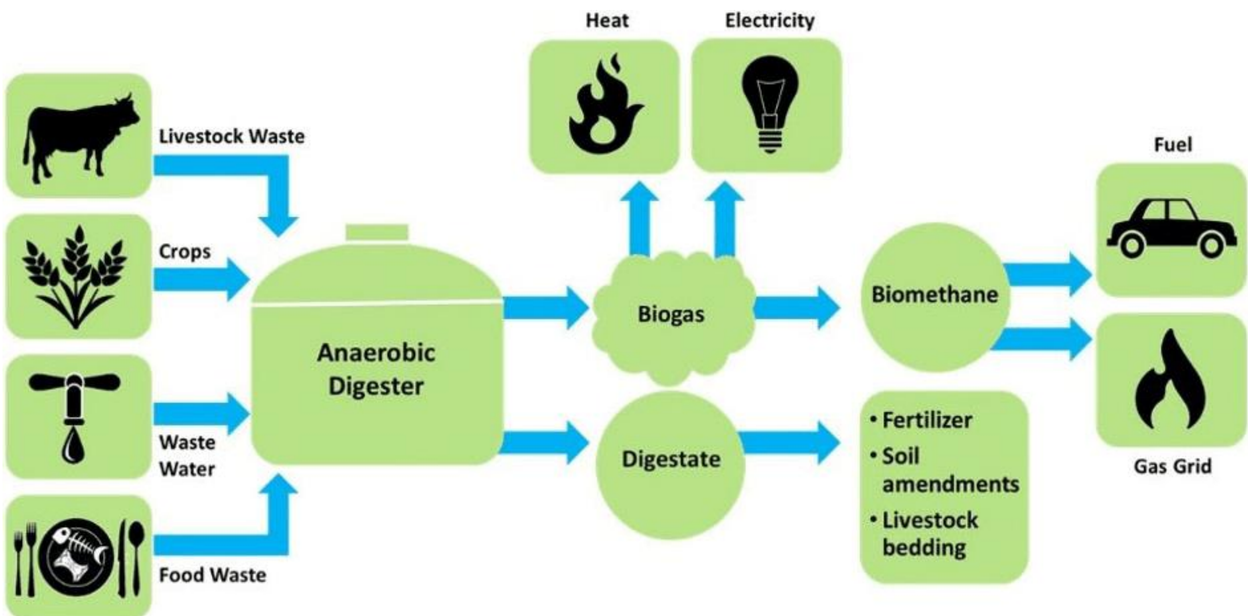


Figure 15. Simplified flowchart of the anaerobic digestion process(New Post: Biogas Production [beehiiv.com])

Cost

While AD systems are expensive to install, they have the benefit of free feedstock (waste products). AD systems are typically installed at sewage plants, landfills, dairy farms or universities — where manure, food waste, organic waste or sewage sludge can all be used to feed the digester. A literature review of AD operating costs and subsequent economic modeling using Aspen Plus and CAPDET by Bhatt and Tao found that biogas has the potential to be cost competitive with natural gas, and that the cost is variable depending on the feedstock and the scale of production (see Figure 17).[39] Some of their models calculated a cost of $10-20 per GJ for biogas, while the average U.S. cost of natural gas in May 2023 was $16.71 for residential and $10.51 for commercial. AD system owners can further reduce this cost by using the energy generated by their digesters locally on site, selling their excess energy back to the grid, and either using or selling the digestate produced as compost.

[39] Bhatt and Tao, "Economic Perspectives of Biogas Production via Anaerobic Digestion."

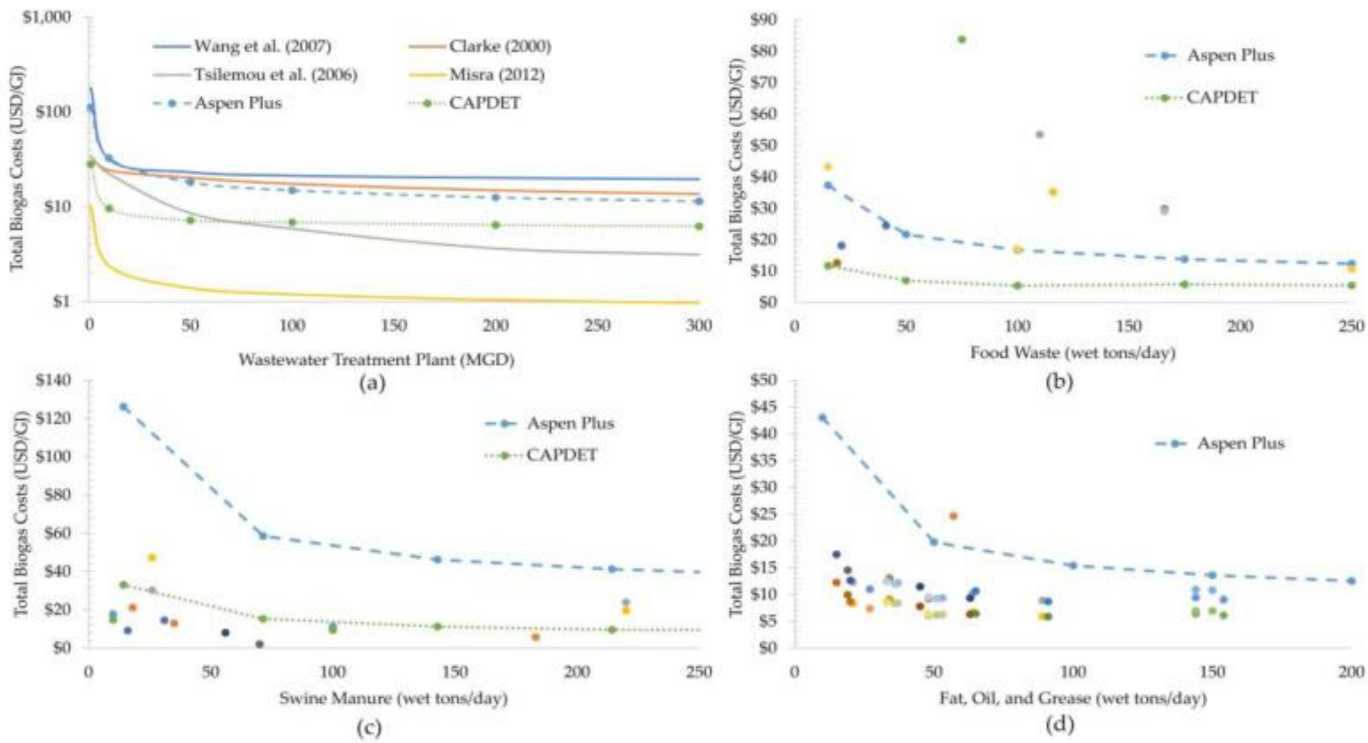


Figure 16. Total biogas production costs in USD/GJ for AD processing (a) wastewater treatment sludge, (b) food waste, (c) swine manure and (d) fat, oil and grease. Note that that y-axis on Figure 17a is plotted on a log-scale (Credit: Bhatt et al. 2020)

The LCAs cited in this report reviewing seaweed as AD feedstock all note that seaweed only becomes economically viable as a feedstock when you also factor in the market price of agar or other extracts pre-digestion, and factor in the economic and environmental impacts of digestate as compost post-digestion. This is because seaweed, perhaps apart from Caribbean sargassum, is not a free waste product — the cost and energy involved in cultivation and harvest must be included in the LCA.

Performance

This report considers the results of a handful of LCAs and academic studies on seaweed-based biofuel in comparison to the conventional alternatives of ethanol and natural gas.

Study	Details	Energy Output	GHG Offset Potential
Life cycle assessment of seaweed biomethane, generated from seaweed sourced from integrated multi-trophic aquaculture in temperate oceanic climates[40]	Biomethane was produced using *Laminaria digitata* that was co-cultured alongside salmon farming in Ireland (SW-SF refers to seaweed from salmon farms).	Biomethane was composed of 97% methane and 3% CO_2 and other gases, then compressed and injected into gas grid. The electrical input of biomethane compression to 250 bar was estimated at 0.23 kWh/m^3 of gas introduced into compression unit.	The baseline scenario SW-SF performs worse than natural gas and gasoline in almost all impact categories, except for global warming potential (GWP) and marine eutrophication. In terms of GWP, this scenario provides 27% carbon savings when compared to natural gas and 44% when compared to gasoline.
Life cycle assessment of biofuel production from brown seaweed in Nordic conditions[41]	Biogas and bioethanol were produced from *L. digitata* grown on longlines in Denmark. In Scenario 1 (S1), only biogas was produced and digestate was used as replacement for fertilizer. In Scenario 2 (S2), bioethanol was produced and blended with gasoline at 5%, and the digestate was then used to produce biogas.	S1 produced a net gain of 555 kWh (2.00 GJ) of electricity per one tonne of dry seaweed. S2 produced a net gain of 916 kWh (3.30 GJ) of electricity per one tonne of dry seaweed.	Energy production delivered large savings; 603 and 616 kg CO_2-eq. per one tonne of dry seaweed for S1 and S2, respectively.
Improving gaseous biofuel yield from seaweed through a cascading circular bioenergy system integrating anaerobic digestion and pyrolysis[42]	*L. digitata* and *Saccharina latissima* from Ireland were placed in AD along with biochar from waste wood to demonstrate the mass and energy balance of a cascading circular AD-pyrolysis system. Surplus heat from pyrolosis was used in the AD system for heating the digester and drying the solid digestate. The dried digestate was pyrolyzed together with waste wood to produce more bio-oil, biochar and syngas. See Figure 16.	Net energy gain in the AD-Pyrolysis system was 6688.8 MJ. The process efficiency was 59.7%, which is lower than that of an individual Py system (62.4%) but much higher than the efficiency of an individual AD system (38.1%).	Not calculated

[40] Czyrnek-Delêtre et al., "Life Cycle Assessment of Seaweed Biomethane, Generated from Seaweed Sourced from Integrated Multi-Trophic Aquaculture in Temperate Oceanic Climates."
[41] Alvarado-Morales et al., "Life Cycle Assessment of Biofuel Production from Brown Seaweed in Nordic Conditions."
[42] Deng et al., "Improving Gaseous Biofuel Yield from Seaweed through a Cascading Circular Bioenergy System Integrating Anaerobic Digestion and Pyrolysis."

A close-loop integrated approach for microalgae cultivation and efficient utilization of agar-free seaweed residues for enhanced biofuel recovery[43]	*Gracilaria mulipartita* was turned into biogas following agar extraction. The leftover digestate was then mixed with synthetic wastewater and used to grow *Scenedesmus* (green algae) to make biodiesel.	Estimated energy output from the agar-extracted biomass was 4624 MJ per ton^{-1}. Estimated energy output from the SWW-fed algae was 5098.9 MJ per ton^{-1} of dry *Scenedesmus obliquus*.	Not calculated

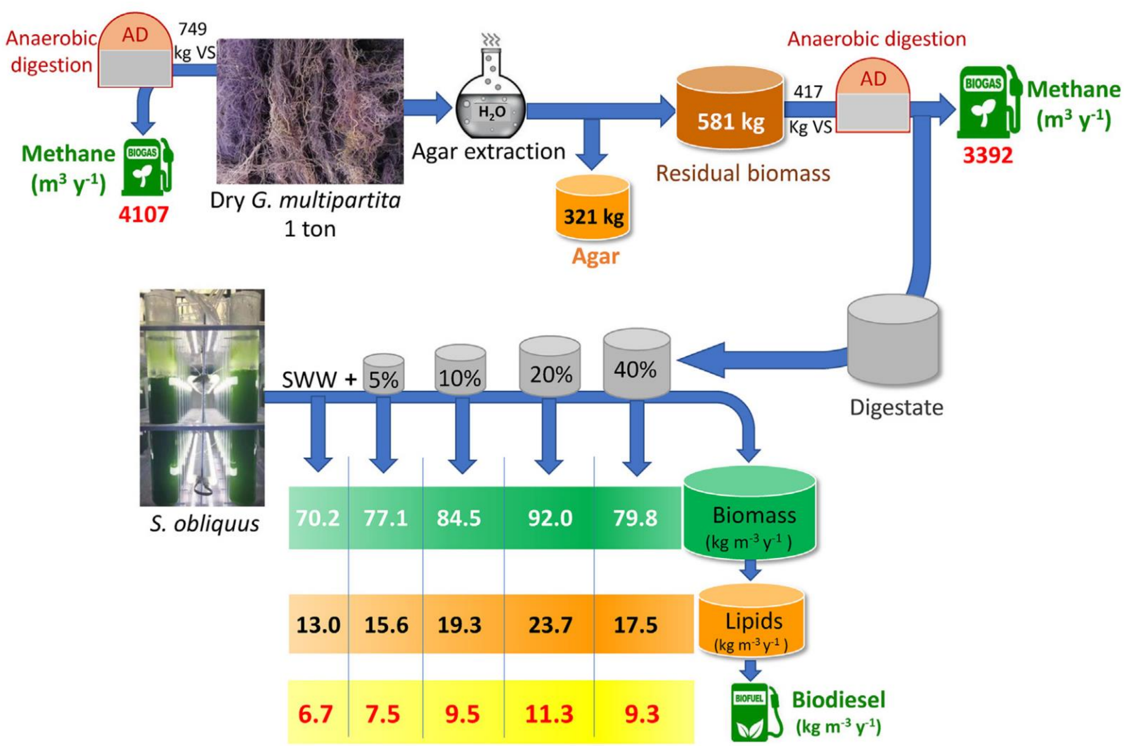
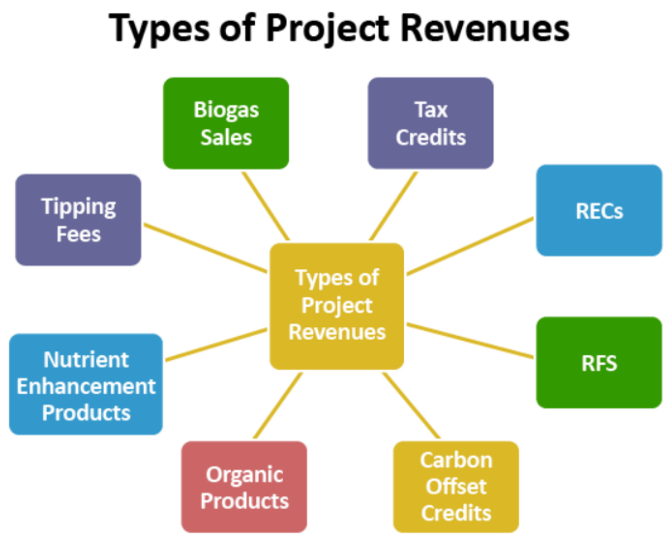


Figure 17. Biomass, agar, biomethane and biodiesel produced from 1 ton of dry Gracilaria multipartita *and* S.obliquus *grown on synthetic wastewater (SWW) with different ratios of anaerobic digestate (Credit: Abomohra et al).*

[43] Abomohra and Almutairi, "A Close-Loop Integrated Approach for Microalgae Cultivation and Efficient Utilization of Agar-Free Seaweed Residues for Enhanced Biofuel Recovery."

Opportunities and challenges

Anaerobic digestion systems are costly. The economic feasibility of AD is driven by the assumption of multiple revenue streams, but economic assessments rarely include the cost of feedstock, since it is assumed to be organic waste. The challenge in using seaweed as AD feedstock is that it takes time, energy and money to grow, reducing the profit margin from biogas produced. On the other hand, any type of seaweed can be used in anaerobic digestion, and it doesn't need to be whole feedstock. Seaweed waste is also suitable for making other products. Thus, anaerobic digestion could be one piece of a cascading production system that would replace multiple GHG-intensive products. For example, seaweed could be fermented for biostimulant, then the leftover biomass could be digested for gas, and the remaining digestate could be used as a fertilizer replacement.



(Credit: Project Planning and Financing | US EPA).

Textiles

Overview

There are only a handful of companies with seaweed fabric on the market. The three companies summarized in this report are Smartfiber AG, Soarce and Carbonwave. Smartfiber AG is a European company that produces a seaweed-eucalyptus blend, which is commercially available and used by multiple fashion brands. Soarce is an American startup which is currently in the research and development phase. They have multiple companies testing their product. In 2024 U.K. shoe designer Nicholas Kirkwood will be releasing a line of shoes using Soarce's seaweed leather.[44] Carbonwave is also producing seaweed leather, which is still in research and development.[45]

Other companies included in the index but not summarized in this section, due to lack of data regarding their process: Karma Beach Club, Uncommon Alchemy and Keel Labs.

Company	Product	Development Stage
Smartfiber AG	Seaweed lyocell blend	Globally commercial
Soarce	Seaweed fabric and leather	Product testing
Carbonwave	Seaweed leather	Research and Development
Karma Beach Club	Seaweed cotton blend	Small-scale commercial
Uncommon Alchemy	Seaweed leather	Research and Development
Keel Labs	Seaweed fabric	Research and Development

The plant-based leather market was estimated at $67.6 million in 2022[46], and the regenerated cellulose fiber market (viscose, lyocell, modal) was $18 billion in 2022.[47]

Sourcing and species considerations

Brown seaweed is harvested through a variety of methods. Smartfiber AG harvests knotted kelp (*A. nodossum*) from Iceland with mechanical harvesters, rotating through patches that get harvested once every four years. Soarce uses seaweed from two providers: KIMICA, a Japanese company, which collects bull kelp (*Nereocystis luetkeana*) washed up on the beaches in southern Chile, and Origin by Ocean, which collects sargassum (Phaeophyceae) washed up on beaches in the Caribbean.[48] Soarce reports that they are trying to shift away from KIMICA because of concerns about their environmental impact but did not elaborate further. Carbonwave uses washed-up sargassum from the Caribbean and Mexico.

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[44] Michel, Interview with Patrick from Soarce.
[45] McGonagill, Meeting with Allen from Carbonwave.
[46] "Bio-Based Leather Market Size | Global Industry Forecast."
[47] ltd, "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."
[48] Michel, Interview with Patrick from Soarce.

Cultivation and harvest

Harvest

KIMICA, Soarce's main supplier, uses washed up kelp from the coast of Chile. They hire local community members to collect the kelp by hand.[49] Soarce's secondary supplier, Origin by Ocean, uses sargassum harvested from Caribbean beaches and coasts. Carbonwave also uses washed-up sargassum as their source material. Because sargassum washes up in such large quantities, the collection method usually involves loaders and dump trucks.

Processing

Drying and extraction

For Soarce, most of the seaweed is air-dried before processing. Their bull kelp supplier in Chile (KIMICA) uses large warehouses in the Atacama Desert to store the seaweed while it dries. In KIMICA's process, they allow air flow through the warehouse, but keep it shaded to prevent sun damage and contamination. They claim that the Atacama Desert provides the perfect conditions for air-drying. The drying process for Carbonwave and Smartfiber AG are unknown.

After drying, sodium alginate powder is extracted from the dried seaweed. In this process, ground seaweed is soaked in dilute acidic solutions to remove fucoidans, laminarins, proteins and polyphenols that could modify alginate features. Then, alginic acid is transformed into sodium alginate employing alkaline solutions. Solid residues are removed by centrifugation and filtration. Then, alginate is precipitated with ethanol to obtain sodium alginate.[50] A general infographic of the alginate extraction process is provided in Plastic.

The sodium alginate is mixed with other ingredients before being turned into fabric. Smartfiber AG mixes their alginate with eucalyptus (and an unspecified 'chemical treatment' to preserve the nutrients in the seaweed). Soarce uses a 'proprietary blend' of additives but claims that the blend is natural, with no chemicals or plastic. Smartfiber's SeaCell fiber contains 19% alginate by volume (only 4% by weight). Soarce's ratio of seaweed to other material is unknown. Carbonwave reports that their seaweed leather will need to contain 10% synthetic material to meet durability standards for alternative leather.

[49] "Sustainability-Report_Web.Pdf."
[50] Montes et al., "Impact of Drying on the Sodium Alginate Obtained after Polyphenols Ultrasound-Assisted Extraction from Ascophyllum Nodosum Seaweeds."

Yarn

Smartfiber AG's SeaCell fiber is produced in the same factory that makes lyocell, and except for the addition of alginate, follows the same process as lyocell. First, fiber spinnerets create long fibers. The fibers are washed and dried, then coated with a lubricant to prevent tangling. The fibers are then spooled and can be sent to clothing manufacturers to spin into fabric. In lyocell production, amine oxide solvent is used to dissolve the cellulose before spinning, and then diluted amine oxide is used again after spinning to set the fibers. Most lyocell systems are closed-loop; the amine oxide is collected (~99% captured), water is evaporated out, and the solvent is re-used.[51]

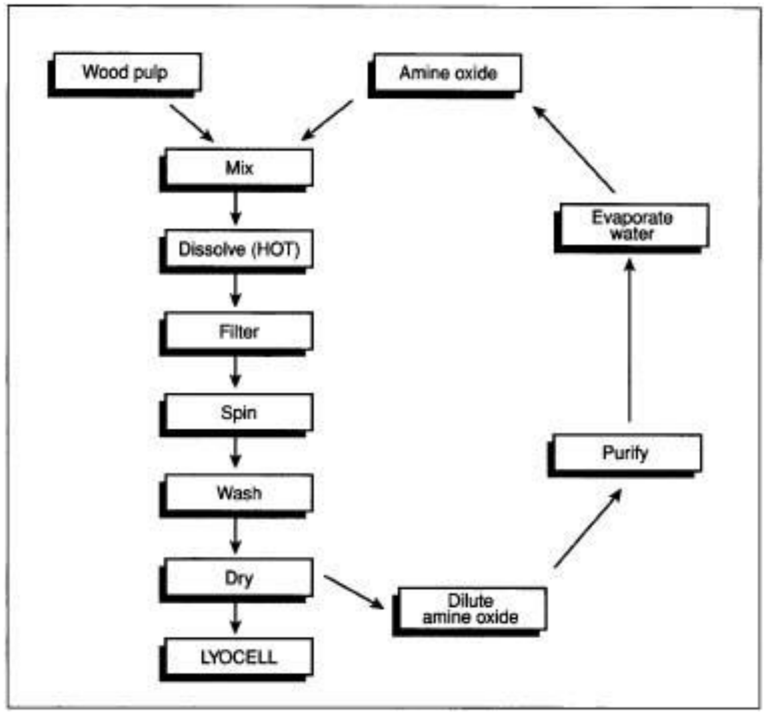

Figure 18. The lyocell process (Credit: Madehow.com)

Leather

The process for seaweed leather is different than the lyocell process mentioned above. Soarce's seaweed leather is produced by pouring the liquid alginate compound into a textured mold and then heating and pressing it into sheets.[52] Afterward they add an unspecified backing to the sheet, presumably fabric (PU and PVC leathers use a backing made of fabric or suede). This process is like the one used for other vegan leather. The diagram below is the process used by Fruit Leather Rotterdam, which makes leather from discarded mangoes.[53] Soarce described their process similarly, but without the addition of the PVC coating. The process is similar among all vegan leather companies, but the compounds added in step one are the distinguishing competitive edge among manufacturers and, therefore, kept secret. Presumably the additives increase durability and prevent decomposition.

[51] "How Lyocell Is Made - Material, Manufacture, Making, Used, Processing, Steps, Industry, Machine."
[52] Michel, Interview with Patrick from Soarce.
[53] *How Vegan Leather Is Made From Mangoes | World Wide Waste*.

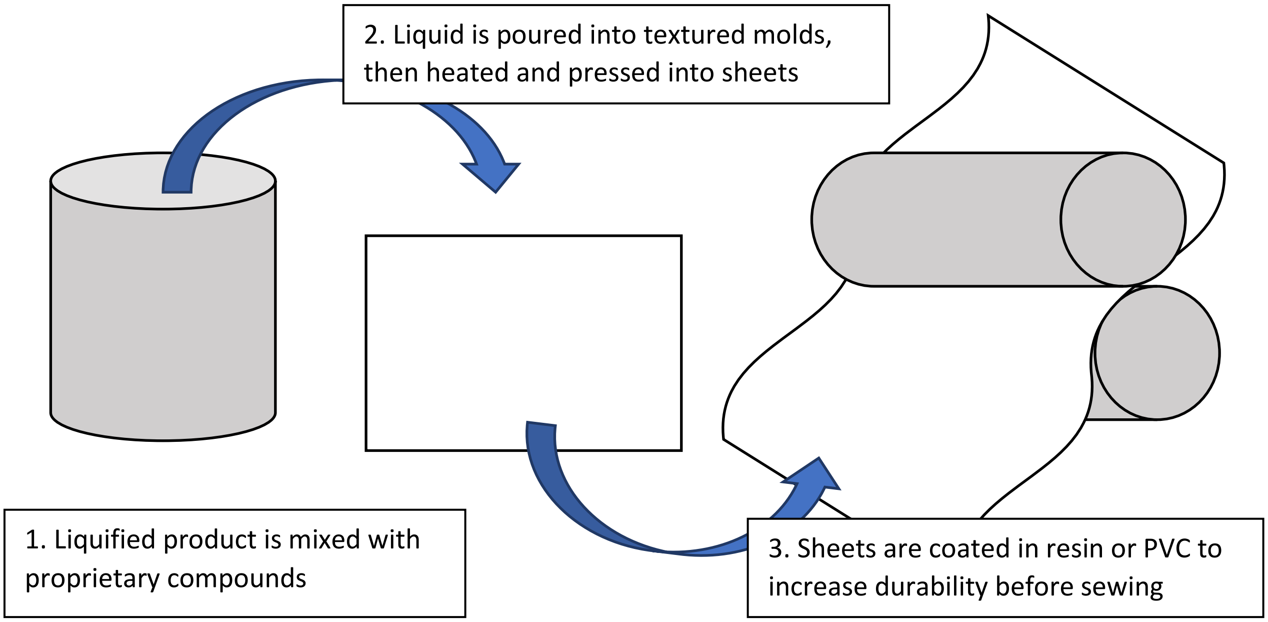

Figure 19. The vegan leather process.

Transportation

	Source	Processing	Primary Market
Smartfiber AG	Iceland	Austria	U.S., U.K., Germany, China and Hungary
Soarce	Chile, Caribbean	Orlando	U.S.
Carbonwave	Mexico, Caribbean	Mexico	Not on the market yet

Cost

The companies evaluated in this study did not want to disclose the cost of supplied sodium alginate used in their product, nor the cost of production. All admitted that their textile is more expensive than traditional alternatives, but still competitive with their target markets. Soarce describes their leather as a premium product. According to their marketing team, premium leather sells for $60-$120 per square meter, and their seaweed alternative will range from $75-$80 per square meter. The mango leather produced by Fruit Leather Rotterdam is also priced at $75 per square meter. Another notable company in the vegan leather industry, Piñatex, sells their pineapple leather at $62 per linear meter, which calculates to roughly $40 per square meter.

No wholesale price could be found for SeaCell fabric, although the brands using their material are high-end. It should be assumed that the additional cost of adding seaweed to the lyocell process makes it more expensive than other cellulose fabrics made with 100% eucalyptus or bamboo. Calida, one of the retailers of SeaCell fabric, sells T-shirts made with SeaCell and traditional lyocell blend for $60 each.

Performance

Soarce claims the following properties for its material: heat shielding, fire resistant, 97% shielding of UVA & UVB, naturally white without dye or bleach, anti-microbial. No studies have been provided to support these claims.

Smartfiber AG claims that its SeaCell fiber is 50% more breathable than cotton, two times stronger when dry and three times stronger when wet, moisture wicking, UPF 50, and produces no microfibers in the wash.[54] Smartfiber AG also claims that nutrients from the seaweed fiber are absorbed into the skin by contact, with a 22% drop in effectiveness after 50 washes. Smartfiber AG's SeaCell fabric is certified as 'home compostable' by TÜV AUSTRIA and certified as biodegradable by Thuringian Institute for Textile and Plastics Research (TITK).

Technical data

Cellulose fiber with incorporated seaweed (Ascophyllum nodosum) produced according to the modified viscose and lyocell process. Fibre composition in conditioned state (% by weight):

SEACELL Lyocell

Cellulose	≥ 85 %
Seaweed powder (~19 % measured in volume)	4 %
Fiber finish	0.32 %
Moisture	≤ 12 %
Appearance	light brown

Average textile physical fiber data:

Titer	dtex	1.7	6.7
Cut length	mm	38	60
Tenacity dry	cN/tex	29	21
Elongation dry	%	11.2	9
Tenacity wet	cN/tex	25	17
Elongation wet	%	16.1	14
BISFA wet modulus	cN/tex/5%	7.6	5.5

SEACELL Modal

Cellulose	≥ 83 %
Seaweed powder (~19 % measured in volume)	4 %
Fiber finish	0.3 %
Moisture	≤ 12 %
Appearance	light brown

Average textile physical fiber data:

Titer	dtex	1.7
Cut length	mm	38/60
Tenacity dry	cN/tex	≥ 25
Elongation dry	%	11-14
Tenacity wet	cN/tex	≥ 13
Elongation wet	%	11-14
BISFA wet modulus	cN/tex/5%	≥ 4

Figure 20. Smartfiber AG technical specifications for SeaCell (Credit: SmartFiber AG)

Lifespan

The lifespan of clothing depends on the owner and the type of garment and can often pass through multiple owners before ending up in a landfill, making this difficult to measure. A 2015 study in Norway found that people kept their garments 5.4 years on average.[55] This study encompassed a range of ages and garment types, although the nationality and culture of the subjects was homogenous.

Common estimates for lyocell in a landfill say that it biodegrades within six months to two years. A study by students at the Scripps Institution of Oceanography concluded that lyocell biodegrades in a marine environment in less than three months.[56] Research is lacking on vegan leather biodegradation. Vegan leathers that contain some percentage of plastic degrade much slower and are not compostable.

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[54] "SMARTFIBER AG | SEACELL."
[55] Laitala, "Consumers' Clothing Disposal Behaviour – a Synthesis of Research Results."
[56] Royer et al., "Degradation of Synthetic and Wood-Based Cellulose Fabrics in the Marine Environment."

Emissions considerations

Scope 1, 2 and 3 emissions

Scope 1 emissions are from sources that an entity owns or controls directly. Scope 2 emissions are caused indirectly by energy sources that produce the energy the entity purchases and uses. Scope 3 emissions are not produced by the entity itself and are not the result of activities from assets owned or controlled by them but by those that it is indirectly responsible for up and down its value chain.

The factory that produces Smartfiber AG's SeaCell fabric plans to run on 100% renewable electricity by 2024, although the Scope 3 emissions of sourcing the eucalyptus and seaweed will still account for roughly 53% of their self-reported emissions in the value chain.[57] Lenzing has received multiple Canopy audits of their emissions, the most recent of which can be reviewed here: [Lenzing Canopy Style Audit 2022.]

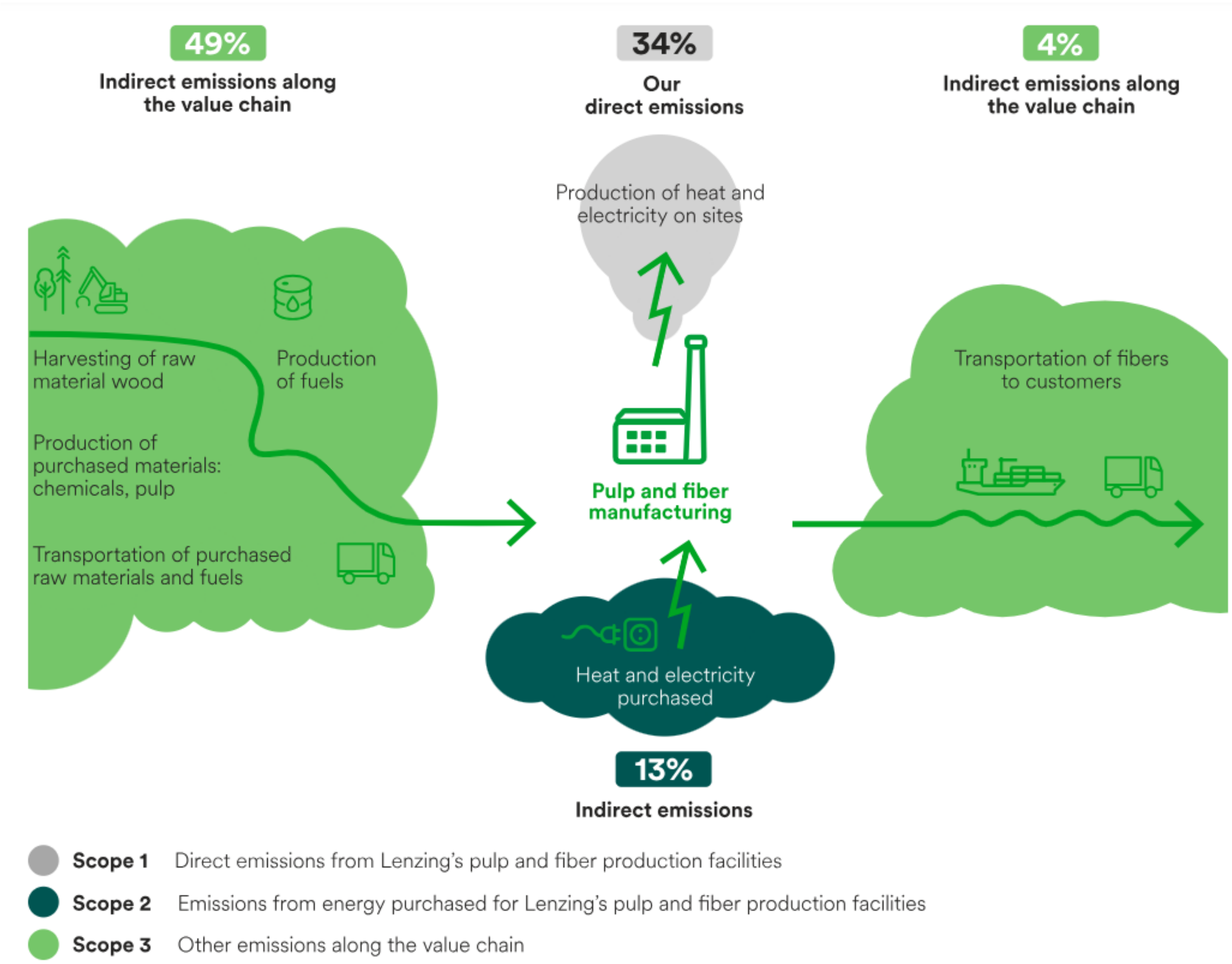

Figure 21. Lenzing AG's self-reported emissions scopes (Credit: Lenzing AG)

[57] "Www.Lenzing.Com.Pdf."

Water use

According to the World Wildlife Fund (WWF), the production of one average cotton T-shirt consumes up to 2,700 liters (713 U.S. gallons) of water.[58] Multiple sources suggest that Lyocell uses less than half that amount, but none of the companies included in this report have provided exact figures. A 2010 UNESCO report calculates the water footprint of leather as 17,100 gallons per cow. One cow produces around 5 m^2 of leather, for a total footprint of 3,420 gallons of water per m^2. Since seaweed leather doesn't require irrigation or tanning, the water footprint is significantly lower, though it is not possible to calculate without more specific details on the manufacturing process used by the companies in this study.

Opportunities and challenges

The seaweed textile industry is still very small, and the textiles are marketed as premium products due to the cost of production. There are not sufficient companies operating at a commercial scale to replace the demand for traditional leather or cotton. The supply chain for seaweed textile is long, mostly due to downstream transportation and the distance between Asian clothing factories and American and European retailers. Soarce reports that the major barrier to scale is funding — investors have lost interest in seaweed textiles because very few companies have yet produced tangible products.

[58] "Help Us Save the T-Shirt."

Plastic

Overview of product

Bioplastics can fall into several categories: PE (polyethylene), PET (polyethylene terephthalate), PA (polyamides), PHA (polyhydroxyalkanoates) and polylactic acid (PLA). Additionally, bioplastics can either be biodegradeable or simply biobased. Biobased plastics are 'drop-in', meaning they use the same technical process and equipment as conventional plastics, but they are made with plant-based oil instead of petroleum. As of 2022, biobased, non-biodegradable plastics altogether make up for more than 48 % of the global bioplastics market.[59]

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)

Seaweed bioplastics are largely PLA or cellulose based, depending on the type of seaweed and process used. There are fewer than 100 companies working on seaweed bioplastics in the world, most of them are in the research and development phase.[60] The companies reviewed in this section of the report are Rhodomaxx, Sway, Loliware and NotPla.

[59] EUBIO_Admin, "Market."
[60] "Phyconomy Seaweed."

Company	Product	Development Stage
Rhodomaxx	Plastic Film	Pilot / Demonstration, Malaysia
Sway	Plastic Film, resin pellets	Pilot / Demonstration, USA
Notpla	Rigid plastic, paper, paper coating, film, edible film	Pilot / Scale-up, U.K.
Loliware	Straws, injection-molded utensils, resin pellets	Scale-up, USA

To supplement industry insights from the companies mentioned, this report also draws on LCAs of seaweed bioplastics:

Institution	Study	Scope
University of California, Santa Barbara	Seaweed: The Solution to Pollution? A Comparative Life Cycle Assessment of LDPE and Algal Flexible Film Packaging	Cultivation through production
Aalborg University, University of Copenhagen	Life Cycle Assessment of pilot scale production of seaweed-based bioplastic	Cultivation through degradation
Jiangsu University, Tanta University, Harbin Institute of Technology, University of Patras, Sapienza University	Bioplastic production in terms of life cycle assessment	Cultivation through degradation
Ecole Polytechnique Fédérale de Lausanne, Paul Scherrer Institute	Algal cellulose, production and potential use in plastics: Challenges and opportunities	Cultivation through degradation

Sources and species

Red, green or brown seaweed is suitable for bioplastic, depending on the compounds being targeted. The common genera used in bioplastic are *Ulva, Kappaphycus, Gracilaria, Gelidium* and *Sargassum.*[61]

Green seaweed, compared to red or brown, tends to have more cellulose and stores carbohydrates as starch. *Ulva* has a high carbohydrate content, potentially making it useful for starch-based PLA film. None of the companies reviewed in this section are using green seaweed.

Brown seaweed tends to have the highest levels of alginate. Alginate and fucoidans are the main chemicals being extracted when brown seaweed is used in plastic production. The companies producing plastic from brown seaweed are mainly using sargassum. More common brown seaweeds, like *Laminaria* and *A. Nodosum*, are more valuable as food and pharmaceutical additives. Notpla uses brown seaweed but does not disclose which species.

[61] Zanchetta et al., “Algal Cellulose, Production and Potential Use in Plastics.”

Red seaweed is commonly chosen for its high levels of agar and carrageenan, which are useful in plastic production because of their film-forming properties. The companies in this report using red seaweeds are Rhodomaxx (*Kappaphycus*) and Sway (*Gracilaria*). Rhodomaxx grows *Kappaphycus* in Malaysia, claiming that it is commercially scalable and has the right cellulose structure for their process.[62] Sway sources *Gracilaria* from suppliers in Chile and Indonesia, specifically for the agar content[63], and is studying the potential for using other types of seaweed. Notpla also uses red seaweed but does not disclose which species.

Cultivation and harvesting

The seaweed used by Rhodomaxx and Sway are farmed. Rhodomaxx shared that there was nothing new or different about how their seaweed was cultivated. They report that in southeast Asia, seaweed farming is well established and lean already — even the buoys are recycled bottles. An LCA of pilot-scale seaweed plastic by Ayala et. al. measured a common cultivation method, seeded longlines. In this process, seaweed spores are settled into ropes and incubated in tanks, which contain filtered seawater and a growing solution containing nutrients and pesticides to support their growth.[64] After four to six weeks of growth, the inoculated seeding lines are then rolled around larger ropes and placed into the ocean in horizontal lines strung between buoys. A similar method, called direct seeding, skips the onshore incubation step.

Drying and extraction

Sway reports that their suppliers sun-dry the harvested seaweed by simply laying it on the beach. The dried seaweed is then run through a three-step alkali extraction process to distill the phycocolloids. The largest energy input during drying and extraction is probably the heating of the alkali baths.

The result of the agar extraction process is a food-grade substance. Since bioplastics only require a semi-refined agar powder, Sway is currently working with their suppliers on ways to simplify the extraction process and reduce energy use. They report that their suppliers so far have been open to making a less refined product because it is cheaper and reduces their carbon footprint slightly. However, the process will look largely similar. Logistics are complicated when it comes to overhauling the extraction process.

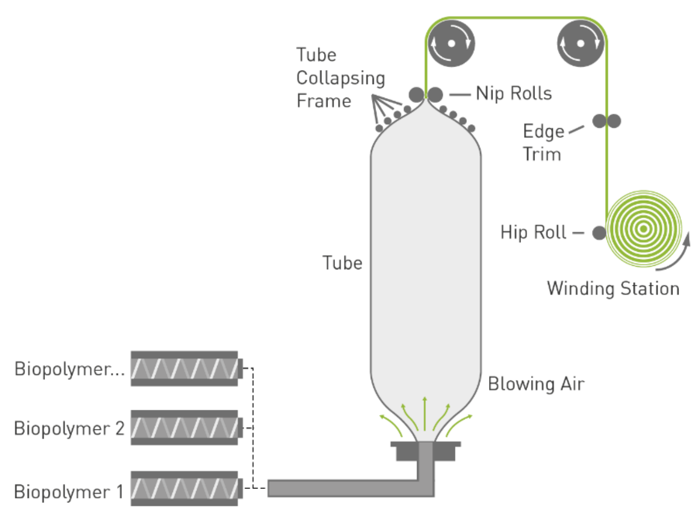

Figure 23. Blown film extrusion process (Credit: NUREL Biopolymers)

Processing

Seaweed extract, whether it's alginate/cellulose from brown seaweed or agar/cellulose from red seaweed, can be turned into plastic easily. Mixing the

[62] Chung Ngin and Faizal, Interview with Rhodomaxx.
[63] Mayes and Pace, Interview with Sway.
[64] Ayala, Thomsen, and Pizzol, "Life Cycle Assessment of Pilot Scale Production of Seaweed-Based Bioplastic."

powder with water and heating it produces a thick gelatin that can be spread into sheets and dried into film.[65] The result is brittle, so many plastic film manufacturers add glycerin to make it more flexible.

The plastic produced through this method is thermoplastic, meaning that it can be re-shaped by heating. Sway's flagship method used for testing is a manually produced film (solution-based cast), although they report that by the end of 2023, they will have developed a plastic that will be 'drop-in', allowing it to be used in conventional plastic production machinery (typically blown-film extrusion).

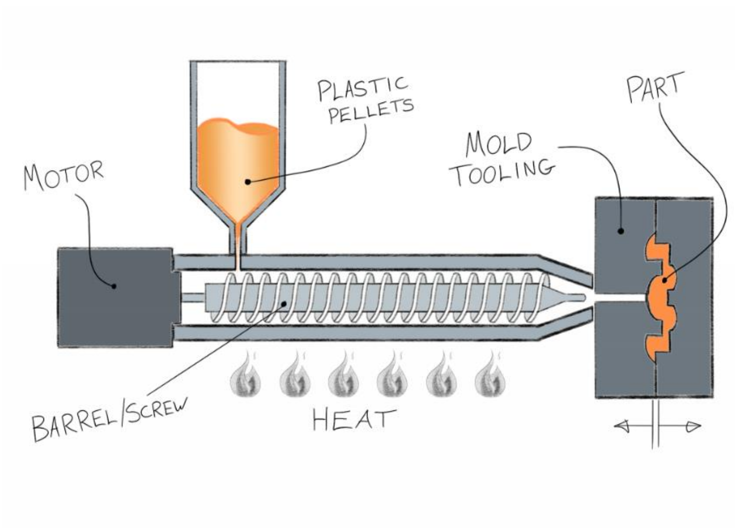

Figure 24. Plastic injection molding process (Plastic Injection Molding Process Guide 2019: Full Process Explained [cdn-inc.com])

Loliware's product is already drop-in – they produce resin pellets made from seaweed powder and seashell powder (chitin) which can be used in traditional injection-molding equipment for a more rigid plastic. For instance, they are currently launching a line of utensils in the U.K.

Transportation

Sway reports that their seaweed is dried and processed within 50-100 km of where it is farmed. The processed agar is then shipped internationally to get to Sway's plastic production plant.

	Source	Processing	Primary Market
Sway	Chile, Indonesia	California	U.S.
Rhodomaxx	Malaysia	Malaysia	Malaysia
Notpla	Chile, Scotland, France, Spain, Indonesia, Philippines, Japan	U.K.	U.K.

Cost

Agar as a feedstock is not cost competitive with plastic resin pellets. Depending on the source, it can range from $4/kg (southeast Asia) to $20/kg (U.S.). Sway asserts that in a couple years, based on projections, bioplastics will be competitive with conventional PLA plastics. They think U.S. regulatory pushes for bioplastics combined with the rising cost of PLA will make it a more competitive market.

[65] *How To Make A Seaweed Bioplastic - The Basics*.

NotPla shared that although their feedstocks are around £4 per kg, the market for their products within the U.K. is bolstered by the EU's 2019 Directive on Single-Use Plastics, which banned several single-use items from the market starting in 2021.[66] Starting July 2021, Member States were banned from offering certain single-use plastic items (e.g. cutlery, plates, stirrers) on the market, and marking requirements have been made law. Loliware chose the U.K. as their primary market for their seaweed utensils for this exact reason.

Figure 25. Mandatory EU label for plastic cups, beginning in July 2021 (Credit: SUPs marking specifications [europa.eu]).

Performance

Sway reports that their product testers are enthusiastic about using seaweed bioplastic, but they can tell there's a difference between seaweed film and conventional plastic. They report that there is still a need for moisture resistance in the product. The best and most common application of seaweed plastic on the market is film-grade, suitable for food or clothes packaging.

Lifespan

Notpla mentioned that they do not use the word 'sequestration' when they talk about their environmental impact, because they're designing home-compostable alternatives to single-use plastic. This is true of Sway and Notpla as well. The goal is to keep plastic out of landfills and oceans.

Once used, the decomposition rate of seaweed plastics varies depending on the product and the compost conditions. The pilot-scale LCA carried out by Ayala et. al. determined that 42% of the sequestered CO_2 contained in the plastic would be stored in a composting end-of-life scenario but would eventually be released. Their study didn't have a long enough timeline to determine exactly how long that delayed release would take. During decomposition, methane would also be released. In industrial composting scenarios, the methane from anaerobic digestion could be captured and used. In a home composting scenario, it would simply become GHG. Sway claims that based on the chemical profile of their product it would produce less GHG during decomposition than, say, a banana peel.

[66] "Directive (EU) 2019/904 of the European Parliament and of Th... - EUR-Lex."

Emissions considerations

The main energy inputs during the production process of seaweed bioplastic are the electricity used for heat when drying the seaweed, extracting the agar/alginate and during the plastic extrusion.

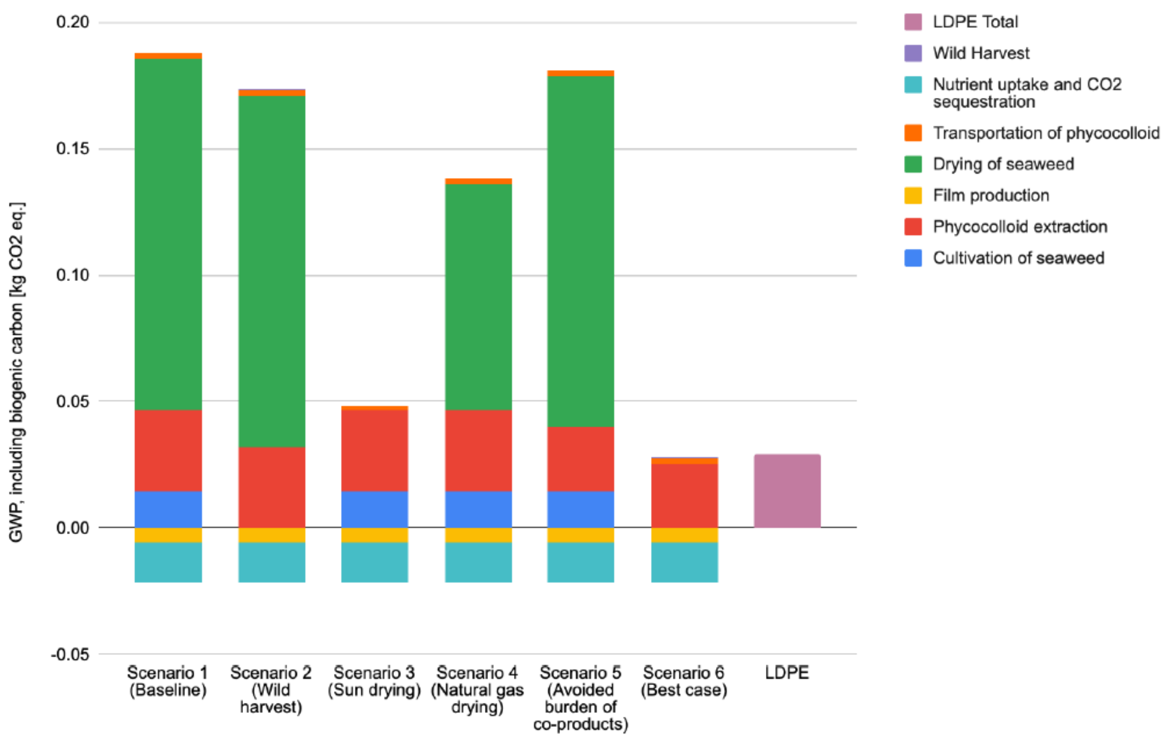

Figure 26. global warming potential of seaweed plastic vs. LDPE, comparing different methods of drying (Credit: Seaweed: The Solution to Pollution? A Comparative Life Cycle Assessment of LDPE and Algal Flexible Film Packaging | UCSB Bren School of Environmental Science & Management).

The LCA carried out by the University of California, Santa Barbara found a significant energy reduction when seaweed was sun-dried instead of dried with electricity from the grid.[67]

Understandably, the largest footprint for commercial operations remains Scope 3. Notpla reports their 2022 Scope 3 emissions make up 99.5% of their overall footprint. The raw material that they source from 7 different countries makes up 56% of their Scope 3 emissions, with transportation and delivery of that material constituting another 22.8%.[68]

Opportunities and challenges

In the LCA conducted by Ayala et. al., the carbon emissions for 1 kg of wet-weight (WW) seaweed was 0.082 kg CO_2-eq, which falls within the range of other similar LCAs.

[67] "Seaweed: The Solution to Pollution? A Comparative Life Cycle Assessment of LDPE and Algal Flexible Film Packaging | UCSB Bren School of Environmental Science & Management."
[68] "Notpla-Impact-Report-2022.Pdf."

The main impact of seaweed-based alternatives to plastic lies in their ability to offset emissions from traditional plastic production, and to reduce landfill waste and marine microplastic generated by single-use plastics. Notpla's 2022 impact report claims that 4.4 tonnes of traditional plastic were displaced by using their products (seaweed plastic-coated take-out boxes), which translates to 19 tonnes of CO_2 equivalent.

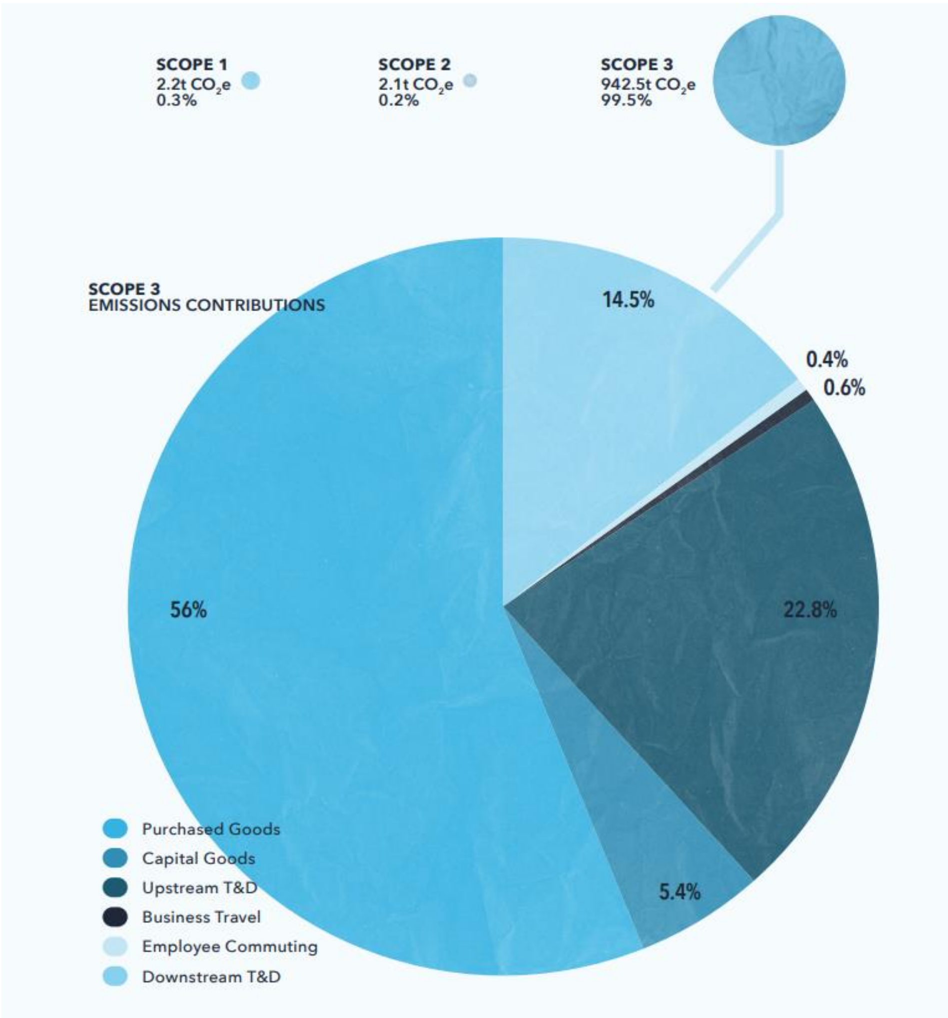

Figure 2722. Notpla 2022 impact report; Scope 3 emissions (Credit: NotPla).

Current compostable plastics are commonly made with corn or sugarcane. There is some debate whether this will cause land-use change issues if consumer demand and policies like the EU Single-Use Plastic Directive continue to improve market conditions for bioplastics. Seaweed and food waste are two viable bioplastic feedstocks that do not directly compete with current land use.

Construction materials

Overview of product

Seaweed biomass has potential as a construction material by using cellulose, alginate, or ash from seaweed as a fiber fill or binding agent in a variety of applications. A 2021 systematic review conducted by J.A. Rossignolo et al. identified 31 studies using different species of seaweed in the form of fibers or additive in panels, polymer composites, pavement and adobe; ash in Portland cement composites; and direct application of algae on roofs and facades.[69] This report draws on those studies, alongside available data on a couple companies attempting commercialization:

Company	Product	Development Stage
BlueBlocks	Medium Density Fiberboard (MDF)	Research and development / pilot
BlueGreen	Adobe bricks	Commercial in Mexico
AgriSea	Nanocellulose	Research and development /pilot
Grupo Dakatso de México (Dakatso)	Concrete blocks	Small-scale commercial
NeptuTherme.	Insulation	Small-scale commercial

Sources and species

Because the materials that can be made from seaweed and the methods for producing them are heterogenous, it is not possible to pinpoint one species. The table below summarizes the application, species and source for the studies listed in the systematic review by J.A. Rossignolo et al.

Product (# of studies)	Application	Species	Seaweed source
Panels (4)	MDF, Particleboard	*K. alvarezii, Gracilariopsis longissimi, Posidonia oceanica*	Greece, Mediterranean coast, Spain
Polymeric composite (11)	Fiber	*L. japonica, Ulba clathrate, Enteromorpha crinite, Ulva Linnaeus, Ulca armoricana, P. oceanica, Gelidium corneum*	South Sea of Korea, Baltic Sea, France, Spain, Mediterranean coast, Morocco, Portugal
Portland cement composites (7)	Fiber, Additive, Ash	*Cladophora* sp. Kützing, *Kappaphycus alvarezii, Gracilaria* sp. Greville	Turkey, Malaysia, Singapore
Pavement (4)	Additive, Fiber	*Sargassum* sp. C.Agardh, brown algae (unidentified), *P. oceanica*	Singapore, Mexico, Mediterranean coast
Adobe (3)	Additive, Fiber	Brown algae (unidentified), *Laminaria hyperborea*	United Kingdom, Scotland, Mexico
Roof and Façade (2)	Roof cover, Facade	*Zostera marina* Linnaeus and *Z. noltei* Hornemann	China

Of the companies surveyed in this report, most are using brown seaweed:

[69] Rossignolo et al., "Algae Application in Civil Construction."

Company	Species	Source
BlueBlocks	Undisclosed / multiple	Holland
BlueGreen	*Sargassum*	Quintana Roo, Mexico
AgriSea	Spiny Kelp	New Zealand
Grupo Dakatso de México (Dakatso)	*Sargassum*	Mexico
NeptuTherme.	*P. oceanica*	Albania and Tunisia

Cultivation and harvesting

The companies in this report all use wild collected seaweed. BlueGreen uses Sargassum that washes up on beaches in Quintana Roo — Business Insider reports that they collect 40 metric tons per day (typically between April and October). NeptuTherm uses Neptune Balls that wash up on beaches in the Mediterranean, collected by hand. Since sargassum washes up in such large quantities, it is usually removed manually using pitchforks, or mechanically with front-end loaders.

Figure 238. Sargassum removal in Mexico (Credit: Dakatso).

Dakatso's main business is contracting with beach owners in Mexico to prevent sargassum wash-up. They use GIS to track sargassum movement at sea, and then install barriers offshore to catch the sargassum. The barriers are made of nylon mesh and a polyethelene flotation system. It is anchored to the seafloor using underwater drills powered by the Stanley HP8BA, HP8BD, and HP8BM hydraulic power units.

Figure 29. Dakotso sargassum collector vessel (Credit: Dakatso).

After the sargassum mat has been blocked by the barrier, Dakatso uses a boat with a conveyor belt that collects the sargassum and dumps it into nylon net bags that hold 1 meter^3 of sargassum. The harvester can hold eight of these bags, so smaller vessels (usually three at a time) follow the harvester to collect the filled bags — up to five at a time — and bring them to shore. This process allows Dakatso to collect 15-20 tons of sargassum per hour.

The harvester appears to be patented by Dakatso, but the name ‘Swega’ appears on the control console of the ship — Swega is a Mexican company that manufactures street sweepers and line painters for road construction. Dakatso also uses a conveyor belt that loads sargassum from beaches into either dump trucks or trailers pulled by a tractor.

After collection, Dakatso uses an on-site shredder to reduce the volume of the collected sargassum by 20% before further transport. They use a 20-horsspower electric shredder powered by a 30kw diesel generator, capable of processing 10 tons of sargassum per hour. The generator can run 8-10 hours per day for three days, or up to 250 hours per month.[70]

Figure 30. Dakatso electric shredder (Credit: Dakatso).

Drying and extraction

BlueBlocks and AgriSea create their products from the fiber waste created by other seaweed products. In the case of BlueBlocks, the fibers are left over from alginate extraction, which requires the seaweed to be dried before processing (see Plastics). In the case of AgriSea, the fibers are left over from biostimulant processing, which doesn’t necessarily require drying (see Biostimulants).

BlueGreen makes adobe using shredded sargassum. It is unclear how they dry their sargassum, but the United Nations Development Programme report on their process makes no mention of any drying equipment, suggesting that it is sun-dried.

There is no necessary extraction process for any of these materials.

Company	Product	Drying
BlueBlocks	MDF	Fibers used are leftover waste from BlueBlocks’ alginate extraction
BlueGreen	Bricks	Not specified
AgriSea	Nanocellulose	Feedstock is leftover waste from AgriSea’s biostimulant production
Dakatso	Concrete	Sargassum is ‘UV dehydrated’ according to Dakatso. Based on a video of their process, this appears to be sun — drying on plastic sheets.
NeptuTherme.	Insulation	Neptune balls air — dry or sun — dry on the beach before collection.

[70] “Grupo Dakatso de México S. A. de C. V. - Innovadores Por Naturaleza.”

Processing

The processing requirements depend on the product in question. In most cases, the seaweed only needs to be shredded to the right size and mixed with other ingredients in the right proportion. The processing for concrete, insulation and MDF using seaweed are fairly like the industry standard.

Adobe and concrete

BlueGreen's production process has evolved — originally it was made in a similar manner to adobe, using shredded sargassum, compost and clay. A business insider report from July 2023 explained the current process[71]: the dry sargassum is ground into a powder with rocks, and then mixed with dirt left over from construction sites. The dirt and sargassum is shoveled through a sieve and then mixed with water and other natural materials. The other materials are a secret, but the ratio of sargassum in the bricks is about 40%. The bricks are pressed in an Adopress machine manufactured by Ital Mexicana S.A.[72], and retrofitted by BlueGreen. Based on photos, it appears to be the 2400 model and can produce 3000 bricks per day. After coming out of the machine, the bricks are sun-dried.

Dakatso runs a more scaled-up process than BlueGreen. After being shredded using an electric shredder and dried in the sun, it is mixed into concrete at a concrete plant. Based on a promotional video released by Dakatso[73], they are using machinery that seems like the Ital Mexicana S.A. Hidramatic[74]. This plant allows them to produce cinder blocks, pavers, molded concrete, or poured concrete. Dakatso does not publicize their mixture, but it appears to be standard concrete with some percentage of pulverized sargassum added.

Insulation

NeptuTherm uses Neptune Balls — clumps of Neptune grass (*Posidonia oceanica*) that wash ashore in fist-sized balls. The clumps are dried and shaken to remove sand, and then they are shredded to break up the balls and prevent re-clumping. The shredded seagrass is packed into plastic bags and can be stuffed by hand or blown using a standard insulation blower. It is uncertain what equipment they use for drying or shredding.

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[71] Bieber, "This Mexican Entrepreneur Builds Houses out of Bricks Made from Invasive Seaweed. Then He Gives Them Away."

[72] "Ital-Adoberas.Pdf."

[73] *SargaCreto - Concreto Hecho a Base de Sargazo*.

[74] "Ital-Hidramatic-615---1215.Pdf."

Figure 241. BlueGreen's retrofitted Ital Mexicana S.A. Adopress (Credit: Dakatso).

Around 2018 AgriSea, a New Zealand biostimulant producer, was partnering with Scion, a government owned forestry research company, to produce nanocellulose hydrogels. After three years of research, the technology for producing the hydrogel was licensed to AgriSea, and they are currently building a facility for mass production[75]. Although AgriSea/Scion's process is not publicly available, one possible method is described by Berglund et. al.[76]:

1. Fresh seaweed is cut into smaller pieces prior to purification by bleaching with $NaClO_2$ (1.7%) in an acetate buffer (pH 4.5) at 80 degrees C for 2 hours.
2. After purification, the material is washed until a neutral pH is achieved.
3. The purified seaweed is further processed in an MKZA6-3 ultrafine friction grinder (Masuko Sangyo Co., Ltd., Kawaguchi, Japan) equipped with coarse silica carbide (SiC) grinding stones to separate the cellulose fraction into nanofibers. The fibrillation process requires an energy of 1.0 W·h/kg.
4. Alginate Cellulose Nanofiber Aerogels are prepared by ice templating; a 1.0 wt% water suspension is stirred for 30 minutes and defoamed with a planetary mixer (THINKY ARE-250, Thinky Corp., Tokyo, Japan) for three minutes prior to being poured inside a polytetrafluoroethylene mold and unidirectionally frozen at a constant cooling rate of 40 degrees C per hour starting from room temperature. Cooling is provided by a liquid nitrogen bath, which is in contact with the copper bottom plate of the mold via a copper rod. The temperature of the bottom plate is controlled using a proportional integral derivative-controlled heating element attached to the top part of the copper rod.

75 "Nanocellulose Hydrogel I AgriSea New Zealand."
76 Berglund et al., "Seaweed-Derived Alginate–Cellulose Nanofiber Aerogel for Insulation Applications."

5. The aerogels are immersed in an ethanol/ $CaCl_2$ solution at room temperature for five hours for crosslinking. The solutions can be prepared at 1, 5 and 10 wt% $CaCl_2$ to obtain different degrees of crosslinking.
6. The aerogels are thoroughly rinsed with ethanol to remove $CaCl_2$ and dried in a vacuum oven at 24 degrees C overnight to remove ethanol.

MDF and particleboard

Medium-Density Fiberboard (MDF) is a simple production process; dried and ground seaweed fibers can be mixed with sawdust and adhesive and hot-pressed into sheets. This can be done using standard MDF processing equipment. The ratio of seaweed, sawdust and adhesive is dependent on the manufacturer's discretion, though studies have found that a mixture of half sawdust and half seaweed is sufficient to meet international durability standards. In MDF production 11-12% adhesive is common.

Particleboard is produced similar to MDF, although it uses wood pulp or chips instead of sawdust, making it cheaper to produce. Seaweed particleboard like SeaWood (BlueBlocks) uses larger seaweed fibers left over from other seaweed applications, mixed with wood pulp.

Figure 25. BlueBlocks' seawood fibreboard (Credit: BlueBlocks).

Transportation

The only materials in this report that are commercially available are Dakatso's Sargacreto, BlueGreen's Sargablock, and NeptuTherm. The table below lists sourcing and primary markets for each product.

	Source	Processing	Primary Market
Sargacreto (Dakatso)	Cancun	Cancun	Cancun
Sargablock (BlueGreen)	Cancun	Cancun	Cancun
NeptuTherm	Albania and Tunisia	Germany	Germany

Performance

Cement

Mixing sargassum into cement or concrete for bricks or for pavement is generally observed as an improvement. The systematic review by J.A. Rossignolo et al. noted a few different methods for adding seaweed; ash from burned seaweed, alginate powder, and shredded seaweed fibers (this third method is the one used by BlueGreen and Dakatso).

Seaweed additive	Ash	Alginate	Fibers
Observed qualities	Lower water permeability	Reduction in water absorption and a significant increase in compressive and tensile strength	Increased the bending stress of concrete by 2.7 times

Dakatso claims that the algae in their concrete allows marine life to grow on it, making it useful for artificial reef construction[77], although this claim has not been scientifically tested.

MDF and particleboard

The systematic review identified a few studies which tested different ratios of seaweed, sawdust and adhesive against various national standards for MDF and particleboard. Although 100% seaweed fiber is not strong enough for any of the standards, the treatments using 50% sawdust, 50% fiber from *K. alvarezii*, and 12% of adhesive complied with the Japanese Industrial Standards for panels (JIS A 5905-2003).[78]

Insulation

NeptuTherm boasts the following properties:

- Heat storage capacity of up to 2,599 J/kg· K. This performance is approximately between 20% and 300% higher than the values of all other insulation materials
- Primary energy consumption of 37 kWh/m³ (stuffed or poured) to 50 kWh/m³ (blown in) and thus up to 30 times lower than other competitors
- Excellent sound insulation
- High mold resistance according to class 1
- Building material class DIN 4102-B2 (normally flammable)
- The ability to absorb, buffer and release more than three times its own weight in water vapor without any deterioration in the thermal insulation capacity afterward
- Thermal conductivity λD of 0.039 W/(m· K), the rated value λ according to DIN 4108 is 0.046 W/(m· K), each with an installation density of 65-75 kg/m³
- Rot resistance, as it does not contain any proteins
- Compostable

[77] "'Sargacreto', the New Construction Material Made of Sargassum - The Yucatan Times."
[78] Yushada et al., "Mechanical Properties of Particleboard from Seaweed (Kappaphycus Alvarezii)."

Nanocellulose aerogels were produced by Berglund et al. as a potential green insulation material. They found its insulating properties to be competitive with other natural insulation materials, with the added benefit of being naturally flame retardant.[79]

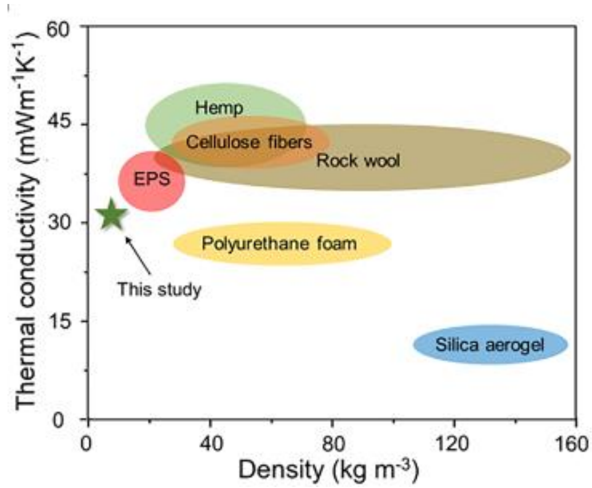

Figure 263. Ashby plot of thermal conductivity as a function of density for commonly used insulation materials, silica aerogels, and the results of Bergland et al.'s study (Credit: Bergland et al.).

Lifespan

Seaweed used in construction applications has the longest potential lifespan of any product category in this report, meaning long-term lock-in of sequestered GHGs. In addition, seaweed used in concrete blocks has the potential for re-use. BlueGreen reports that if their sargablocks break, they can be ground up and re-used to make new ones.

Opportunities and challenges

Sargassum-based concrete is the most commercially active product in this category, because the primary feedstocks (sargassum and dirt) are so abundant and cheap (Dakatso and BlueGreen make a profit by collecting sargassum from beaches). On top of that, the production process is low cost. In the case of BlueGreen, the profit comes from collecting sargassum and all the houses they build from the bricks are donated to low-income families free of charge. Replicating this business model with farmed seaweed or in other countries might not be feasible.

The opportunity presented by seaweed as a construction material is that waste seaweed can be used as a feedstock. As a cement additive or MDF additive, for instance, producers can use seaweed waste leftover from alginate extraction, biostimulant production, or biorefining. Achaby et. al produced nanocellulose from both raw red seaweed and red seaweed waste left over from agar extraction. The waste produced a better yield.

This report considered nanocellulose's potential for insulation, but nanocellulose has dozens of applications, ranging from food/pharmaceutical additive to diapers to bendable substrates for solar panels and computer components. It is unclear which AgriSea intends to pursue with their nanocellulose.

The small number of companies producing seaweed construction materials suggests that this is not a mechanically or economically scalable use for seaweed on its own. However, the potential to use waste seaweed from other primary applications to produce low-cost construction materials is worth exploring further.

[79] Berglund et al., "Seaweed-Derived Alginate–Cellulose Nanofiber Aerogel for Insulation Applications."

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