# Oilgae Guide to Fuels from Macroalgae

A Report by Oilgae

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# Preface

In recent years, there has been considerable interest in obtaining biofuels from algae, owing to the superior aspects of algae in terms of yield, growth environment and the possibility to couple biofuels production with bioremediation.

Most efforts and research have been conducted with a focus on microalgae. Microalgae have been the preferred starting point owing to their fast growth and high oil content of selected strains. In addition, microalgae can grow in a range of media, from fresh water to marine water to wastewater and sewage.

Deriving fuels from microalgae, however, presents some significant challenges. There are high costs attached to cultivation and harvesting of microalgae, rendering them economically infeasible as a biofuel feedstock with current technologies and processes. In addition, the vulnerability of microalgae to contaminants and elements necessitates the use of sophisticated systems such as bioreactors which increase the cost and complexity of operations.

The macroalgae route to biofuels presents an equally interesting opportunity as that offered by its microalgae counterpart. While macroalgae do have limitations on the environments of growth and in terms of the lipid compositions, they present significant advantages in their ease of cultivation and harvesting, and the subsequent low costs for each of these.

Macroalgae to biofuels is currently a much less researched topic than the microalgae to biofuels route, but interest in this topic is accelerating. This report, with its clear focus on macroalgae to fuels, hopes to fulfill the need of researchers and industry for a guide to this important topic.

This report was prepared by Oilgae, an authoritative source of information and data for the energy from algae domain. The report was last updated in April 2010.



# List of contents

1. Introduction
1.1 Introduction to Macroalgae
1.2 Comparison between Macroalgae and Microalgae
1.3 Why Macroalgae for Fuel Generation?
2. Various Types of Macroalgae & their Composition
2.1 Types of Macroalgae
2.2 Composition of Macroalgae10
3. Cultivation of Macroalgae 13
3.1 Introduction
3.2 Wild Seaweed Cultivation
3.3 Aquacultured Seaweed Cultivation
3.4 Feasibility of Cultivating Macroalgae on a Large Scale22
A Harvesting of Macroalgae 24
4.1 Introduction 24
4.2 Prominent Harvesting Methods
4.3 Methods Employed for Harvesting Specific Strains25
4.4 Harvesting Equipments Employed27
4.5 Macroalgae Harvesting - Highlights29
5. Yield of Macroalgae 30
6. Products from Macroalgae 33
6.1 Introduction
6.2 Energy Products from Macroalgae



6.3 Non-Energy Products from Macroalgae	37
7. Cost and Economics	41
8. Advantages of Macroalgae	46
9. Challenges & Bottlenecks	48
10. Companies and Universities	50
10.1 Companies in Macroalgae to Fuel Efforts 10.2 Universities in Macroalgae to Fuel Research	50 55
11. Case Studies in Fuel Production from Macroalgae	62
12. Research and Experiments	68



# **Chapter 1 - Introduction**

- **1.1 Introduction to Macroalgae**
- 1.2 Comparison between Macroalgae and Microalgae
- 1.3 Why Macroalgae for Fuel Generation?

# **1.1 Introduction to Macroalgae**

Macroalgae or seaweeds belong to lower plants. They do not have roots, stems and leaves. Instead, they are composed of a thallus (leaf-like) and sometimes a stem and a foot. Some species of macroalgae have gas-filled structures to provide buoyancy.

Macroalgae are subdivided into three groups - red, green and brown macroalgae.

• Red Macroalgae

Red macroalgae come in a variety of shades of red due to additional red protein pigments. The red colour is not uniform and some species are purple, mauve, orange or even yellow. These pigments allow the red algae to grow at far greater depths than the green and brown algae. Red algae can occur down to 200 metres.

• Green Macroalgae

Green macroalgae get their colours from the photosynthetic chlorophyll pigments. They come in a variety of shapes including flat sheets, cylinders, and strings of beads, spheres, or hair-like filaments. Green algae are common in the intertidal zones and in shallow water as well as in some freshwater habitats, where light is plentiful.

• Brown Macroalgae

Brown macroalgae have additional pigments which mask the green chlorophyll. These pigments allow the brown algae to extend their range down into deeper waters because the pigments are more efficient than green chlorophyll in absorbing the sunlight down away from the ocean surface.

Macroalgae are one of the important sources of food, feed, chemicals and fertilizers. Some edible species of fresh seaweeds are cultivated and are commonly eaten in China and Japan. Apart from their use in food, fertilizer, animal feed, recently macroalgae have also been used for production of phycocolloids. Some of the intensively cultivated macroalgae include the brown algae *Laminaria japonica* and *Undaria pinnatifida*, the red algae Porphyra, Eucheuma,



Kappaphycus and Gracilaria, and the green algae Monostroma and Enteromorpha (Lüning and Pang 2003).

# **1.2 Comparison between Macroalgae and Microalgae**

Often, the terms "microalgae" and "macroalgae" are used in an attempt to distinguish between microscopic organisms such as phytoplankton and larger organisms such as seaweed or kelp. The biomass can be derived from both macroalgae and microalgae sources, which may represent an economically and environmentally sustainable renewable fuel source.

However, microalgae are being widely researched as a fuel (mainly biodiesel) since they have much more oil than macroalgae, and grow faster. In the case of macroalgae, they are being considered for the natural sugars and other carbohydrates they contain, which can be fermented to produce either biogas or alcohol-based fuels.

Parameters	Macroalgae	Microalgae
Size	Macroalgae can reach sizes of up to 60 m in length (Mc Hugh 2003)	Microalgae are very small plant-like organisms (+/- 1 to 50 $\mu$ m), which can be seen through a microscope
Physical structure	Macroalgae are composed of a thallus and sometimes a stem and a foot	Microalgae do not have roots, stems and leaves
Energy density	Medium	High
Biomass yield	Medium	High
Ease of cultivation	Macroalgae are cultured in natural environments such as ocean	Microalgae are cultured in photobioreactors or open ponds
Ease of harvesting	Easy	Difficult
Oil yield	Macroalgae produce only small amounts of lipids	Microalgae produce comparatively high amounts of lipids

The following table lists the major differences between microalgae and macroalgae.

# **1.2 Why Macroalgae for Fuel Generation?**

Until now, seaweed has been valued mainly as food, fertilizer, animal feed, and recently for a growing phycocolloid industry producing algin, agar and carrageenan. But it could also be a potential source of fuel, especially when you consider the amounts of "waste seaweed".



Wild seaweeds which grow along the coastal line due to heavy nutrient discharge many times wash up on the sea shores. These seaweeds will rot and begin to smell if left as such in the coastal areas. Collection and disposal of these seaweeds is a major burden for local governments along the coast. To give an example, China cleaned up around 100,000 tons the seaweeds in its coast during Beijing Olympic, 2008. These wild seaweeds are in fact an untapped source of energy and it is essential that steps are taken to utilize their potential. The use of seaweed as an energy source dates back to 1970. This was attempted through Giant Kelp Project in USA. Later the research attempts were made to produce various fuel sources like electricity, ethanol and methane from these seaweeds.

Though the use of macroalgae for energy production has received less attention so far than that for microalgae, they have significant potential for biomass production and CO<sub>2</sub> bioremediation.

The idea of using marine biomass for energy was first conceived by Howard Wilcox in 1968. The use of marine biomass energy was investigated in the United States and Japan as an alternative energy in the 1970's after the oil crises, but the studies were discontinued when oil prices stabilized. In Japan, research on energy production from marine biomass was conducted from 1981 to 1983. *Laminaria japonica*, one of the largest seaweeds in Japan, was proposed as a cultivation species and an energy production system using *Laminaria japonica* was designed.

The Marine Biomass Energy Program was conducted jointly among governmental organizations, universities, and private corporations in the United States until 1990. The program proposed the usage of giant brown kelp (*Macrocystis pyrifera*) as a cultivation species. In Costa Rica and Japan, seaweed farming has been re-established to produce energy, in some cases, electricity.

There are several advantages with macroalgae in its use as a source of energy:

- High biomass productivity (faster growth in dry weight/ha/yr than for most terrestrial crops)
- No need for agricultural land for cultivation
- No need for fresh water
- Harvesting and cultivation costs are less when compared to microalgae
- Low biomass transportation costs at sea
- High scalability
- Large area available (73 % of the planet)
- No or minor need for fertilizers
- No or minor need for pesticides
- No conflict regarding indirect land use changes
- Growth in ocean implies that there is no need to clear areas

All these advantages make macroalgae a suitable source for deriving energy.



## Summary

Macroalgae, which belongs to and resembles the lower plants are divided into the red, green and the brown algae. Macroalgae can produce high yields with low cultivation and harvesting costs and thus provide environmentally and economically feasible alternatives to fossil fuels.

Macroalgae generally do not contain lipids and are hence preferred for fermentation techniques to exploit their carbohydrate content. Though they yield less amount of oil when compared to microalgae, they are preferred due to their ease of harvesting and culturing in natural environments.



# **Chapter 2 - Various Types of Macroalgae & their Composition**

#### 2.1 Types of Macroalgae

2.2 Composition of Macroalgae

# 2.1 Types of Macroalgae

Seaweeds are classified into three broad groups based on pigmentation and other characteristics:

- Green (Chlorophyceae)
- Brown (Phaeophyceae)
- Red (Rhodophyceae)

#### **Green Seaweeds**

Green seaweeds or Chlorophyta are usually found in the intertidal zone (between the high and low water marks) and in shallow water where there is plenty of sunlight.

One of the common green seaweeds is sea lettuce (*Ulva lactuca*), which forms bright green sheets up to 30 cm in diameter. As its common name suggests, it is edible, although prolific growth often indicates sewage pollution. Gut weed (*Enteromorpha intestinalis*), a tubular green seaweed, also favours high-nutrient sites. Common green seaweed, sea rimu (*Caulerpa brownii*), is also edible and looks very much like the foliage of the large tree rimu.

#### **Brown Seaweeds**

The Phaeophyta, or brown seaweeds (Class Phaeophyceae, Division Heterokontophyta or Phaeophyta, Kingdom Protista or Plantae or Chromalveolata), are a large group of multicellular, mostly marine algae, and include many seaweeds of colder Northern Hemisphere waters.

One example of brown algae seaweed is Sargassum, which creates unique habitats in the tropical waters of the Sargasso Sea.

Kelps are large seaweeds belonging to the brown algae and are classified in the order Laminariales. There are about 30 different genera. Kelp grows in underwater forests (kelp forests) in clear, shallow oceans. They require nutrient rich water below about 20 °C. Kelp is known for its high growth rate and is the largest seaweed. Macrocystis, a member of the Laminariales, may reach 60 meters in length and grows up to 30 centimeters per day.



#### **Red Seaweeds**

There are 550 species of red seaweeds, otherwise called Rhodophyceae, making them the largest group. One of the best-known red seaweeds is the edible karengo (Porphyra species), which grows on rocks near high-tide level and resembles sheets of light purple cellophane. It is a close relative of the Japanese nori, used for sushi. Another familiar red is the fern-like agar weed (*Pterocladia lucida*) which has been harvested for agar production in New Zealand since 1943. The coralline seaweeds are a group of reds that deposit calcium carbonate in their cell walls, forming pink skeletons or paint-like crusts on coastal rocks. Scientists have discovered that some crust-forming seaweeds release chemicals that encourage pāua (abalone) larvae to settle and mature.

## **2.2** Composition of Macroalgae

Composition of Macroalgae Collected from Wild Stocks at Chwaka Bay and Matemwe, Zanzibar, Tanzania<sup>1</sup>

Species	Protein	Carbohydrate	Ash	Phosphorus	Fiber	
Ingredient (% ir	Ingredient (% in dw) on stocking					
Ulva retticulata	18.9 ± 4.0	23.1 ± 5.4	22.2 ±	$0.1 \pm 0.0$	37.7± 3.6	
Gracilaria crassa	11.4 ± 2.3	28.2 ± 3.1	37.7 ±	$0.1 \pm 0.0$	22.7± 2.2	
Chaetomorpha crassa	$10.1 \pm 1.0$	13.4 ± 4.3	39.7 ±	$0.1 \pm 0.0$	35.7± 4.2	
Eucheuma denticulatum	2.0	15.2	56.9	0.1	25.9	
Ingredient (% ir	n dw) at the end	of the experime	nts			
Ulva retticulata	25.7 ± 1.7	21.1 ± 2.0	18.3 ± 0.6	$0.1 \pm 0.0$	38.5 ± 2.9	
Gracilaria crassa	13.2 ± 0.7	33.1 ± 4.4	15.0 ± 0.9	$0.04 \pm 0.0$	38.7 ± 2.9	
Chaetomorpha crassa	13.1 ± 1.1	15.6 ± 6.7	35.3 ± 9.3	$0.1 \pm 0.1$	36.0 ± 2.8	
⁺Eucheuma denticulatum	7.6 ± 0.3	23.5 ± 4.4	46.6 ± 6.9	$0.04 \pm 0.0$	22.3 ± 3.8	

<sup>+</sup>material from control units

#### **Representative Composition**

- Protein 15-20%
- Carbohydrate 20 30%

<sup>&</sup>lt;sup>1</sup> <u>http://iodeweb1.vliz.be/odin/bitstream/1834/33/1/WIOJ12117.pdf</u>



- Ash 20 35%
- Fiber 20 40%

The table below gives the chemical composition of selected, representative macroalgae, some of which are currently used for food or have been used as food in the past. All figures, except for water (as percentage), are given as grams per 100 grams of dry matter. Where no data are available, it is denoted by "nd".

Parameters	Ascophyllu	Laminaria	Alaria	Palmaria	Porphyra	Ulva
	m	digitata	esculenta	palmata	yezoensis	species
	nodosum					
Туре	Brown	Brown	Brown	Red	Red	Green
Water (%)	70-85	73-90	73-86	79-88	nd	78
Ash	15-25	73-90	73-86	15-30	7.8	13-22
Total	-	-	-	-	44.4	42-46
carbohydrates						
Alginic acid	15-30	20-45	21-42	0	0	0
Xylans	0	0	0	29-45	0	0
Laminaran	0-10	0-18	0-34	0	0	0
Mannitol	5-10	4-16	4-13	0	0	0
Fucoidan	4-10	2-4	nd	0	0	0
Floridoside	0	0	0	2-20	nd	0
Protein	5-10	8-15	9-18	8-25	43.6	15-25
Fat	2-7	1-2	1-2	0.3-0.8	2.1	0.6-0.7
Tannins	2-10	1	0.5-6.0	nd	nd	nd
Potassium	2-3	1.3-3.8	nd	7-9	2.4	0.7
Sodium	3-4	0.9-2.2	nd	2.0-2.5	0.6	3.3
Magnesium	0.5-0.9	0.5-0.8	nd	0.4-0.5	nd	nd
Iodine	0.01-0.1	0.3-1.1	0.05	0.01-0.1	nd	nd
References	Baardseth	Haug &	Haug &	Morgan et	Nisizawa	Arasaki &
	(1970)	Jensen	Jensen	al. <i>,</i> (1980)	et al.,	Arasaki
		(1954);	(1954);		(1987);	(1983);
		Gayral &	Baardseth			Nisizawa
		Cosson	& Haug			et al.,
		(1973);	(1953);			(1987);
		Jensen	Jensen			Levring et
		(1956a,	(1956a <i>,</i>			al. (1969)
		1956b)	1956b)			

#### *Chemical Composition of Macroalgae*<sup>2</sup>

<sup>2</sup> <u>http://www.oceandocs.org/bitstream/1834/33/1/WIOJ12117.pdf</u>



#### Summary

Macroalgae or seaweeds are classified into three groups (on the basis of pigmentation and other characteristics), namely, Chlorophyceae, Phaeophyceae and Rhodophyceae. Green seaweeds are usually found in areas where there is plenty of sunlight. They are edible algae with high nutrient content. Eg. *Ulva lactuca, Enteromorpha intestinalis, Caulerpa brownie.* Brown algae include seaweeds of colder Northern Hemisphere waters.

Kelps, a member of this group, have 30 different genera and are the largest seaweeds known so far. Red seaweeds contain around 550 species of algae making them the largest group. Examples of red seaweeds include Porphyra species and *Pterocladia lucida* - used for agar production.

Study on the composition of various macroalgae like *Ulva retticulata*, *Gracilaria crassa*, *Chaetomorpha crassa*, *Eucheuma denticulatum*, *etc* revealed that macroalgae usually contain protein (15-20%), carbohydrate (20 - 30%), ash (20 - 35%), phosphorus and fiber (20 - 40%).



# **Chapter 3 - Cultivation of Macroalgae**

- **3.1 Introduction**
- 3.2 Wild Seaweed Cultivation
- **3.3 Aquacultured Seaweed Cultivation** 
  - 3.2.1 Land-based Cultivation Systems
  - **3.2.2** Seaweed Cultivation in the Sea
- 3.4 Is it Technically and Economically Possible to Grow Macroalgae on a Large Scale?

## **3.1 Introduction**

Early attempts to cultivate seaweeds for biofuels date back to the 1970s, particularly in the USA through what came to be known as the Giant Kelp Project, with a counterpart in Japan, and sought to produce methane from biomass. Such efforts faced several seaweed and energy production problems and were regarded as unfeasible.

Annual global seaweed (marine macro-algae) production was reported to be on the order of 1.4 million dry tons per annum. According to the analysis, seaweed-based value chains generated a range of products with annual production value estimated at US\$5.5 -7 billion/annum. Of this, human food products accounted for about 90%, hydrocolloids for about 6-8% and other products such as agricultural nutrients accounted for the rest (FAO, 2006).

Seaweeds are mainly produced for these end uses in Asian countries such as China, the Philippines, North and South Korea, Japan and Indonesia. The USA, Canada and European countries such as France, Germany and the Netherlands are attempting to establish large-scale seaweed cultivation (Pérez 1997; Buck and Buchholz 2004; Reith et al. 2005).

Based on the source, seaweed can be classified as wild seaweed and aquacultured seaweed.

## **3.2 Wild Seaweed Cultivation**

The natural population of seaweed is a significant resource. Depending on the temperature of water, some groups will dominate, like brown seaweeds in cold waters and reds in warmer waters. In 1995, about 3.6 million tonnes wet weight were collected globally from natural stocks (*Lithothamnion* not included). This was about 48% of the total global seaweed biomass harvested with the balance produced by aquaculture. More recent numbers (FAO, 2006) give about 1 million tonnes harvested annually from natural stocks, making up only 6% of the global resource, with over 15 million tons produced by aquaculture.

Seaweed exploitation in Europe is currently restricted to manual and mechanized harvesting of natural stocks. The majority of Asian seaweed resources are cultivated. There is a marked difference in the cost of seaweed between the two regions. Costs are discussed in a later section along with yield. Seaweeds are normally sold in modest volumes and delivered fresh for



further processing at local factories. They possess about 80- 85% moisture content and are costly to transport.

#### Drift Seaweeds

Another primary natural source is drift seaweeds which are common worldwide, and over 230 species are known. Almost all drift seaweeds are initially attached, but then detach and continue to grow unattached. The drift seaweeds accumulate in lines left behind by the receeding tide. Occasionally, drift species produce large biomass as in the case of Massachusetts, Bermuda, and the Venice lagoon. Some reports suggest as much as 20% of *L. hyperborean* stocks are being washed up on shore every year in Ireland. The location and seasonal availability of these resources are unpredictable. It has traditionally been collected by coastal communities on a small scale to use as fertilizer or soil-conditioner. Annually green tides in France generate about 60,000 tonnes of wet *Ulva sp.* which is about 8,000 tonnes dry weight<sup>3</sup>.

#### **3.3 Aquacultured Seaweed Cultivation**

Seaweeds can be cultured either in sea or in ponds or tanks. A wide range of techniques is used to cultivate seaweed, depending on the species being farmed, the life cycle and biogeographic factors. In the American Biomass Program, several types of large-scale cultivation systems were designed and tested for applications in the open sea (Chynoweth 2002).

In general, fragments of adult plants, juvenile plants, sporelings or spores are seeded onto either ropes or other substrata in nurseries and the plants are on-grown to maturity at sea. Some of the commonly employed cultivation systems are as follows:

#### 3.3.1 Land-based Cultivation Systems

#### Tanks

These systems generally use seaweeds growing in tanks receiving a steady stream of aeration and seawater. The aeration provides vigorous water movement in the tanks, sending the algal thalli up and down in the water column in a circular pattern. This vigorous aeration permits rapid uptake of dissolved carbon dioxide, and bringing the biomass to the surface into the light. The use of tanks may provide the greatest productivity per unit area per day and is more efficient than any other type of farming. Efficiency of these systems is very much dependent on the input of various types of energy (compressed air for bubbling, CO<sub>2</sub>, and pumping water) and nutrients. Carbon supply can be improved by either pumping more seawater or by adding CO<sub>2</sub>. The temperature and salinity also can be manipulated by pumping more seawater. The pH of the tanks should be managed in the range of 7.9 to 8.3, and the nutrient status of the medium

<sup>&</sup>lt;sup>3</sup> <u>http://www.seambiotic.com/uploads/algae%20report%2004%202009.pdf</u>



must be monitored. Tanks should be cleaned regularly and epiphytes must be controlled. Tank systems also may hold promise for the processing of polluted water for specific products, the removal of extra nutrients from wastewater, or for energy production.

#### Ponds

Macroalgae can also be grown in ponds. An advantage of this approach is the low-operating costs. Generally, water exchange in the ponds is accomplished by use of tide gates. Seaweed yields are low because of the lack of water movement in the ponds. Tank systems are usually in smaller modules that allow a predictable maintenance schedule, several steps however, can be precisely controlled and managed to reduce the labor input, although this type of system has high operational costs. Unlike tank systems, ponds are larger, and a significant outbreak of epiphytes or other weedy species may be much harder to bring under control. Some macroalgae species grown using land-based cultivation systems include:

- Ulva rotundata
- Gracilaria
- Porphyra
- Laminaria digitata
- Gracilariopsis longissima

#### 3.3.2 Seaweed Cultivation in the Sea

Aquaculturists grow most macroalgae in the sea as opposed to land. Cultivation occurs along coastal areas. To hold the seaweeds in place, a variety of farm structures are used. These include long lines to which ropes with seaweeds are attached, nets stretched out on frames, and ropes supported by poles. The capital costs associated with these systems vary depending on locality, water depth, and local economies. The operating costs for these kinds of macroalgal culture systems vary as a function of harvest frequency and lifetime of materials in a site-specific environment.

Some macroalgae species grown using sea-based cultivation systems include:

- Undaria
- Porphyra
- Eucheuma
- Kappaphycus
- Macrocystis pyrifera

The seaweed cultivation in sea can be accomplished using any of the following methods:

a. Long-Line Cultivation Systems



In the 1950s, China developed a highly successful method for cultivating *Laminaria*. In this method, sporelings ("seedlings") are produced in cold water in greenhouses and later planted out in the ocean.

The following picture depicts a Chinese long-line farm for cultivation of Laminaria wherein the long line is anchored by a rope at each end and held afloat by buoys. Culture lines with attached *Laminaria* include a spacing segment at the top and bottom of the 2- to 5-m-long rope and weighed. The anchor ropes are held by stakes or concrete weights.



Long-Line Cultivation Systems<sup>4</sup>

For cultivation, *Laminaria* plants are dried for a few hours and placed in the seeding container which is filled with cool seawater. The seed string (a synthetic twine of 2 to 6 mm in diameter or palm line 6 mm in diameter) is placed on the bottom of the same container.

The strings are then cut into small pieces that are transferred to the sea and inserted into the warp of large diameter, 60 m long culture rope. The ropes with the young sporophytes (the sporophyte is what is harvested as seaweed) are kept floating by buoys fixed every 2–3 m.

Each end of the rope is anchored to a wooden peg driven into the sea bottom. The ropes with the young sporophytes attached hang down from this rope at 50 cm intervals. These slowly develop into the large sporophytes that we harvest.

<sup>&</sup>lt;sup>4</sup> <u>http://aquanic.org/species/documents/6 Algae 3 Culturing.pdf</u>



The principal difficulties in this kind of cultivation lie in the careful control of water temperature, nutrients and light. The Japanese use a forced cultivation technique to produce plants with 2-year-old characteristics in a single growing season by controlling the water temperature and light. By the same method, the Japanese also farm similar kelp, *Undaria*, which is sold as the food wakame.

#### b. Net-Style Farm Systems

*Porphyra*, or nori, is the world's most valuable marine crop. The crop is valued at more than 1 billion dollars worldwide and is used mainly for human food. These plants grow mainly in cooler waters.

The algal spores are seeded onto nets that are then put in place on fixed support systems. The fixed support system exposes the nets to the atmosphere at low tides. This periodic exposure and drying improve the growth of nori and inhibit fouling organisms (e.g., other seaweed species or diatoms). Nori grows as a flat sheet and has a high surface area/volume ratio, a feature that aids nutrient uptake.

*Porphyra* are allowed to grow to 15–30 cm in about 40–50 days before they are harvested. The remaining thalli are allowed to grow and may be ready for a second harvest after another 15 to 20 days. Several harvests may be made from the same nets in one growing season.

The harvested crop is washed and transferred to an automatic nori-processing machine, which cuts the blades into small pieces. The nori is then processed by the cultivator into dried rectangular sheets or processed by the manufacturer per market requirements.

The following figure shows a Japanese *Porphyra* culture net system where the poles hold the net in place so that it is exposed at low tides. The Porphyra grows attached to the nets.



Net-Style Farm Systems

c. Line and Rope Farm Systems



Fishermen in the Philippines use rope and lines to grow tropical seaweeds. These seaweeds comprise species of genera *Eucheuma* and *Kappaphycus* which are important carrageenophytes (80% of world's carrageenan production). The seaweeds are tied to the lines, and the lines are then staked over the bottom. The water level should be 0.5-1.0 meter during low tide and not more than 2.0-3.0 m during high tide. The lines are constructed to form plots or units of a standard size. Seedlings weighing between 50 and 100 g are tied to the monolines at 25- to 30-cm intervals using soft plastic tying material called *tie-tie*. Usually the plants are harvested after 45 days when each seedling weighs up to 1 kg. The best looking healthy plants are selected to serve as seedlings for the next crop. The remaining plants are sun dried or sold fresh in the market.

#### d. Offshore or Deep-Water Seaweed Cultivation

Various attempts were made to cultivate the brown alga *Macrocystis pyrifera* on farm structures designed for use in deep water. The nutrients for these seaweeds were to come from cold, deep waters that would be pumped up into the growing kelps. The benefit of this approach is that growth of macroalgae would not be constrained by available shallow nearshore regions. Despite several trials using different farm designs, operational problems prevented the production of actual kelp crops. However, the experiments did establish that *M.pyrifera* could grow in an open ocean environment, and that deep waters supplied ample nutrients for sustained growth without toxic side effects. It is probable that these research results could be extended to other brown kelps, such as *Laminaria* spp.or *Undaria* spp.

#### Maintenance for Seaweed Cultivation in the Sea<sup>5</sup>

Assurance for good farm production largely depends upon farm management, procedures and practices (Juanich, G. 1980). A few significant procedures to maintain a seaweed farm:

- Sea urchins, starfishes, rocks, dead corals and other obstacles found inside the farm has to be removed everyday.
- Since the seaweeds are cultivated in the shallow part of the sea, the fluctuation in the salinity of water needs to be closely monitored because it affects the quality of the seaweeds.
- A boat (with or without engine) would be required depending upon the distance of the residence to the farm site.
- Slow-growing plants are replaced immediately with fast-growing ones.

<sup>&</sup>lt;sup>5</sup> <u>http://www.fao.org/docrep/field/003/AC416E/AC416E00.htm#ch5</u>



- The plant should not be allowed to grow more than 5 kg for it will be destroyed by the water current.
- All unhealthy and loose plants have to be completely harvested. Eel grasses and other seaweeds may tend to overcrowd and so they are to be consistently cut.
- Any loose nets have to be tightened and broken lines and destroyed stakes need to be repaired.

### 3.3.2 Species-specific Cultivation Methods Employed<sup>6</sup>

The techniques used to cultivate seaweed mainly depend on the species being farmed, the life cycle, and biogeographical factors. In general, fragments of adult plants, juvenile plants, or sporelings are seeded onto ropes in nurseries and then the plants are grown to maturity at sea. The complex life cycles of many types of seaweed convey that detailed knowledge of the species being cultivated is critical.

The following section provides inputs on the methods that are used for cultivating a few prominent species of seaweed.

#### Cultivation of Laminaria

Laminaria japonica is one of the several species successfully cultivated in commercial scale.

#### 1. The floating raft method of artificial cultivation

This method is characterized by three important processes.

- The first is the spore collection and sporeling cultivation process.
- The second is the setting-up of the floating raft for cultivation. The superiority of the raft method lies in maintaining the plants at the desired water level. This is one of the keys to successful cultivation.
- The third is the sporeling transplantation. This is a crucial process ensuring appropriate density for the growth of the plants.

#### 2. Method of low temperature culture of summer sporelings

Spore collection takes place in early summer instead of autumn. Gametophytes and young sporelings are cultured under controlled low temperature conditions. In late autumn, the sporelings are taken off to the open sea. This method enhances the production by 50%, as the summer sporelings have an advantage of two to three months' growth (Tseng, 1955).

<sup>&</sup>lt;sup>6</sup> <u>http://www.fao.org/docrep/field/003/AB728E/AB728E02.htm</u>



#### 3. Southward transplantation

Southward transplantation of L. japonica is native to the cold temperate coastal regions along northern Japan and Siberia. Experimental results showed that, although the optimal temperature for Laminaria growth was 5–10 °C, growth was still good enough at 13 °C; even at 20 °C, a frond of 1–2 m was still able to attain some growth. Based on the above experiments, Chinese phycologists conducted an experiment in 1956 on the cultivation of the Laminaria at Gouqi Island, Zhejiang Province. The results of the experiment strongly confirmed their postulation that Laminaria of commercial standard can be cultivated along the Eastern China sea coast. Production in the area accounts for one third of China's entire production (Tseng, 1957).

#### 4. Genetical studies and breeding of new strains

Genetic studies showed that natural populations of the Laminaria under cultivation in China are genetically mixed in nature and are considered to possess a high level of hybridity. In the sixties, three varieties were bred, one with broad frond, one with long frond and one with thick frond. In the seventies, two new varieties with high iodine content and high yield were bred, which answered better the demands of the iodine industry of China (IOAS and QIMF, 1976).

#### 5. Frond tip-cutting method

By this method the distal part of the frond, sometimes as much as one third of the entire frond, are cut off at certain time to improve the lighting condition of the frond. Such measure improves the conditions for the growth of the frond and enhances the quality of the product. The cutoff distal part of the frond will be cast off anyway under the natural condition; this part is not good for food but is good raw material for the algin industry. By taking such measures, the increase of production generally amounts to about 15% (Wu et al., 1981).

Since the mid-fifties, the above achievements for enhancing the production and improving the quality of Laminaria have been successfully devised one after the other. Now, commercial cultivation of Laminaria is being practiced on the China coast from Dalian of the north to Fujian Province of the south. In the 1978–1979, more than 18,000 hectares of farms were engaged in the commercial cultivation of Laminaria, and about 275,500 tons in dry weight of this alga were produced.



## Cultivation of Porphyra

Both Japan and China have a long history of the cultivation and utilization of Porphyra. Commercial cultivation of Porphyra in Japan was initiated more than 300 years ago by the primitive method of inserting bundles of bamboo twigs, called hibi, for collecting spores. In China, more than 200 years ago, the simple 'rock clearing' method of cultivation was devised by mechanically clearing seaweeds from the rocks in early autumn. This was done just before the mass liberation of the spores. The surface of the rock would then provide the substratum for the spores to attach and grow. The whole process is simple, but people have to depend upon nature's mercy to give them spores. This condition is similar to the Japanese 'bamboo-hibi planting' method. Up to the early fifties the source of the spores had been a mystery to the phycologists. In the early fifties, Drew discovered the conchocelis as a stage in the life history of Porphyra.

Later on, both the Japanese and the Chinese phycologists (Tseng & Chang, 1954) independently discovered the missing link, the conchospore. The shell of Meretrix sp., was found to be an excellent substrate for conchospore. It was not until the '60's that, with the introduction of the artificial collection of conchospores, the commercial cultivation methods became truly modernized.

In China, the intertidal semifloating raft method for growing the leafy Porphyra from conchospores is preferred over the fixed pillar method. Conchospore-seeded nets are first allowed to stay in the intertidal zone until the leafy Porphyra appear and then are transferred to deeper areas. In Japan, with the innovation of the cold-storage net and the use of floating nets, Porphyra production increased steadily. P. tenera and P. yezoensis are the two principal species cultivated, although six species are grown commercially. In 1981, the Japanese farmers produced 34,000 t (dry weight) of Porphyra. In China 9,987 t of Porphyra was produced in 1981, while the Republic of Korea has been produced 8,000 t annually these past few years.

#### Cultivation of Undaria

The other seaweed now under commercial cultivation and qualified to be called a marine crop is Undaria. Undaria pinnatifida is the main species under cultivation while Undaria undariodoides and Undaria peterseniana are cultivated to a minor extent. In Japan, the cultivation of Undaria has been developed only in the sixties when the natural resources were not sufficient to cover the ever-increasing demand for this alga. At present, production of Undaria through culture is estimated to be 91,000 t (wet weight) in Japan (1981), 100,000 t (wet weight) in the Republic of Korea these few years, and several thousand tons in China in the eighties each year.

The cultivation of Undaria consists of the following three stages:

#### 1. Collection of zoospores and growing of sporelings



Collection of zoospores begins at about April to June when the plants become fertile. The matured sporophylls are kept in a dark moist container for several hours to induce the mass discharge of the spores. These spores attach themselves to substrates and develop into male and female gametophytes. The fusion of the gametes results in the formation of zygotes which give rise to young sporophytes. The favourable temperature for the growth of gametophytes and the formation of oogonia and antheridia is at 15–25 °C (Li et al., 1982). In China and northern Japan the seeded ropes were directly cultured in the open sea under a raft where the young sporelings are allowed to grow to about 2–3 cm long.

#### 2. Outgrowing of the plant

The outgrowing of sporelings starts in the autumn when the water temperature is about 20 °C. The sporeling ropes are cut into 5–6 cm long pieces, which are inserted and are tied in the twists of the cultivation ropes. The cultivation ropes with the attached sporelings are set into the sea. The depth of the water where outgrowing is done ranges from 0.5–5 m depending on the transparency of the water. The range of optimum temperature is at 5–10 °C (Zhang, 1984). The plants are harvested when they reach a length of 0.5–1 meter. In areas where the growing season is long, several harvests can be made from the same ropes. Since Undaria has an early short-growing season, maturing much earlier than Laminaria, it is often mixed-planted with Laminaria in China. In that case, Undaria does not interfere with the growth and maturation of Laminaria, which is harvested in June (Tseng, 1981).

# 3.4 Feasibility of Cultivating Macroalgae on a Large Scale

The world uses about 85 million barrels of oil per day, which is about 3.5 billion gallons per day of oil consumption, or about 1300 billion gallons per year. Of this, gasoline accounts for about 500 billion gallons per year. In order for macroalgae to be in a position to supply even a small portion of this fuel need, it is apparent that it needs to be cultivated on very large scales.

Assuming a 30% ethanol yield by dry weight and a productivity of 50 T (dry weight) per hectare per year, we get a yield of about 5000 gallons of ethanol per hectare per year. Ethanol has an energy density that is only 62% that of gasoline, so that'd be 3100 gallons gasoline equivalent per hectare per year.

In order to replace even 1% of total gasoline usage through ethanol produced from macroalgae, an area of more than 1.5 million hectares need to be used for macroalgae cultivation.

While there has been no experimentation of algae cultivation on such large scales for biofuel production, countries such as Japan, Korea, Taiwan and China have cultivated macroalgae (nori or porphyra) on areas of about 80,000 hectares in total. These possibly represent the largest scales on which macroalgae have been cultivated in an organized manner by the industry – most other countries have cultivated macroalgae on much smaller scales (Vietnam, for instance, is reported to have about 5,000 hectares under cultivation for macroalgae).



Thus, even though cultivation of macroalgae on millions of hectares does not appear infeasible, we currently do not have adequate understanding of all the factors that could affect such feasibility. It is however likely that many of the processes and methods that are being used to cultivate algae by countries such as Japan and Korea could be employed by the macroalgae-based biofuel industry in future.

#### **Summary**

Based on their mode of cultivation, seaweeds are classified as wild seaweed and aquacultured seaweed. About 1 million tonnes of macroalgae are harvested annually from natural stocks. For some macroalgae like the drift seaweeds, location and seasonal availability are unpredictable. Hence land-based seaweed cultivation is usually preferred where they can be cultured either in ponds or tanks.

The use of tanks may provide the greatest productivity per unit area per day and is more efficient than any other type of farming as they can provide the necessary aeration and nutrients to the growing algae under controlled conditions. Ponds are larger, and hence it might prove to be difficult to grow the seaweeds under control. Aquaculturists prefer growing the macroalgae in the sea.

The major outbreak in growing macroalgae on a large scale was ascertained when they were found to grow in wastewater (tested at US institutions), where they not only grew extensively and also cleaned up the wastes. In Costa Rica and Japan, seaweeds are cultivated to extract energy from them as they can quickly yield large amounts of carbon-neutral biomass, which can be burnt to generate electricity and other high-value compounds.



# **Chapter 4 - Harvesting of Macroalgae**

- **4.1 Introduction**
- **4.2 Prominent Harvesting Methods**
- 4.3 Methods Employed For Harvesting Specific Strains
- 4.4 Harvesting Equipments Employed
- 4.5 Macroalgae Harvesting Highlights

## **4.1 Introduction**

Macroalgae grow either attached to a solid substrate or free-floating in water. Macroalgae are harvested either manually or using some special equipments. In addition to the traditional hand cutting methods using a sickle or scythe, various methods of mechanical harvesting are employed.

In case of attached macroalgae, it is necessary to cut the algae. This raises the energy consumption for harvesting slightly. With free-floating algae, harvesting can be made by simply raising a net installed in the pond. At present, attached seaweeds are gathered using hand harvesting practices. The equipment employed is limited. Some companies use diving apparatus, hand picking, knives and sacks for harvesting macroalgae, while some companies use boats for shore access and knives or hands for cropping plants.

The amount of the targeted plant removed is dependent on two main factors, the species selected and the company's or harvester's cutting practice.

#### **4.2 Prominent Harvesting Practices**

The common procedure for the majority of targeted species is to harvest the total biomass of each plant; the thallus is removed either by hand grabbing or cut using a cutting implement.

Exceptions to this practice are the harvesting practices used with species like Alaria, Laminaria and Himanthalia, in which the plant is cut above the holdfast to enable regeneration.

A seaweed harvesting company professes to use a species-specific harvesting practice for the following species.

- Alaria is cut above the receptacles taking only the frond of the plant
- Laminaria is cut 5 cm above the stipe
- Himanthalia is cut above the button holdfast.



Following the collection, the processing of harvested seaweeds vary according to the desired end product, but commonly involves washing, usually with freshwater, sorting, drying (using inhouse drying apparatus, or outside drying in suitable weather) and final packaging<sup>7</sup>.

In case of other species, the seaweed grows in belts between the boundaries of the lowest tides and the half tides. It is harvested floating when the tides are not too high. The fully grown seaweed is harvested with spade wheels and rafts made of steel floats (or even spade wheels, adjustable cutters). After the conveyor belts have collected the right volume of weed, it is dumped into large sacks and left afloat until a boat collects a whole load to take it to the factory<sup>8</sup>.

# 4.3 Methods Employed for Harvesting Specific Strains

Some macroalgae are attached to rocks by holdfast. Holdfasts are just like tree's roots which hold down the kelp. Such macroalgae are harvested by tearing off top portions and leaving the holdfast to allow re growth.

Strains like Ascophyllum nodosum and Chondrus crispus, Mastocarpus stellatus are difficult to harvest owing to their morphology. Such strains are either harvested using a sickle / knife or through mechanical means like using raking from boats using a cutter rake. In certain species, hand cutting, hand raking and drag rakes towed behind inshore fishing vessels are also employed<sup>9</sup>.

Mechanization has been successfully applied in similar situations in a number of other countries, notably Norway and France. In Norway, both Ascophyllum and *Laminaria hyperborea* are harvested mechanically using a range of custom-built devices and boats (Briand 1991). There are several Norwegian solutions for Ascophyllum harvesting and these need to be tested in Ireland. In Francean equipment called scoubidou is used extensively for the harvesting of *Laminaria digitata* (Briand 1991)<sup>10</sup>

Country	Strain	Harvest method
UK	Ascophyllum nodosum	Cutting done by hand using a sickle
	Chondrus crispus, Mastocarpus stellatus	Hand cutting and hand raking
Ireland	Ascophyllum nodosum	Done by hand using a sickle
	Chondrus crispus, Mastocarpus	Hand cutting and hand raking

Harvesting Methods Followed in Different Countries for Various Strains

<sup>&</sup>lt;sup>7</sup> <u>http://www.ni-environment.gov.uk/seaweed\_harvesting\_amended1.pdf</u>

<sup>&</sup>lt;sup>8</sup> <u>http://www.nat.is/travelguideeng/plofin\_seaweed\_harvesting.htm</u>

<sup>&</sup>lt;sup>9</sup> <u>http://www.cne-siar.gov.uk/minch/seaweed/seaweed-03.htm</u>

<sup>&</sup>lt;sup>10</sup> <u>http://www.seaweed.ie/uses</u> Ireland/IrishSeaweedHarvesting.html



	stellatus		
France	Ascophyllum nodosum	Done by hand using a sickle	
	Chondrus crispus, Mastocarpus stellatus	Hand cutting and hand raking	
Norway	Ascophyllum nodosum	Various methods of mechanica harvesting	
Canada	Ascophyllum nodosum	Raking from boats using a cutter rake, or by cutting at low tide using a sickle or knife	
	Chondrus crispus, Mastocarpus stellatus	Hand-operated rakes or drag rakes towed behind inshore fishing vessels.	
Iceland	Ascophyllum nodosum	Mechanical harvesting.	
USA	Chondrus crispus, Mastocarpus stellatus	Hand-operated rakes or drag rakes towed behind inshore fishing vessels.	

# Name of Species and the State in Which They Are Harvested<sup>11</sup>

Phylum	Species harvested in Northern Ireland	Species Harvested (Common Name)	State Harvested
Green algae	Ulva spp.	Sea lettuce	Attached
Brown algae	Alaria	Tangle, Wakame	Attached
	<i>Fucus vesiculosus</i> (Possibly F. serratus)	Bladder wrack (serrated wrack)	Attached
	Himanthalia elongate	Thongweed, buttonweed, sea spaghetti	Attached
	Laminaria digitata	Oarweed, kombu	Drift
	Laminaria hyperborea	Oarweed	Drift
	Laminaria saccharina	Seabelt, sweet kombu	Drift and attached
	Alaria esculenta	Dabberlocks	Attached
Red algae	Mastocarpus stellatus	Carrageen moss, Irish moss	Attached
	Chondrus crispus	Carrageen moss, Irish moss	Attached
	Palmaria palmate	Dulse	Attached
	Porphyra spp.	Laver, sloke, nori	Attached
	Corallina officinalis		Attached

<sup>11</sup> <u>http://www.ni-environment.gov.uk/seaweed\_harvesting\_amended1.pdf</u>



# 4.4 Harvesting Equipments Employed

Macroalgae is harvested by using tools and equipments that are designed to assure future vitality of the target species and to minimize damage to substrate, juvenile seaweed and non-target species. Some of the equipments that are employed are as follows:

#### Drag Rake

The drag-rake in present use evolved from the hand rake (Pringle et al., 1981). The drag rakes are secured to the bottom of a steel bar.

Drag rake boats are rigged for Irish moss harvesting in one of two ways, with the size of the vessel generally dictating the method. Harvesters with smaller boats (7-10 m) use the "hauler" technique where up to 6 drag rakes are secured independently to the bulwark by rope (2.5 cm x 20 m). The boat is run in a circular direction when cropping. The drag rakes are returned to the boat via the lobster trap hauler which is a steel cone-shaped cap driven in a circular motion via the power takeoff of the vessel's engine. The skipper assists in the rake recovery operation.



## Winchers<sup>12</sup>

"Winchers", are rigged with a centrally located iron spar, a pair of iron booms, secured at 45° angles to the deck amid ship and a pair of winches forward of the boom base. Cable, attached to each drum, is strung through pulleys and attached to an iron tow bar.

<sup>&</sup>lt;sup>12</sup> <u>http://www.fao.org/docrep/x5819e/x5819e05.htm#TopOfPage</u>



Drag rakes are hooked in triplicate to the tow bar, but they are not attached laterally to each other. A set of drag rakes is used for both the starboard and port sides of the boat.

The boat, while harvesting, moves continuously on a straight course; the skipper runs the winches and the boat. While one set of drag rakes is cropping, the deckhand removes the harvest from the opposite rakes. The crop is loosened from the tines with a couple of blows to the drag rake by an iron bar.



#### **Cutter Blade**

Harvesting techniques in some regions such as Canada apply a modified aquatic weed harvester driven by paddle wheels through hydraulic motors powered by a diesel engine. A reciprocating cutter blade cuts a swath; shoots are picked up by a conveyor belt and moved into a 1.4 t capacity storage bay. The operator controls cutting height by raising the forward conveyor belt. Once the holding capacity is reached, the vessel moves to a barge and off-loads.

#### Suction Harvester<sup>13</sup>

A suction harvester is propelled by water jets near the stern which point sideways, rearward and forward. A bladed impeller at the end of suction pipe simultaneously draws up and cuts shoots. The operator hydraulically controls lifting and lowering of the suction head. Water and cut shoots are discharged into a net bag which is ejected and towed behind the vessel or moored together awaiting a collecting vessel.

<sup>&</sup>lt;sup>13</sup><u>http://www.fao.org/docrep/x5819e/x5819e04.htm#5.%20harvesting,%20biomass%20recovery%20and%20econ</u> omics





# 4.5 Macroalgae Harvesting - Highlights

- More easy and economical to harvest than microalgae
- Labour intensive (Seaweed harvesting in Ireland currently employs about 400 people); mechanization techniques can reduce manpower requirements (*E.g.* Ascophyllum, *Laminaria hyperborean*)
- Unlike in the case of microalgae, cannot be harvested on a daily basis (harvesting is done every 3-6 months, based on the species)
- Regeneration of the harvested population is necessary
- Easy to grow in wastewater and sewage treatment plants

#### Summary

Macroalgae are harvested either manually or using some equipments. With free-floating algae, harvesting can be made by simply raising a net installed in the pond. In case of attached algae, they have to be cut with cutting equipments after which they are collected and transported with haulers and winchers.

Strains like Ascophyllum nodosum and Chondrus crispus, Mastocarpus stellatus are difficult to harvest owing to their morphology. Such strains are either harvested using a sickle / knife or through mechanical means like using raking from boats or with a cutter rake. The state and type of harvesting usually differ from species to species. Some strains which necessitate the use of mechanization for harvesting use equipments like the drag rakes, winchers, cutting blades and suction pipes.

Though macroalgae take longer times than microalgae for regeneration, and require labor intensive practices for harvesting, the major advantage is that they are economical to harvest when compared to microalgae.



# **Chapter 5 - Yield of Macroalgae**

Macro-algae are cultivated and harvested for food products, agar, carrageenan, alginate and minor products. Obtaining reliable data on biomass yields is difficult, as most macro-algae are harvested from wild populations. While there is a large amount of reported productivity data for a range of seaweed species worldwide, making generalizations is still quite difficult owing to a number of reasons.

The only yield which can be reported as commercially achieved and sustained is the cultivation of *Laminaria japonica* in China, which yields 25 t/ha/year dry matter. This is via the long-line cultivation of seaweeds which are artificially fertilized or naturally fertilized through integration with other aquaculture. Availability of nutrients is a key productivity factor. Some reported yields assume no external nutrient supply, others propose siting to take advantage of coastal run-off or fish-farm effluent (Kelly, et al., 2008), while yet more yield assumptions are based around the artificial upwelling of deep ocean water (Chynoweth, 2002). Other yield assumptions are based around the development of precision nitrogen dosing techniques (Reith, et al., 2005).

For optimized cultivation systems, macroalgal yield of 45 dry T/ha/yr has been estimated. The productivity for macro-algae ranges from 150 to 600 T/ha/yr fresh weight (dry weight - 15 – 60 T/ha/yr), that is much higher than the typical value for sugarcane that ranges from 70 to 170 T/ha/yr fresh weight. This means that under the best operative conditions macroalgae would be a better energy source than terrestrial biomass. (Michele, 2003)

The demonstrated energy yields of Gracilaria and Ulva are 2.5 x 106 and 3.0 x 106 J/m<sup>2</sup> day, respectively. (J. H. Ryther et al, 1984).

The productivity of macroalgae is in the range 1-15 kg m<sup>-2</sup> y<sup>-1</sup> dry weight (10-150 dry T/ha/yr) for a 7-8 month culture. (Energy from Macro-Algae, Michele et al, 2003)

Species	Yield Dry t/ha/yr	Location	Source	Notes
L japonica	31	Japan	Yokoyama et al, Citing Japan Ocean Industries Association	Corrected from dry ash-free value
L. japonica	25	China	Kelly,citingChinaFishAnnals 2003	Commercially achieved yields

#### Yield of various macroalgae species cultivated in various parts of the world



L. japonica	60	China	Kelly, citing Tseng 1987	Experimental plots. High cost and poor quality	
Alaria	12	Ireland	Kelly, citing Kraan 2007	Hybrid species	
Saccharina lattisima	15	Scotland	Kelly, citing Sanderson 2006 unpublished	Experimental plots near fish farms as nutrient source	
S. polyschides	25.5	Scotland	Kelly, citing Sanderson 2006 unpublished	Experimental plots near fish farms as nutrient source	
Ulva	22.5	Pennsylvania	Rasmussen 2007, citing Moll 1998	Converted to annual yields using 6 months	
Ulva	45	Denmark	Rasmussen pers. Comm. 2008	Basedonextrapolationof4-month trials	
	15	New England			
	13	White Sea		Corrected for growth loss prior	
Ascophyllum	23	Spain	Coursons 1064		
nouosum	20 – 26	Nova Scotia (pre-harvest)	Cousens 1904	Cousens 1964	
	6.1 – 28.2	Nova Scotia			
Eucheuma	36		Doty (1973), Parker (1974)	Productivity data in terms of world crop & dollar Values	
Macrocystis	12.3 -14.8	California	North et al., (1982)	Considering dry weights of Macrocystis harvested from beds within California	
Gracilaria	16–43	Taiwan	Chiang (1981)	Commercially achieved yields	



Gracilaria	80-91	Florida	Hanishak & Sauel (1987)	Produced small fre floating with annual production	d in e- cultures average vity
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Source: EPOBIO, FAO

#### Summary

Obtaining reliable data on biomass yields is difficult, as most macro-algae are harvested from wild populations. Hence various yield assumptions were made to determine the productivity of macroalgae. The yield commercially achieved and sustained is of *Laminaria japonica* in China, with 25 t/ha/year dry matter.

It is estimated however that the productivity ranges from 10 - 150 dry T/ha/yr, which is much higher than crops such as sugarcane. This means that under the best operative conditions, macroalgae would be a better energy source than terrestrial biomass.



# **Chapter 6 - Products from Macroalgae**

- **6.1 Introduction**
- 6.2 Energy Products from Macroalgae
- 6.3 Non-energy Products from Macroalgae

# **6.1 Introduction**

Macroalgae could produce a combination of end products. These end products can be broadly categorized as energy products and non-energy products from macroalgae which are explained in this section.



## 6.2 Energy Products from Macroalgae

Various seaweeds have been considered to be potential energy crops such as *Macrocystis pyrifera*, Laminaria, *Gracilaria*, *Sargassum*, Ulva, etc. These seaweeds have a high productivity which is required for energy production. *Macrocystis pyrifera* may be the most appropriate species among them because it grows quickly to large sizes, and can be harvested several times a year.

In addition, its biochemical methane potential is larger than that of other seaweeds like *Laminaria* or *Sargassum*. However, *Macrocystis pyrifera* does not grow in some places like Japan. Among the seaweeds indigenous to Japan, the best species for energy production is considered to be *Laminaria japonica*, as it grows faster than any other seaweed in Japan.



There are Various Pathways through which Fuel can be Derived from Macroalgae<sup>14</sup>

Source	Process	Fuel
Seaweed/ Macroalgae	Anaerobic Digestion	Methane
	Fermentation	Ethanol
	Transesterification	Biodiesel
	Pyrolysis/ Gasification	Hydrocarbons and derivatives

#### Methane

Research to determine the technical and economic feasibility of bio-methane production from marine biomass was conducted from 1968 until 1990 under the sponsorship of the U.S. Navy, the American Gas Association and Gas Research Institute, and the U.S. Department of Energy, and was reviewed by Chynoweth (2002). The study compared the technical potential of different biomass sources (marine algae, wood and grass species, municipal solid waste) to be used in energy farms, and concluded that marine biomass offered the highest potential. The growth rates of marine macro-algae exceed land plants; however, growth is often limited by the availability of nutrients. A sufficient nutrient supply in the open ocean could be achieved through upwelling of nutrients, but the study suggests that this option is too costly and that, farming of macro-algae near shore with nutrient supply through recycling of wastes from conversion processes would be a better option (Chynoweth 2002). In a study about the feasibility of methane production from macro-algal biomass (Chynoweth 2002), base case scenarios assumed yields of 11 dry t ha<sup>-1</sup> y<sup>-1</sup> (based on data from commercial growers).

#### Ethanol

Production of ethanol from macroalgae is regarded as a promising alternative to food crops for biofuel production. Various species of macroalgae were proposed as candidates for bio-ethanol crops, including *Gracilaria* sp. and *Ulva* sp. (Hanisak 2008), as well as ocean based culture of larger kelp species (Adams et al. 2008, Kraan 2008). The processing technology to provide ethanol from macroalgae exists and the substitution from current food crops to macroalgae should not be difficult (Adams et al. 2008).

Cellulose content of macroalgae *Ulva* is 10 - 20% of its dry weight where as *Laminaria* has 60% of fermentable sugars for its dry weight.

<sup>&</sup>lt;sup>14</sup> <u>http://www.waset.org/journals/waset/v28/v28-58.pdf</u>



#### **Biodiesel from Macroalgae**

The oil content of macroalgae is less than that for microalgae. It has been reported that on average, macro algae contain lipid content of 1.3-7.8% (DW). Pohl and Zurheide reported that lipids of some macroalgae (seaweeds) were reported to be very high, up to 51% of total fatty acids. Vincecate suggested that seaweeds contain about 5.5% oil<sup>15</sup>.

Oil content of select macroalgae:

Chaetomorpha linum	Oil content – 15%
Pterocladiella capillacea	Oil Content - 7.5%

Though these values suggest that biodiesel can be produced from macroalgal oils, the low oil content makes macroalgae biodiesel production commercially infeasible.

#### Hydrocarbons and Derivatives through Thermochemical Route

This includes production of syngas using gasification of the biomass, and conversion of the syngas to hydrocarbon fuels through catalytic synthesis. The thermochemical route includes two processes:

- Pyrolysis Pyrolysis is a thermochemical process in which biomass is heated in the absence of oxygen. During pyrolysis, which takes place at temperatures in the range of 400-800°C, most of the cellulose and hemicelluloses, and part of the lignin will disintegrate to form smaller and lighter molecules which are gases at the pyrolysis temperature. Depending on the residence time and the temperature, three main products result from pyrolysis in varying ratios: producer gas, bio-oil and high-carbon char. Pyrolysis is done in a pyrolyzer.
- Gasification A process that converts carbonaceous materials, such as coal, petroleum, biofuel, or biomass, into carbon monoxide and hydrogen by reacting the raw material at high temperatures with a controlled amount of oxygen and/or steam. The gasification process is carried out in a gasifier. Biomass gasification offers an attractive alternative energy system. Biomass gasification technology is also environment-friendly, because of the firewood savings and reduction in CO<sub>2</sub> emissions.

The syngas can be processed through various pathways to make fuel as well as other chemicals. The following flow chart published in biomass magazine explains the various possibilities of deriving fuel from biomass.

The chart below provides the complete range of products that can be derived from syngas.

<sup>&</sup>lt;sup>15</sup> <u>http://www.scipub.org/fulltext/ajbb/ajbb43250-254.pdf</u>





Range of Products that can be Derived from Syngas

Source: Biomass Magazine

Employing thermochemical technology such as gasification and catalytic synthesis for deriving fuel from macroalgae is an attractive option that is seeing a lot of interest and investments. Though the capital investments associated with gasification is high, this technology is simple and overcomes most of the bottlenecks associated with other processes.

Although macroalgae to gasification route is promising, high ash content of macroalgae is one of the major disadvantages associated with this technology. Ash chemistry restricts the use of macroalgae for direct combustion and gasification. In addition, high ash content reduces the calorific value of the feedstock. Pyrolysis produces a range of pentosans and a significant proportion of nitrogen containing compounds. High char yields are produced.


# 6.3 Non-Energy Products from Macroalgae

The world market of non-energy products from macro-algae has been estimated to have a size of US\$ 5.5 - 6 billion per year (McHugh 2003; Pulz and Gross 2004). US\$ 5 billion is generated by the food industry, of which US\$ 1 billion is from "nori", a high-value product worth US\$ 16,000  $t^{-1}$ ; a further US\$ 600 Mio was generated by hydrocolloids (55,000 t) extracted from cell walls of macroalgae (Anders et al, 2007).

The species of marine macro-algae (seaweeds) that are predominantly used in industry currently belong to the divisions *Rhodophyta* and *Phaeophyta*, and about 7.5 – 8 Mio t of wet seaweed is harvested annually.

The various non-energy products obtained from algae are explained in detail as follows:

# Food

The use of seaweed as food has been traced back to the fourth century in Japan and the sixth century in China. Those two countries and the Republic of Korea are the largest consumers of seaweed as food. However, as nationals from these countries have migrated to other parts of the world, the demand for seaweed as food has followed them, for example, in some parts of the United States of America and South America. Increasing demand over the last fifty years outstripped the ability to supply requirements from natural (wild) stocks. Research into the life cycles of these seaweeds has led to the development of cultivation industries that now produce more than 90 percent of the market's demand. In Ireland, Iceland and Nova Scotia (Canada), a different type of seaweed has been traditionally eaten, and this market is being developed. Some government and commercial organizations in France have been promoting seaweeds for restaurant and domestic use, with success. An informal market exists among coastal dwellers in a few developing countries where there has been a tradition of using fresh seaweeds as vegetables and in salads.

China is the largest producer of edible seaweeds, harvesting about 5 million wet tonnes. Kombu is produced from hundreds of hectares of the brown seaweed, *Laminaria japonica*, which is grown on suspended ropes in the ocean. The Republic of Korea grows about 800 000 wet tonnes of three different species, and about 50 percent of this is for wakame, produced from a different brown seaweed, *Undaria pinnatifida*, grown in a similar fashion to *Laminaria* in China. Japanese production is around 600 000 wet tonnes and 75 percent of this is for nori, the thin dark seaweed wrapped around a rice ball in sushi. Nori is produced from red seaweed - a species of Porphyra. It is a high value product, about US\$ 16,000/dry tonne, compared to kombu at US\$ 2 800/dry tonne and wakame at US\$ 6 900/dry tonne (FAO,2004).

The following species have been used in Europe for human consumption either traditionally or more recently.



Macroalgae	Type of food
Palmaria palmate	Can be eaten raw, dried or in powder form
Laminaria sp.	Can be eaten either fresh, dried or pickled.
Ascophyllum nodosum	Used as healthfood
Fucus vesiculosus	Boiled and used as a health drink.
Ulva lactuca	Added to soups or used in salads.
Porphyra	The laver is boiled then minced to produce laverbread

#### Fertilizers

Fertilizer uses of seaweed date back at least to the nineteenth century. Early usage was by coastal dwellers, which collected storm-cast seaweed, usually large brown seaweeds, and dug it into local soils. The high fiber content of the seaweed acts as a soil conditioner. It also assists in moisture retention. The mineral content of seaweed is a useful fertilizer and source of trace elements. In the early twentieth century, a small industry was developed based on the drying and milling of mainly storm-cast material, but it dwindled with the advent of synthetic chemical fertilizers. Today, with the rising popularity of organic farming, there has been some revival of the industry, but not yet on a large scale; the combined costs of drying and transportation have confined usage to sunnier climates where the buyers are not too distant from the coast.

The growth area in seaweed fertilizers is in the production of liquid seaweed extracts. These can be produced in concentrated form for dilution by the user. These fertilizers can be applied directly onto plants or they can be watered in and around the root areas. There have been several scientific studies that prove these products to be effective. In 1991, it was estimated that about 10 000 tonnes of wet seaweeds were used to make 1 000 tonnes of seaweed extracts with a value of US\$ 5 million. However, the market has probably doubled in the last decade because of the wider recognition of the usefulness of the products and the increasing popularity of organic farming, where they are especially effective in the growing of vegetables and some fruits.

Seaweed fertilizers contain growth-promoting hormones and are fortified with nitrogen (N), phosphorous (P) and potassium (K) needed by plants. It can also be produced from pretreatment wastes in agar/carrageenan production (or the slightly basic extract of old or enzyme-degraded brown seaweeds); waste that would otherwise be discarded. Being water soluble, these fertilizers use only natural components that do not harm the soil.

#### Hydrocolloids

Various red and brown seaweeds are used to produce three hydrocolloids: agar, alginate and carrageenan. A hydrocolloid is a non-crystalline substance with very large molecules and which



dissolves in water to give a thickened (viscous) solution. Alginate, agar and carrageenan are water-soluble carbohydrates that are used to thicken (increase the viscosity of) aqueous solutions, to form gels (jellies) of varying degrees of firmness, to form water-soluble films, and to stabilize some products, such as ice cream (they inhibit the formation of large ice crystals so that the ice cream can retain a smooth texture).

These hydrocolloids are either located in cell walls or within the cells serving as storage materials. A characteristic of marine algae is the abundance of sulphated polysaccharides in their cell walls. In total, these phycocolloids represent a world market of some US\$ 600 Mio/yr.

The group of phycocolloid polymers commonly termed hydrocolloids includes the alginates, carrageenans and agars. Hydrocolloids possess a number of unique properties. The polymers are used in many food and industrial products to thicken, emulsify and stabilize.

Alginates are polymers from the cell walls of a wide variety of species of the brown algae, particularly species of Laminaria, Macrocystis and Ascophyllum. Alginates are commonly used in the food and pharmaceutical industries as stabilizers for emulsions and suspensions, e.g. ice cream, jam, cream, custard, creams, lotions, tooth paste, as coating for pills.

*Carrageenans* are linear galactans derived from cell walls of red algae (Mc Hugh 2003). They are extracted from the cell walls with hot water. Carrageenans are used in the food, textile and pharmaceutical industry and function as a stabilizer for emulsions and suspensions.

*Agars* are also extracted from cell walls of red algae. The genera Gelidium and Gracilaria supply most of the raw material for agar production (Zoebelein 2001). Gelidium used for commercial agar production is harvested from the wild, whereas Gracilaria species is also cultivated in Chile, China and Indonesia, in protected bays in the ocean, on lines ropes or nets, or in ponds on land (Mc Hugh 2003). About 90% of the agar produced was for food applications and the remaining 10% were used for bacteriological and other biotechnological us

Parameters	Alginate	Carrageenan	Agar
Species	Laminaria, Macrocystis and Ascophyllum	Chondrus crispus and Mastocarpus stellatus	Gelidium and Gracilaria
Uses	This chemical is used as a stabilizer or emulsifier in a variety of products such as shampoos and syrups.	Carrageenan is used to gel, thicken or suspend, most frequently in food production, especially dairy products	Agar is used as a bacteriological medium and in cell culture, and in the food and pharmaceutical industries, frequently as a gelling agent, preservative or stabilizer



#### Cosmetics

Ground or powdered seaweed, as well as phycocolloids, are used in the manufacture of cosmetic products including soaps, shampoos, powders, creams and sprays. Very often the algal content of such products will be small, even where the use of seaweed is highlighted in the marketing of a product.

A variety of seaweeds are used in cosmetics. Among the brown algae, *Laminaria sp.* is among the most common, although the bladder wracks such as *Fucus vesiculosus* and *Ascophyllum nodosum* are also utilized. *Chondrus crispus, Mastocarpus stellatus* and *Porphyra sp.* are some of the red algae which may be employed as cosmetic ingredients. Overall, the quantities of seaweed used in this sector are minimal.

# Summary

Macroalgae could produce a variety of products: both energy and non-energy products. The various energy products that are obtained from macroalgae include methane (Anaerobic Digestion), ethanol (Fermentation), biodiesel (Transesterification), hydrocarbon and its derivatives (Pyrolysis/ Gasification). The oil content of macroalgae is lesser than that of microalgae. It has been reported that macro algae contain lipid content of 1.3-7.8%. The species that are capable of producing energy products include *Macrocystis pyrifera*, Laminaria, *Gracilaria, Sargassum*, Ulva, etc.

Macroalgae biomass can also be gasified to produce syngas. The chart provided in this chapter gives the complete range of products that can be derived from syngas.

The non energy products derived from macroalgae include food, fertilizers, hydrocolloids and cosmetics. China is the largest producer of edible seaweeds. Seaweed fertilizers contain growth-promoting hormones and are fortified with nitrogen (N), phosphorous (P) and potassium (K) needed by plants. Various red and brown seaweeds are used to produce three hydrocolloids: agar, alginate and carrageenan. Ground or powdered seaweed, as well as phycocolloids, are used in the manufacture of cosmetic products including soaps, shampoos, powders, creams and sprays.



# **Chapter 7 - Cost and Economics**

This chapter provides inputs on the costs of making various fuel products from macroalgae.

While computing the total cost of fuel production from macroalgae, two distinct stages of cost computations can be considered.

- 1. Cost of obtaining dry macroalgal biomass
- 2. Cost of converting the macroalgae biomass into fuels

# **Cost of Macroalgae Biomass**

The cost of production of macroalgae varies widely, depending on the region in which it is grown and the species. In countries such as India, macroalgae can be cultivated at a cost of about \$100 or less per dry ton, while estimates of macroalgae cultivation in western, developed countries range between \$100 - \$300 per dry ton.

The following are some data for the cost of macroalgae production in some countries worldwide.

Country	Species	€/t wet	€/t dry	Origin	Harvest
Ireland	Asco/ Fucus	50	333	Natural	Manual
France	Laminaria	40	267	Natural	Mechanized
France	Asco/ Fucus	30	200	Natural	Manual
Philippines	Carrageen		165	Cultivated	Manual

Macroalgae cultivation involves a significant amount of manual labour. This is likely to result in higher cultivation costs in developed countries than in the developing countries such as India.

Costs of cultivation are likely to decrease with increased scales of operation and with improvement in cultivation, harvesting and drying technologies.

We expect that currently, macroalgae can be cultivated for about \$150 per dry ton on a continuous basis at current scales of operations. We also estimate that the cost could be about half this figure (\$75 per dry ton) if cultivation happens on much larger scales with improved cultivation and harvesting techniques.

#### **Cost of Converting Macroalgae Biomass to Fuels**

The following are the end products for which preliminary costs are worked out:

Electricity



- Ethanol
- Biodiesel

The processes being considered are:

- Gasification
- Direct combustion
- Anaerobic digestion
- Cellulose fermentation

# Preliminary Cost Calculations for Various Processes and Products Using Macroalgae

The calculations below have been made for macroalgae species with high cellulosic/starch content (40-50% by dry weight), and with a total biomass production cost of about \$150 per T, dry weight. It is assumed that cultivation and harvesting are done in medium wage or low wage countries.

(\$ denotes US \$; c denotes US cents)

Products and Pathways	Cost
AB → syngas → electricity	<ul> <li>For macroalgae 0.0008 T is required to generate 1 kWh through syngas process.</li> <li>The production cost alone (without feedstock cost) for electricity production from syngas is about 5c/kwh.</li> <li>At an algae biomass production cost of 150\$/T. The total cost of electricity production comes down to 17c/ kWh (including depreciation data)</li> </ul>
AB $\rightarrow$ direct combustion $\rightarrow$ electricity	<ul> <li>The production cost alone (without feedstock cost) for electricity production from direct combustion is about 7c/kwh.</li> <li>At an algae biomass production cost of 150\$/T.</li> <li>The total cost of electricity production comes down to 15-16c/ kWh (we are assuming a throughput requirement of 0.0006 T of biomass for 1 kWh)</li> </ul>
AB → anaerobic digestion → electricity	<ul> <li>Operating cost without depreciation = 2 c/kwh.</li> <li>Capital costs are approximately \$3500/KW. Assuming 20 hrs of operations per day and 15 yr</li> </ul>



	<ul> <li>depreciation period, the total cost including depreciation is about 5.5 c/kWh.</li> <li>To this the cost of algae biomass per kWh need to be added, which is about 9 c / kWh assuming requirements of 0.0006 T of biomass for 1 kWh</li> <li>The total cost thus is 14.5 c/kWh</li> </ul>
AB $\rightarrow$ cellulose fermentation $\rightarrow$ Ethanol	<ul> <li>\$1.2 per gallon including capital cost depreciation</li> <li>Assuming a biomass cost \$150 per T and at 100 gal yield of ethanol per T gives \$1.5 per gallon of feedstock</li> <li>Total cost = \$2.7 / gal</li> </ul>
AB → syngas → ethanol / biodiesel	<ul> <li>\$ 0.8/gallon of fuel production cost (operating costs)</li> <li>Capex is about \$0.8 / gal (taking 10 year depreciation)</li> <li>Add \$2 per gallon for feedstock (@250 Kg of fuel yield per T)</li> <li>Total cost = \$3.6 / gal</li> </ul>

AB=Algae Biomass

Comparison of Cost Calculations for Various Processes and Products Using Macroalgae at \$150/ T DW algal biomass with \$75 / T DW algal biomass

Products and Pathways	Cost @ \$150/ T DW algal biomass	Cost @ \$75/ T DW algal biomass
$AB \rightarrow syngas \rightarrow electricity$	17 c/ kWh	11 c/ kWh
AB $\rightarrow$ direct combustion $\rightarrow$ electricity	16 c/kWh	11.5 c/kWh
AB $\rightarrow$ anaerobic digestion $\rightarrow$ electricity	14.5 c / kWh	10 c/kWh
AB $\rightarrow$ cellulose fermentation $\rightarrow$ Ethanol	\$2.7 / gallon	\$1.9 / gallon
$AB \rightarrow syngas \rightarrow ethanol / biodiesel$	\$3.6 / gallon	\$ 2.6 / gallon

AB=Algae Biomass

From the above table, it can be seen that at current costs of macroalgae production, the costs of fuel and electricity production from macroalgae are not competitive. But at macroalgae



production costs of \$75 / dry ton which can be achieved at large-scale production, the costs of electricity and fuels from macroalgae start becoming more competitive.

In the case of ethanol alone, it should be noted that the costs will not be competitive even at an algal biomass production cost of \$75 per dry ton. Ethanol has an energy density which is about 65% that for gasoline; thus, as a gasoline replacement, the cost of one gallon of ethanol (gasoline equivalent) will be \$4.15 and 2.92 respectively, making them more costly than gasoline at 2010 prices.

In the case of biodiesel, owing to the fact that the energy density of biodiesel is only about 6% lower than that of petro-diesel, the costs are more favourable than in the case of ethanol. However, the actual costs of thermochemical processes required for producing biodiesel from algal biomass are not known with a good amount of certainty as of 2010.

The key driver for the cost of fuel or production from macroalgae is the cost of biomass. Current costs of macroalgal biomass (\$150 and above per ton dry weight) cannot provide fuel or power at competitive costs. At half the current production cost - \$75 per ton dry weight – levelized production costs become more competitive. For such a significant reduction to occur in the cost of algae biomass, dramatic improvements in technologies and processes used for cultivation and harvesting are required.

#### Note on costs:

- 1. All data used for calculations had been obtained from secondary sources. The Oilgae Team tried to ensure the authenticity of sources to the extent possible. But it should still be noted that these are only preliminary cost estimates. During our research, the team came across cost estimates that were significantly different from the estimates we have provided above.
- 2. The cost data provided for biodiesel or ethanol production using the syngas route is debatable, given the fact that there is a lack of clarity on the precise costs of large-scale gasification / chemical synthesis route for hydrocarbon production.

# Summary

Macroalgae cultivation involves a significant amount of manual labour and hence the cost of production of macroalgae varies widely, depending on the place and kind of species grown (India- \$100 or less per dry ton; western, developed countries- between \$100 and \$300 per dry ton).

Costs of cultivation are likely to decrease with increased scales of operation and with improvement in cultivation, harvesting and drying technologies. Oilgae expects that currently,



macroalgae can be cultivated for about \$150 per dry ton on a continuous basis (at current scales of operations) and that the cost could be about half this figure (\$75 per dry ton) if cultivation happens on much larger scales with improved cultivation and harvesting techniques. The current costs of macroalgae production, the costs of fuel and electricity production from macroalgae (listed in the table provided in this chapter) shows that the costs of electricity and fuels from macroalgae would become more competitive with a biomass cost of \$75 per dry ton.



# **Chapter 8 - Advantages of Macroalgae**

Macroalgae have significant potential to become a source for biofuel because of the following advantages.

1. High yields compared to other biomass

Macroalgae yields are in the range of 10 - 15 ton per year per 1000 m<sup>2</sup>, about 10 times more than the current yield of corn.

# 2. No need for agricultural land for cultivation

Macroalgae can be grown in open ocean, and thus they do not compete with other energy crops and food crops for the availability of land. This makes macroalgae a unique option for countries which have very little land but are surrounded by plenty of seawater.

#### 3. Do not use fresh water

Unlike other energy crops macroalgae can grow well in marine water. Hence they do not compete with other crops for fresh water.

#### 4. Do not increase food price

Macroalgae can eliminate the problems associated with first and second generation energy crops. They do not have food versus fuel problem as they do not compete for both land and fresh water required for growing food crops. Hence growing macroalgae will not increase food prices.

#### 5. High in carbohydrate/polysaccharide content

Macroalgae have high carbohydrate content which makes them a potential source for cellulosic ethanol production.

#### 6. Consumes CO<sub>2</sub> while growing

Similar to microalgae, macroalgae can also sequester carbon dioxide while growing. Cultivation of macroalgae apart from giving us a viable biomass source will also help in the reduction of  $CO_2$  emission.

#### 7. Low cost of harvesting

Harvesting of some floating macroalgae such as Sargassum can be done very easily compared to microalgae harvesting which is an energy intensive process.

#### 8. High scalability

Open ocean cultivation can be scaled up to any desired level because of the huge availability of ocean land.



#### 9. Low cost cultivation

The cost of cultivation is low compared to microalgae. It is also possible to utilize the wild seaweed which almost eliminates the cultivation costs. In some parts of the world, drift seaweeds are available seasonally. Utilization of these seaweeds reduces the cost associated with harvesting and transportation in addition.

# **Summary**

When compared to other biomass, macroalgae have higher carbohydrate content and hence yield higher, require no land for growth, consume even wastewater for its growth and above all have lower cultivation and harvesting costs. These factors make macroalgae a potential source of biofuel for the future.



# **Chapter 9 - Challenges & Bottlenecks**

There are several challenges associated with cultivation of macroalgae as well as conversion of macroalgae to fuels. Several ecological factors affect the growth and production of macroalgae in sea-based cultivation.

Challenges Associated with Macroalgae Cultivation in Wild Environments

- A major limitation of mass culturing seaweeds is the low mass transfer coefficients in seawater, limiting the supply of CO<sub>2</sub>, nitrates and phosphates, and possibly other nutrients. Large energy inputs would be required to mix seawater and break down diffusion barriers near the surface of seaweed blades.
- It is widely recognized that the temperature regime and the nutrient contents of some bodies of water could be important in determining the distribution and production of macroalgae. The general occurrence of upwelling areas can have some effect on the high production rates of these seaweed populations.
- There will be a significant macroalgal biomass reduction in the months with extreme low tides during clear daylight hours. Even high tides can damage the systems used for cultivation
- Other problems which are not so easily remedied include some bacterial diseases and grazing of the macroalgae by isopods and gastropods.
- Eutrophication in the coastal areas may provide nutrients to the macroalgae cultivating areas to some extent, but most of the causative elements of coastal eutrophication such as industrial discharge, domestic sewage, and agricultural runoff contain undesirable constituents. Industrial pollution, particularly that which contains cadmium, mercury, and other highly toxic elements poses threat to macroalgae cultivation.
- Careless harvesting practices can have serious and long-lasting effects on the productivity of macroalgae. In case of Gelidium sp, cutting of erect axes always has resulted in less destruction and faster re-growth of the various species than scraping of the substratum (Santelices, 1974). Scraping of the substratum normally destroys the creeping axes allowing for the invasion of other algal species.

Challenges Associated with Conversion of Macroalgae to Fuels

• High moisture contents in macroalgae will reduce the thermal efficiency since heat is used to drive off the water and consequently this energy is not available for the reduction reactions and for converting thermal energy into chemical bound energy in the gas. Therefore high moisture contents result in low calorific value.



- Although macroalgae to gasification route is very promising, high ash content of macroalgae is one of the major disadvantages associated with this technology. Ash chemistry restricts the use of macroalgae for direct combustion and gasification. Also high ash content reduces the calorific value of the feedstock
- In the case of anaerobic digestion, it is essential to pretreat the macroalgal biomass. The cell walls are rich in lignin and cellulose which restricts digestion. It is essential to homogenize the macroalgal biomass by mechanical crushing.

Although these challenges are significant, the broad public benefit of successfully commercializing macroalgal biofuels warrants placing a high priority on the needed research. Thus, the techniques and technologies for growing macroalgae on a large-scale can be more efficiently developed to overcome these challenges.

# **Summary**

A major limitation of mass culturing seaweeds is the low mass transfer coefficients in seawater, limiting the supply of  $CO_2$ , nitrates and phosphates and other nutrients. In addition, several bacterial diseases and grazing harm the growth of macroalgae and hence reduce their production. Tides, climate and temperature changes have also got a role to play in the production of macroalgae. Careless harvesting practices can have serious and long-lasting effects on the productivity of macroalgae. In the case of anaerobic digestion, it becomes essential to homogenize the macroalgal biomass before the treatment. High moisture contents and high ash content reduce the calorific value of the feedstock and thus make biofuel production difficult.



# **Chapter 10 - Companies and Universities**

**10.1 Companies in Macroalgae to Fuel Efforts 10.2 Universities in Macroalgae to Fuel Research** 

# **10.1 Companies in Macroalgae to Fuel Efforts**

Most companies in the algae to fuels domain use microalgae as the feedstock. A few companies have however started exploring macroalgae as the starting point for biofuel production. This chapter provides more inputs about these companies.

# Seaweed Energy Solutions<sup>16</sup>

Seaweed Energy Solutions AS (SES), a Norwegian based company, built on the development of large-scale offshore cultivation of seaweed and conversion of the same into Biogas and Bioethanol. Their primary goals include:

- Implementing a cost-effective and sustainable ocean farming system for the large scale cultivation of seaweed.
- To develop ideal bio-conversion strategies for the production of Bioenergy from seaweed.
- Maximum utilization of byproducts.
- To ensure overall low costs and optimum environmental effects.

Seaweed Energy Solutions has patented the first ever modern structure, 'the Seaweed Carrier', a breakthrough compared to previous cultivation methods. The Seaweed Carrier, a sheet-like structure basically copies a very large seaweed plant, moving freely back and forth through the sea from a single mooring on the ocean floor. The Seaweed Carrier will allow seaweed cultivation to become a possibility in deeper and more exposed waters, opening the way for large scale production that is necessary to make seaweed a viable source of energy. The Seaweed Carrier is expected to explore the full potential of the seaweeds to be used as a renewable source of energy.

# Technology Used

Seaweed Energy Solutions uses bio-conversion technology to convert biomass into fuel. The carbohydrate content present in the brown seaweeds like mannitol, laminarin and alginate are

<sup>&</sup>lt;sup>16</sup> <u>http://www.seaweedenergysolutions.com</u>



converted to Biogas and Bioethanol. SES is currently running several research and development projects to develop more efficient conversion processes for both biogas and bioethanol. Seaweed Energy Solutions aims to get commercialised through more funds, to mention one from The Research Council of Norway for their ongoing research projects. Patent applications have been filed and future development with existing and new partners are expected to result in compelling competitive energy solutions.

# POD Energy<sup>17</sup>

POD Energy is an open ocean algae biofuel producer which is also involved in CO<sub>2</sub> sequestering and climatic change solution.

# Technology Used

It is a simple technology wherein they use Algae like Kelp, Sargassum which will grow on the top few meters of the oceans utilizing carbon dioxide. These would be harvested and placed in large plastic bags suspended in the sea. Natural bacteria in the bags would digest the kelp, breaking it down into  $CO_2$  and methane. The two gases would be separated, with the  $CO_2$  sent to the deep ocean for permanent storage and the methane piped to the surface for use as a renewable heating and cooking fuel.

# Green Gold Algae and Seaweed Sciences Inc<sup>18</sup>

Green Gold Algae and Seaweed Sciences Inc. is an owned subsidiary of Seaweed Bio-Technology Incorporation (SBTI). GGASS mission is to focus on the usage and applications of macro algae for biofuel. GGASS is based on the growing technologies developed in Israel by NoriTech Seaweed Biotechnologies Ltd. Nori Tech has been growing macroalgae in land based ponds for many years, and it has investigated the use of macro algae growing techniques, including boosting the growth with CO<sub>2</sub>, in order to increase the algae biomass for biofuel applications.

GGASS targeted to produce ethanol from algae owing to the demand of ethanol in US. The choice of macroalgae for the production of ethanol is based on the characteristics that the macroalgae possess such as high carbohydrates/polysaccharides and thin cellulose, high yield per growing area, feasibility to grow in open ponds, relatively low growing costs and CO<sub>2</sub> can be used to boost the growing.

# Technology Used

Algae are converted to ethanol through a series of upstream processes like ethanol fermentation, distillation and centrifugation. It further combines certain proprietary technologies like increasing the synthesis of polysaccharides, preventing nutrient burden by

<sup>&</sup>lt;sup>17</sup> <u>http://www.podenergy.net/</u>

<sup>&</sup>lt;sup>18</sup> http://www.gold-green.com/GGASS/Templates/showpage.asp?DBID=1&LNGID=1&TMID=10000&FID=552



controlling the concentration of fertilizers, using more than one seaweed species in an annual cycle to maximize polysaccharide production, using integrated cultivation, use of inexpensive carbon dioxide source, Using inexpensive hot seawater during winter (from power plants, refineries, etc.) in order to maintain consistent high growth rates, while ambient temperatures are low. These technologies aim at maximum production of ethanol from algae. Thus cultivation technology of macro algae in seawater ponds enriched with commercial CO<sub>2</sub> has been successfully developed and controlled nutrients and growing conditions affected the algal composition such as the ratio of carbohydrates to proteins and volatile solids content.

# Butamax Advanced Biofuels<sup>19</sup>

Butamax Advanced Biofuels was formed in 2009 to develop biobutanol, an advanced premium biofuel molecule.

Biobutanol is an advanced biofuel that will provide improved options for expanding energy supplies and accelerate the move to renewable transportation fuels which lower overall greenhouse gas emissions. This hydrophobic, high energy value biofuel can also be added to gasoline at a higher level without engine modification, and it is believed to have application in both diesel and gasoline blends.

Butamax Advanced Biofuels is a joint venture created by BP and DuPont. It combines BP' expertise in fuels technology, development and infrastructure with DuPont's leading capabilities in biotechnology. The company is based in Wilmington, Delaware, US.

Biobutanol has certain characteristics which serve as an efficient biofuel which includes:

- Having energy content closer to that of gasoline.
- Having a low vapor pressure so that it can be easily added to conventional gasoline.
- It can be used in higher blend concentrations
- Its chemical properties already allow it to be blended at 16% by volume in gasoline, thereby displacing more gasoline per gallon of fuel consumed than the standard 10% by volume ethanol blend.

#### Technology Used

Biobutanol technology mainly focuses on how to produce biobutanol from sugar and starch feedstocks, including lignocellulosic feedstocks, at a price that is competitive with ethanol. The main focus of the new company will be to develop a technology program to produce biobutanol from many different types of feedstocks. In the future, Butamax Advanced Biofuels expects to license the technology to produce biobutanol to other biofuel producers. The company will also work with fuel blenders and distributors globally to introduce biobutanol into the fuels market.

<sup>&</sup>lt;sup>19</sup> <u>http://www.butamax.com/</u>



This joint venture between BP and DuPont will produce and market a next generation of biofuels to help meet increasing global demand for renewable transport fuels.

# Seambiotic Ltd.<sup>20</sup>

Seambiotic an Italian based company, which has been solely concentrating on Microalgae production and deriving products out of it, has unveiled a new technology "efficiently extracting fuel from seaweed", which involves the absorption of  $CO_2$  from fossil-fuel fired power plants. This green technology reports that 1 litre of fuel can be made from 5 kilograms of dried algae. The gas from the plant is passed through a filtration system in which it enters a pool to feed "microscopic seaweed". The technology was developed by Seambiotic Ltd. on an experimental farm located on the site of the Ashkelon power plant, with the support of the Israeli Electric Corporation. The seaweed pools are located several hundred metres from the plant smokestacks, and are filled with seawater that has been used to cool the electric turbines. The seaweed employed grows naturally in the Mediterranean Sea in small amounts, but in the pools the forcing conditions of elevated  $CO_2$  concentrations increase its growth by a factor of one million.

# **Bio Architecture Lab**<sup>21</sup>

Seattle-based Bio Architecture Lab is a pioneer in the application of synthetic biology and enzyme design to the development of biofuels and renewable chemicals from aquafarmed, native macroalgae (seaweed), which is a low cost, scalable, and sustainable biomass. This pioneer company has achieved financial support from many investors. In 2009, BAL was additionally selected by the Department of Energy for an ARPA-E grant in partnership with DuPont as recognition of BAL's breakthrough energy research.

Bio Architecture Lab, a University of Washington spinoff, has built a big part of its business on relationships in Chile. The company has an office in Santiago, and received part of its initial \$8 million venture round from Santiago-based Austral Capital. A Chilean economic development group has poured in another \$7 million, local university and oil industry partners are involved, and some permits have been issued to run a pilot project in Chile's coastal waters.

The U.S. Department of Energy (DOE) Advanced Research Projects Agency-Energy (ARPA-E) has awarded a Technology Investment Agreement to DuPont for the development of a process to convert sugars produced by macroalgae into next-generation biofuels called isobutanol. Bio Architecture Lab (BAL) will be a subrecipient on the program. Under this award, the DOE will fund \$8.8 million and DuPont and BAL will cost share the balance of the total award, forming a joint cost share program between DOE and DuPont. Butamax<sup>™</sup> Advanced Biofuels LLC, a joint

<sup>&</sup>lt;sup>20</sup> http://ergobalance.blogspot.com/2007/07/isreal-makes-biofuel-from-seaweed.html

<sup>&</sup>lt;sup>21</sup> http://www.ba-lab.com/



venture between DuPont and BP, will be responsible for commercialization of the resulting technology package.

This macroalgae-to-isobutanol project will establish technology and intellectual property leadership in the use of macroalgae as a low cost, scalable and environmentally sustainable biomass for biofuel production. Efforts will focus on: improving domestic macroalgae aquaculture; converting macroalgae to bio-available sugars; converting those sugars to isobutanol; and economic and environmental optimization of the production process. More than 60 scientists in Wilmington, Del., and Berkeley, Calif., will work on this research and development program. The macroalgae aquafarming project will be conducted in Southern California.

# Oil fox<sup>22</sup>

Oil fox was established in 1977. Oil Fox and Biocombustibles de Chubut have a joint venture to produce and export biodiesel from seaweed with a \$60m investment. The joint venture was a result of the research conducted by Universidad Nacional de la Patagonia San Juan Bosco. It is expected to produce 800,000 tones of oil per year by 2010.

# Blue Sun Energy<sup>23</sup>

Blue Sun Energy, a Colorado based company is researching on ways of producing Jet Fuel from Seaweed.

Though the costs of fuel production from macroalgae are high, according to the company, the company believes that it has already made advances in biodiesel production that makes it greener and more versatile than other production methods on the market.

# Holmfjord<sup>24</sup>

Holmfjord AS is a small company situated in the northernmost part of Norway. The company is primarily established in a fish - processing plant. Holmfjord has established a small eco-project in Porsanger in Northern Norway as a biofuel production facility.

This project has an advantage of having a vast area for sea weed cultivation. The company plans a biofuel facility using seaweed as raw material. Holmfjord will be cooperating with Norwegian research institutes SINTEF, NOFIMA, NIVA and Bioforsk Nord in this project.

<sup>22</sup> http://www.oilfox.com/

<sup>&</sup>lt;sup>23</sup> <u>http://www.thebioenergysite.com/news/4660/company-developing-biodiesel-from-seaweed</u>

<sup>&</sup>lt;sup>24</sup> <u>http://www.nordicenergysolutions.org/inspirational/biofuel-from-seaweed</u>



# **10.2 Universities in Macroalgae to Fuel Research**

# List of Universities Researching on Deriving Fuel from Macroalgae

University	Link	
Aberystwyth University	http://www.aber.ac.uk/en/	
University of Florence	http://www.unifi.it/	
University of New Haven	http://www.newhaven.edu/	
University of Dundee	http://www.dundee.ac.uk/	
The Energy and Resource Institute	http://www.teriin.org/	
Tokyo University of Marine Science and Technology	http://www.kaiyodai.ac.jp/English/	
University of Minnesota	http://www1.umn.edu/twincities/index.php	
Aarhus University	http://www.au.dk/en	
Scottish Association for Marine Sciences	http://www.sams.ac.uk/	
Sogang University, Korea	http://www.sogang.ac.kr/english/index.html	
Sungkyunkwan University	http://www.skku.edu/eng/	
University of Siena	http://www.unisi.it/internet/home_en.html	
Wessex Institute of Technology	http://www.wessex.ac.uk/	
Israel Oceanic and Limnological Research	http://www.ocean.org.il/MainPageEng.asp	
The Norwegian University of Science and Technology	http://www.ntnu.no/english	
University of Leeds	http://www.leeds.ac.uk/	
Japan's National Institute of Advanced Industrial Science and Technology (AIST)	http://www.aist.go.jp/index_en.html	
Biomara organization	http://www.biomara.org/	
Queen's university Belfast	http://www.qub.ac.uk/	
Dundalk Institute of Technology.	http://ww2.dkit.ie/	
University of ulster	http://www.ulster.ac.uk/	
The Fraser of Allander Institute	http://www.strath.ac.uk/fraser/	
Institute of Technology Sligo	http://www.itsligo.ie/	
University of Strathclyde	http://www.strath.ac.uk/	
The Korea Institute of Industrial Technology (KITECH)	http://www.kitech.re.kr	



The profiles of a few above mentioned universities working on macroalgae are detailed as follows.

# Aberystwyth University<sup>25</sup>

Aberystwyth University is a university located in Aberystwyth, Wales. Aberystwyth was a founding Member Institution of the former federal University of Wales. The Institute of Biological, Environmental and Rural Sciences (IBERS) is a research and education centre at Aberystwyth University.

IBERS is an internationally recognised centre of excellence for the study of biological, environmental and rural sciences, and is a new venture that has brought together staff from the Institutes of Rural Sciences and Biological Sciences at Aberystwyth University, and the Institute of Grassland and Environmental Research (IGER). Around 300 research, teaching and support staff conduct basic, strategic and applied research in biology from the level of genes and other molecules to the impact of climate change and bio-energy on sustainable agriculture and land use. There is formal collaboration with the College of Natural Sciences in Bangor University.

# The Conversion of Marco Algae to Ethanol through Fermentation

The researchers at the Aberystwyth University are doing a project on "The conversion of marco algae to ethanol through fermentation". The project considers the composition and fermentability of selected macroalgae (seaweeds) for their use as a future source of biomass for bioethanol production. This project involves collaboration between universities and research institutes throughout Great Britain and Ireland.

# Tokyo University of Marine Science and Technology<sup>26</sup>

Tokyo University of Marine Science and Technology was established by merging Tokyo University of Mercantile Marine and Tokyo University of Fisheries on October 1, 2003. Tokyo University of Marine Science and Technology plays a significant role in maritime education within Japan, since both pioneering predecessor universities specialized in related fields based upon traditions of over one hundred years.

# Seaweed Farm Holds Promise for Biofuel Production

The Fisheries Research Agency with Tokyo University of Marine Science and Technology started the study on new technologies to produce ethanol from seaweed and water plants in fiscal 2007, funded by the Japanese Fisheries Agency under the project of developing technology for

<sup>&</sup>lt;sup>25</sup> <u>http://www.aber.ac.uk/en/</u>

<sup>&</sup>lt;sup>26</sup> <u>http://www.kaiyodai.ac.jp/English/</u>



utilizing marine biomass as a new energy resource. Based on the study, a research team led by Professor Naoto Urano of the university and Motoharu Uchida, a senior researcher of the agency, confirmed the yield of ethanol per unit weight of seaweed and water plants when being produced through fermentation.

A group of researchers from Marine Science and Technology, Mitsubishi Research Institute, Mitsubishi Heavy Industries and several other private-sector firms envision a 10,000 square kilometer seaweed farm at Yamatotai, a shallow fishing area in the middle of the Sea of Japan. The researchers estimate that the farm will produce about 20 million kiloliters of bio-ethanol per year. This is equal to one third of Japanese fuel consumption per year.

The group is also conducting research on how to develop the production plants and attract investment. Other participants in the project include NEC Toshiba Space Systems, Mitsubishi Electric, IHI, Sumitomo Electric Industries, Shimizu Corporation, Toa Corporation, Kanto Natural Gas Development Co., Ltd., and the Japan Agency for Marine-Earth Science and Technology (JAMSTEC).

The researchers claim that in addition to serving as a source of fuel, the seaweed will also serve a noble duty by cleaning the Sea of Japan. According to Professor Masahiro Notoya of Marine Science and Technology, the seaweed would work to remove some of the excess nutrient salts that flow into the sea from the surrounding land masses.

# Aarhus University<sup>27</sup>

Aarhus University, located in the city of Århus, Denmark, is Denmark's second oldest and second largest university.

# Seaweed for Biofuels

Researchers from the University are looking at a species of seaweed known as 'sea lettuce' (Ulva lactuca) as a potential feedstock for the production of ethanol. Michael Bo Rasmussen of the National Institute of Environmental Research at the University has already carried out two tests with the algae and thinks harvesting them as a biomass source might make sense. The species grows fast, doubling its biomass every three to four days.

Rasmussen estimates the theoretical yearly yield to be between 200 and 500 tons of wet biomass on a 'hectare' basis (even though comparisons with terrestrial plants are difficult). Denmark's total potential would be an annual production of around 80,000 to 100,000 tons. Like Japanese researchers, the Danish scientists are thinking of cultivating the algae on a large scale.

<sup>&</sup>lt;sup>27</sup> http://www.au.dk/en



Rasmussen's project is one of the proposals selected for funding by the Aarhus Research Foundation, which is freeing up 48 million kroner (€6.4/US\$8.8 million) for 16 different projects over the 2007-2011 period.

### **BioMara Research Project**

The Sustainable Fuels from Marine Biomass project, BioMara, is a new UK and Irish joint project that aims to demonstrate the feasibility and viability of producing third generation biofuels from marine biomass.

Researchers from six different institutions across the UK and Ireland are investigating the potential use of both micro and macro-algae as alternatives to terrestrial agri-fuel production.

The partners in the project include:

- Scottish Association for Marine Science
- Centre for Renewable Energy, Dundalk Institute of Technology.
- Centre for Sustainable Technologies, University of Ulster
- Fraser of Allander Institute, University of Strathclyde
- Institute of Technology, Sligo
- The Questor Centre, Queen's University Belfast

BioMara has received €4,874,414 from the European Union's INTERREG IVA Programme, with additional funding from Highlands and Islands Enterprise, the Crown Estate, Northern Ireland Executive and the Irish Government.

The project's lead scientist, Dr Michele Stanley, explains: "With global fossil fuel supplies dwindling and atmospheric carbon dioxide levels affecting climate change, there is an urgent need for new, renewable fuel sources with low net carbon emissions."

# 1. Scottish Association for Marine Sciences<sup>28</sup>

Scottish Association for Marine Science is a leading Marine Research Institute, conducting research and degree level teaching in marine biology, oceanography, climate, renewable energy, and biogeochemistry globally.

Macroalgae for Biofuel Production

<sup>&</sup>lt;sup>28</sup> <u>http://www.sams.ac.uk/research/research-themes/marine-renewable-energy-research/biofuel-from-marine-plants</u>



SAMS scientists are investigating the potential and practicality of using both micro-and macroalgae for biofuel production. In collaboration with five other scientific institutes in the Interreg IV region, the Biomara project utilises SAMS' expertise to investigate the potential of marine algae to meet our energy needs.

Researchers of SAMS are doing research on the following topics:

- Exploring the potential for harvesting and farming seaweeds
- Indentifying the most suitable contender species with regard to growth and fuel conversion rates
- Investigating the most suitable fermentation / digestion procedures
- Exploring the scale-up potential for different options.

# 2. Centre for Renewable Energy at Dundalk IT (CREDIT)<sup>29</sup>

CREDIT was established in June 2002 with a mission to assist Ireland's coming transition to a renewable energy-based economy. It is in the process of becoming a national focal point for renewable energy research and development and academic programmes. Their research themes are wind energy with specific focus on small and medium wind systems, electricity storage in flow battery systems and bioenergy from marine sources.

# 3. Centre for Sustainable Technologies, University of Ulster<sup>30</sup>

The University of Ulster is a multi-campus university located in Northern Ireland and is the largest single university in Ireland, discounting the federal National University of Ireland. The Centre for Sustainable Technologies undertakes multidisciplinary research to design, create, develop, improve, demonstrate and evaluate emerging, existing and alternative sustainable renewable energy, building design, construction materials, transport and environmental modification technologies.

# 4. Fraser of Allander Institute, University of Strathclyde<sup>31</sup>

The University of Strathclyde, Glasgow, Scotland, is Glasgow's second university by age, founded in 1796, and receiving its Royal Charter in 1964 as the UK's first technological university. The Fraser of Allander Institute is a research unit of the University of Strathclyde in Glasgow and is formally part of the Department of Economics and the Strathclyde Business School. The Institute carries out research on regional issues generally and the Scottish economy in particular, including forecasting and the analysis of short-term and medium-term movements in Scottish economic activity.

<sup>&</sup>lt;sup>29</sup> http://ww2.dkit.ie/research/credit

<sup>&</sup>lt;sup>30</sup> <u>http://www.cst.ulster.ac.uk/</u>

<sup>&</sup>lt;sup>31</sup> <u>http://www.strath.ac.uk/fraser/</u>



# 5. Institute of Technology, Sligo <sup>32</sup>

The IT Sligo is one of Ireland's most successful third level educational institutions. IT Sligo is a focus for local business innovation and development and we have an excellent track record in collaborating with businesses, the community and the creative industries across our core disciplines of Business and Humanities, Engineering and Science.

6. Queen's University Belfast<sup>33</sup>

The QUESTOR Centre at Queen's University Belfast is an industry/University Co-operative Research Centre for environmental research and development.

The Centre carries out a multi-disciplinary environmental research programme on behalf of a fee-paying membership that includes industry (both multi-nationals and smaller local companies), government agencies and local councils. Research topics address the needs of the membership and include water and wastewater treatment, remediation of contaminated land, environmental monitoring and analysis, resource management and renewable energy.

# National Institute of Advanced Industrial Science and Technology (AIST)<sup>34</sup>

National Institute of Advanced Industrial Science and Technology (AIST) is a large research institute with a number of branches around Japan and a number of campuses around Tsukuba.

Researchers from the Biomass Technology Research Center at Japan's National Institute of Advanced Industrial Science and Technology are investigating the potential of ethanol production from macro green algae.

They collected 10 species of macro green algae in Thailand, Vietnam and Japan, classified into 3 families, and determined the monosaccharide composition. Cheatomorpha aereas collected in Vietnam was the most glucose-rich sample of these samples, about 300 mg of glucose per gram of organic matter. Experiments of enzymatic saccharification and the ethanol fermentation were carried out by using Ulva spp. collected in Japan. The glucose yield was about 95% by using Acremonium cellulase after pretreatment in an autoclave (120 °C, 20 min).

Efficiency of ethanol fermentation using S. cerevisiae IR-2 after the enzymatic saccharification was about 90%. More than 4 % (w/v) of NaCl concentration inhibited the ethanol fermentation, while the effect of NaCl concentration for the saccharification was small.

<sup>33</sup> <u>http://www.qub.ac.uk/</u>

<sup>&</sup>lt;sup>32</sup> <u>http://itsligo.ie/</u>

<sup>&</sup>lt;sup>34</sup> http://www.aist.go.jp/



# Summary

This chapter provides details on the companies and universities which are actively researching the macroalgae to fuel process. Most companies in the algae to fuels domain use microalgae as the feedstock. A few companies have however started exploring macroalgae as the starting point for biofuel production. Their goal is to develop and implement a cost efficient and sustainable method for the production of bioenergy with low overall costs and optimum environmental effects. A few companies like the Blue Sun Energy are researching ways of turning seaweed into jet fuel.

Most of the companies using macroalgae are still in the initial stages of research and development waiting for an outbreak. List of universities working on macroalgae projects are also tabulated in this chapter.



# **Chapter 11 - Case Studies in Fuel Production from Macroalgae**

# Scientists See Scottish Seaweed as Green Energy Source<sup>35</sup>

#### 30 October 2008

Seaweed farms off Scotland's coast could help the country cut its carbon emissions, according to research by the Scottish Association for Marine Science (SAMS).

Such farms could produce sustainable biofuel while avoiding the problems of producing it on dry land using crops like willow. One of the most serious problems is that growing crops for biofuel takes up agricultural land that could be used for food, driving up food prices. Biofuel crops' heavy use of water is also a concern, and Scotland's cool, wet climate is poorly-suited to growing energy-rich crops.

Seaweed could get round these problems. Marine algae offer a vast renewable energy source for countries around the world that have a suitable coastline available. Fuel that doesn't cause carbon emissions could be a valuable tool in achieving the UK government's recently-announced goal of cutting emissions to 20% of 1990's levels by 2050.

The idea is that kelp would be harvested and placed in a large digester to be broken down by bacteria to form methane or ethanol. This could then be burned for electricity or heat. Comparatively few residues remain - seaweed contains much smaller quantities of tough lignin and cellulose than land plants - but what is left over at the end can be used as a fertilizer.

The potential of marine biomass for anaerobic biogas production suggests that pilot programs be set up in the shallow waters of Scotland's west coast to test the idea. These would probably involve floating rafts, with seaweed growing on surfaces suspended beneath.

#### Harvesting kelp forests

Seaweeds are extremely productive plants, with natural stands of brown kelp thought to produce between 16 and 65 kilos of biomass per square meter each year - a great deal compared to land plants like sugar cane, which produces just 8-18 kilos in the same area. Getting these harvests would probably involve developing some kind of aquatic version of a combined harvester so that banks of kelp could be cut quickly and without too much human input.

<sup>&</sup>lt;sup>35</sup> <u>http://planetearth.nerc.ac.uk/news/story.aspx?id=226</u>



Wild seaweed could be a good starting-point, though. One survey suggests that there is around 8,000 square kilometers of potential seaweed habitat in Scotland's sub-littoral waters - the area between the low tide mark and the edge of the continental shelf - though only around 1,000 square kilometers of this had enough seaweed growing for commercial harvesting to be viable. Kelp forests are dense and fast-growing so they should have no problem recovering from periodic harvesting. Norway has similar seaweed stocks to Scotland, and harvests 130,000-180,000 tonnes per year sustainably.

Another benefit is that the seaweed farms would provide valuable habitat for marine animals, helping increase biodiversity. SAMS did the research on commission from The Crown Estate, which owns most of the seabed as far as 12 nautical miles off the coast and hopes to take advantage of the opportunities for seaweed harvesting.

The Crown Estate estimates that, given Scotland's rugged western coastline and island groups, and relatively clean seas, it is sensible to examine the farming of seaweeds and sustainable harvesting of natural supplies as a source of energy, to heat our homes and fuel our vehicles. Heating and transport make up around three quarters of our energy use so it's vital that we find new ways of meeting that demand according to them.

Scotland can provide for much of its energy needs with sources like wind, rivers and wave power. But biofuel from seaweed could let it diversify its energy supply even further. Seaweed harvesting is a traditional activity in many parts of Britain; during the 17th and 18th centuries, countries including France, Scotland and Norway had flourishing kelp industries, though many, including Scotland's, did not survive the twentieth century.

In the US, though, commercial research continued throughout much of the last century, and today kelp is harvested on a massive scale in China and elsewhere in East Asia.

The idea isn't without its potential problems. For example, it's not certain how far the public will accept the farming of large areas of the sea. But the process is likely to have a much smaller impact than current exploitation of the sea via the fishing industry.

The large-scale culture of seaweeds may prove to be a relatively environmentally inert practice, or even to be beneficial in terms of the sequestering of carbon, providing habitat for fish, increasing biodiversity and extracting nutrients of anthropogenic, agricultural or aquacultural origin from the marine environment.<sup>36</sup>

US - Colorado Company, Blue Sun Energy, is Researching Ways of Turning Seaweed into Jet Fuel.

October 2009

<sup>&</sup>lt;sup>36</sup> <u>http://planetearth.nerc.ac.uk/news/story.aspx?id=226</u>



The project funded by a federal grant, aims at finding a production system that is affordable.

Blue Sun Energy revealed that it costs about \$20 a gallon to produce biodiesel out of algae at the present and the company's aim is to get the costs down to under \$2 a gallon. The company believes that it has already made advances in biodiesel production that makes it greener and more versatile than other production methods on the market.

The company produces a premium fuel that takes care of a lot of the shortcomings of generic bio diesel.

The company says its product reduces emissions of pollutants including global warming gases like nitrogen oxide. According to the company, many biodiesel products actually increase nitrogen oxide emissions.

Blue Sun Energy also claims its additive helps boost fuel economy by seven per cent, reduces wear in fleet vehicles and even improves performance in cold-weather conditions.<sup>37</sup>

#### Japanese Companies and Researchers Working on Macroalgae to Ethanol Production

Jun 2009

A group of researchers from Tokyo University (Marine Science and Technology), Mitsubishi Research Institute, Mitsubishi Heavy Industries and several other private-sector firms envision a 10,000 square kilometer seaweed farm at Yamatotai, a shallow fishing area in the middle of the Sea of Japan. The researchers estimate that the farm will produce about 20 million kiloliters of bioethanol per year. This is equal to one third of Japanese fuel consumption per year.

Macroalgae has long been discussed as an alternative option to produce bio fuel. Most biofuel today is produced from corn and sugar cane. According to the proposal the seaweed to be grown in the farm is from sargasso seaweed (hondawara). This type of seaweed grows rapidly.

There will be floating bioreactors which are special facilities that use enzyme to break the seaweed down into sugars. The seaweed would then be prepared for conversion into ethanol. The conversion will be done at sea and tankers then transport the ethanol to land.

There are two main components of algae/seaweed that raise interest in producing bioethanol. They are Fucoidan and Alginic Acid. While an enzyme for breaking down fucoidan has already been discovered, the scientists are looking for an enzyme that breaks down alginic acid. They are also looking at the possibility of genetically modifying the algae.

The group is also conducting research on how to develop the production plants and attract investment. Other participants in the project include NEC Toshiba Space Systems, Mitsubishi

<sup>&</sup>lt;sup>37</sup> <u>http://www.thebioenergysite.com/news/4660/company-developing-biodiesel-from-seaweed</u>



Electric, IHI, Sumitomo Electric Industries, Shimizu Corporation, Toa Corporation, Kanto Natural Gas Development Co., Ltd., and the Japan Agency for Marine-Earth Science and Technology (JAMSTEC).

The researchers claim that in addition to serving as a source of fuel, the seaweed will also serve a noble duty by cleaning the Sea of Japan. According to Professor Masahiro Notoya from Tokyo University of Marine Science and Technology, the seaweed would work to remove some of the excess nutrient salts that flow into the sea from the surrounding land masses.<sup>38</sup>

# Bio Architecture Lab to Develop Seaweed Ethanol Project to Replace 5 Percent of Chilean Gasoline Usage<sup>39</sup>

#### Nov 2009

In Chile, Bio Architecture Lab is in a research partnership with DuPont to develop seaweed as a biobutanol feedstock, has founded BAL Chile, and will develop a 240-acre pilot seaweed farm on the island of Chilé. The \$5 million project will include a pilot ethanol production facility that will be located in Los Lagos. BAL has developed microorganisms that ferment the algae into ethanol and has partnered with local Chilean companies and universities on the project. The project is expected to increase to a 24,000 acre harvest area spanning the entire coastline of the country that will produce enough ethanol to replace 5 percent of Chilean gasoline consumption.

#### New Seaweed Cultivation Structure may Open up Ocean Floors for Energy Production<sup>40</sup>

#### April 2010

In Norway, Seaweed Energy Solutions has patented the first ever modern structure to enable mass seaweed cultivation on an industrial scale in the world's oceans. The structure, known as the Seaweed Carrier, makes a clean break with past seaweed cultivation methods that have all been based on ropes. The Seaweed Carrier is a sheet-like structure that basically copies a very large seaweed plant, moving freely back and forth through the sea from a single mooring on the ocean floor.

<sup>&</sup>lt;sup>38</sup> <u>http://www.blogonsmog.com/motor-monday/seaweed-farms-hold-promise-for-biofuel-production.html</u>

<sup>&</sup>lt;sup>39</sup><u>http://www.biofuelsdigest.com/blog2/2009/11/26/dupont-bio-architecture-lab-secure-9-million-from-arpa-e-for-macroalgal-biofuels-rd/</u>

<sup>&</sup>lt;sup>40</sup> <u>http://www.biofuelsdigest.com/bdigest/2010/04/08/new-seaweed-cultivation-structure-may-open-up-ocean-floors-for-energy-production/</u>



The Seaweed Carrier will allow seaweed cultivation to become a possibility in deeper and more exposed waters, opening the way for large scale production that is necessary to make seaweed a viable source of energy. According to SES, growing seaweed in farms covering an area of just less than 0.05 percent of Europe's coastal regions would yield a yearly production of 75 million tons of seaweed. This biomass could be converted into an estimated 846 Mgy (3.2 billion liters) of ethanol, about 4.7 percent of the global ethanol production in 2008.

# ARPA-E Funds Dupont, BAL Project to Convert Macroalgae into Isobutanol

March 2010

In Delaware, the DOE's Advanced Research Projects Agency-Energy (ARPA-E) has awarded a Technology Investment Agreement to DuPont for the development of a process to convert sugars produced by macroalgae into next-generation biofuels called isobutanol. Bio Architecture Lab will be a subrecipient on the program. Under this award, the DOE will fund \$8.8 million and DuPont and BAL will cost share the balance of the total award, forming a joint cost share program between DOE and DuPont.

Butamax Advanced Biofuels, a joint venture between DuPont and BP, will be responsible for commercialization of the resulting technology package. The macroalgae-to-isobutanol project will establish technology and intellectual property leadership in the use of macroalgae as a low cost, scalable and environmentally sustainable biomass for biofuel production.

Their efforts will focus on:

- Improving domestic macroalgae aquaculture
- Converting macroalgae to bio-available sugars
- Converting those sugars to isobutanol
- Economic and environmental optimization of the production process.

More than 60 scientists in Wilmington, Del., and Berkeley, Calif., will work on this research and development program. The macroalgae aquafarming project will be conducted in Southern California.<sup>41</sup>

#### Summary

This chapter gives a list of case studies wherein macroalgae is focused for fuel production.

A group of researchers from Tokyo University state that macroalgae would be a better option than cane sugar or corn for biofuels. They use floating bioreactors to break the seaweed down

<sup>&</sup>lt;sup>41</sup> <u>http://biofuelsdigest.com/bdigest/2010/03/05/arpa-e-funds-dupont-bal-project-to-convert-macroalgae-into-isobutanol/</u>



into sugars which would then be prepared for conversion into ethanol. They are also looking at the possibility of genetically modifying the algae.

Blue Sun Energy aims at finding a production system that is affordable and could also reduce emissions. In regions like Scotland where the climatic conditions do not support the growth of biofuel crops, macroalgae proved to have the potential to grow faster and denser and are hence easy to recover after harvesting. Various methods were proposed to harvest macroalgae efficiently. The idea is that kelp would be harvested and converted to methane or ethanol. This could then be burned for electricity or heat. The left over at the end can be used as a fertilizer. Several other studies are also being made on the efficiency and use of macroalgae.



# **Chapter 12 - Research and Experiments**

Production of Biodiesel from Macroalgae by Supercritical CO<sub>2</sub> Extraction and Thermochemical Liquefaction<sup>42</sup>

# October 2005

Comparison of two different techniques for the extraction of biodiesel from macroalgae: the thermochemical liquefaction and the extraction using supercritical carbon dioxide (sc-CO<sub>2</sub>).

The first allows using wet material, while sc-CO<sub>2</sub> requires dry material and uses moderate temperature and pressure so that it can be useful for the extraction of thermolabile compounds which may decompose at the temperature at which thermal methods are carried out. In both cases the extracted oil was characterized quantitatively and qualitatively.

# Biofuel Potential Production from the Orbetello Lagoon Macroalgae: A Comparison with Sunflower Feedstock<sup>43</sup>

#### December 2007

The diversification of different types and sources of biofuels has become an important energy issue in recent times. The aim of this work is to evaluate the use of two kinds of renewable feedstocks in order to produce biodiesel. The potential production of oil from two species of macroalgae considered as waste coming out from a lagoon system involved in eutrophication and from sunflower seeds was analyzed.

Oil extraction yields of both feedstocks were tested. Furthermore, a comparison has been carried out based on the energy approach, in order to evaluate the sustainability and environmental performance of both processes.

The results show that, under present conditions, considering oil extraction yields, the production of oil from sunflower seeds is feasible, because of the lower value of transformity of the final product with respect to macroalgae. On the other hand, the results demonstrate that with improvements of oil extraction methodology, macroalgae could be considered a good residual biomass usable for biofuel production.

<sup>&</sup>lt;sup>42</sup> http://www.springerlink.com/content/70700h325742746m/

<sup>&</sup>lt;sup>43</sup><u>http://www.sciencedirect.com/science?ob=ArticleURL&udi=B6V22-4RWHGRT-</u>

<sup>&</sup>lt;u>1& user=10& rdoc=1& fmt=& orig=search& sort=d& docanchor=&view=c& searchStrld=1075497951& rerunO</u> rigin=scholar.google& acct=C000050221& version=1& urlVersion=0& userid=10&md5=feb27498b1ae8c7d3745e <u>9baaad3593f</u>



# Use of Macroalgae for Marine Biomass Production and CO<sub>2</sub> Remediation<sup>44</sup>

#### November 1993

Biomass production from macroalgae has been viewed as important mainly because of the need for pollution abatement. This report shows that macroalgae have great potential for biomass production and CO<sub>2</sub> bioremediation. Macroalgae have high productivity, greater than the most productive land plants, and do not compete with terrestrial crops for farm land. The review focuses on recent data on productivity, photosynthesis, nutrient dynamics, optimization and economics. Biomass from macroalgae promises to provide environmentally and economically feasible alternatives to fossil fuels. Nevertheless, the techniques and technologies for growing macroalgae on a large-scale and for converting feedstocks to energy carriers must be more fully developed.

# Utilization of Macro-algae for Enhanced CO<sub>2</sub> Fixation and Biofuels Production: Development of Computing Software for an LCA Study<sup>45</sup>

2005

A Life Cycle Assessment study was carried out for evaluating the potential of utilizing marine biomass for energy production. Macro-algae obtained from the Adriatic and Jonian seas have been selected and tested for our initial case. Different techniques (supercritical CO<sub>2</sub>, organic solvents, and pyrolysis) were utilized in this study for the extraction of biofuel. Supercritical CO<sub>2</sub> appears to be the most effective. A computing software has been developed which allows evaluating various options and can be used with either aquatic or terrestrial biomass. It has been used in the studies to make an energetic evaluation of selected marine macro-algae.

# Utilization of Macro-algae for Enhanced CO<sub>2</sub> Fixation and Energy Production<sup>46</sup>

2004

The aquatic biomass represents a very interesting source of energy as it has a higher photosynthetic activity with respect to terrestrial plants, an easy adaptability to grow in different conditions, the possibility of growing either in fresh- or marine waters, avoiding the use of land. Either marine micro-algae or sea-weeds could be used as energy source also if the micro-algae have received much attention with respect to the macro-algae.

<sup>&</sup>lt;sup>44</sup> http://www.springerlink.com/content/p35778p030115277/

<sup>&</sup>lt;sup>45</sup> <u>http://moritz.botany.ut.ee/~olli/b/Aresta05.pdf</u>

<sup>&</sup>lt;sup>46</sup> <u>http://www.anl.gov/PCS/acsfuel/preprint%20archive/Files/49 1 Anaheim 03-04 0855.pdf</u>



The research focuses the use of selected Mediterranean macro-algae as source of biofuel. The extraction of oils and biofuel has been carried out using different technologies under mild energetic conditions. Supercritical-carbon dioxide and solvent extraction has been used efficiently to extract the fuel.

The SC-CO<sub>2</sub> extraction is quite advantageous. SC-CO<sub>2</sub> is not toxic and, as its critic temperature is quite close to room temperature, it could be also used for the extraction of thermo-labile compounds. A preliminary balance, energetic and economic, will be also presented. Particular attention has been dedicated to the preparation of samples for extraction in order to ameliorate the efficiency of the process, and to the characterization of the lipid content.

### Classification of Macroalgae as Fuel and its Thermochemical Behaviour<sup>47</sup>

2007

A preliminary classification of five macroalgae from the British Isles; *Fucus vesiculosus, Chorda filum, Laminaria digitata, Fucus serratus, Laminaria hyperborea, and Macrocystis pyrifera* from South America, has been presented in terms of a Van Krevelen diagram. The macroalgae have been characterized for proximate and ultimate analysis, inorganic content, and calorific value. The different options for thermal conversion and behaviour under combustion and pyrolysis have been evaluated and compared to several types of terrestrial biomass including Miscanthus, short rotation Willow coppice and Oat straw.

Thermal treatment of the macroalgae has been investigated using thermogravimetry (TGA) and pyrolysis-gc-ms. Combustion behaviour is investigated using TGA in an oxidising atmosphere. The suitability of macroalgae for the different thermal processing routes is discussed. Ash chemistry restricts the use of macroalgae for direct combustion and gasification. Pyrolysis produces a range of pentosans and a significant proportion of nitrogen containing compounds. High char yields are produced.

### Bioethanol Potential from Marine Residual Biomass: An Energy Evaluation<sup>48</sup>

Different types and sources of biofuels were recently studied as potential energy issues. The aim is to evaluate the use of new kinds of renewable and alternative feedstocks for producing bioethanol. In particular, the potential production of bioethanol from cellulosic material was analyzed considering two species of macroalgae (*C.linum*, *G.longissima*) as residual biomass from a eutrophic lagoon system.

<sup>&</sup>lt;sup>47</sup> <u>http://www.sciencedirect.com/science? ob=ArticleURL& udi=B6V24-4RKDPK0-</u>

<sup>2&</sup>amp;\_user=10&\_rdoc=1&\_fmt=&\_orig=search&\_sort=d&\_docanchor=&view=c&\_searchStrld=1075534161&\_rerunO rigin=scholar.google&\_acct=C000050221&\_version=1&\_urlVersion=0&\_userid=10&md5=bc802d6e538b25008973 8da54fb644ea

<sup>&</sup>lt;sup>48</sup> <u>http://library.witpress.com/pages/PaperInfo.asp?PaperID=20388</u>



Besides chemical analyses and the evaluation of yields in producing bioethanol, accounting methods are necessary to understand the level of sustainability of the whole production process exploiting natural resources. An assessment was carried out based on the energy approach, in order to evaluate the environmental performance of processes in the case study. Results showed that macroalgae are a good candidate for bioethanol production even if bioethanol conversion from macroalgae biomass was found to be not very efficient. Nevertheless, the feedstock may be involved in processes of biorefinery in systems with high carbohydrate content, in which heat necessary to treat the feedstock and maintain the micro organisms performing the transformation are provided by external sources already existing (e.g. a combined heat and power plant).

### Macroalgal (Seaweed) Biomass: An Attractive Algae Biofuel<sup>49</sup>

#### September 2009

Macroalgae are a most attractive biofuel group. Yields can be much higher than land biofuel crops, while freshwater and arable land is not required. Therefore, microalgae do not compete with food crops. While some microalgae are better suited for biodiesel production, cost is prohibitive, often  $\geq$  US\$ 5000/mt dry weight. Conversely, the bulk of macroalgae trade in international markets is below US\$ 1000/mt dry weight and often well below US\$ 5000/mt dry weight. Macroalgal culture can exhibit a rather positive energy budget; net energy budgets upto 11,000 MJ (3,055 kwh, 2600 million calories)/mt dry weight has been reported. Biomass yield can be as high as 80 mt dw/ha/yr.

The low production costs of macroalgae relative to microalgae result from the much lower cost of infrastructure, maintenance of optimal density and harvest. Being the largest segment in world mariculture, extensive technologies are carried out mostly in warm coastal seawater, using sunlight and nutrients that are brought in by currents of the sea. Finally, cost-effective technologies already exist to turn seaweed biomass into biodiesel, ethanol and methane as well as gasification and direct combustion in power stations.

#### Methane Production from Marine, Green Macro-Algae<sup>50</sup>

#### January 1983

Fermentation studies have been carried out to produce methane from green algae native to Scandinavian waters and suitable for large scale cultivation. Long term semicontinuous fermentations during mesophilic and thermophilic conditions were performed as well as batch

<sup>&</sup>lt;sup>49</sup> <u>http://www.scribd.com/doc/19706159/Neori-AbstractAlgae-as-Biofuels-2nd-Algae-Biomass-Summit-India-Spet-</u> 2009

<sup>&</sup>lt;sup>50</sup> <u>http://www.osti.gov/energycitations/product.biblio.jsp?osti\_id=5283775</u>



fermentations in flasks and syringes. A mixed inoculum was prepared from sediments, rotting seaweed, sewage sludge and rumen contents. Methane production from the seaweed substrate, consisting of ground green algae without any nutrient additions, started immediately in this culture, mesophilicly as well as thermophilicly.

Fermentations were carried out with retention times from 27 to 11 days and loading rates from 1.1 to 2.6 g volatile solids (VS) per litre per day. In the mesophilic fermentation gas yields were 250-350 ml CH/sub 4//g VS and the VS-reduction was around 50 - 55% at all tested retention times and loading rates. The level of volatile fatty acids was very low in this system. In the thermophilic digestor gas yields were somewhat lower although the VS-reduction was around 50% also in this system.

The VFA-levels were higher and the culture more sensitive to disturbances. Thus no advantages were found with the thermophilic fermentation. In mesophilic batch fermentations the gas production was rather rapid and almost completed after 12-15 days, in agreement with the continuous fermentations. The gas yields in batch experiments were 350-480 ml CH/sub 4//g VS.

# Ethanol Production from Seaweed Extract<sup>51</sup>

#### November 2000

Extracts from *Laminaria hyperborea* could possibly be fermented to ethanol commercially. In particular, seaweed harvested in the autumn contains high levels of easily extractable laminaran and mannitol. Four microorganisms were tested to carry out this fermentation, one bacterium and three yeasts. Only *Pichia angophorae* was able to utilize both laminaran and mannitol for ethanol production, and its substrate preferences were investigated in batch and continuous cultures. Laminaran and mannitol were consumed simultaneously, but with different relative rates.

In batch fermentations, mannitol was the preferred substrate. Its share of the total laminaran and mannitol consumption rate increased with oxygen transfer rate (OTR) and pH. In continuous fermentations, laminaran was the preferred substrate at low OTR, whereas at higher OTR, laminaran and mannitol were consumed at similar rates. Optimisation of ethanol yield required a low OTR, and the best yield of 0.43 g ethanol (g substrate)<sup>-1</sup> was achieved in batch culture at pH 4.5 and 5.8 mmol  $O_2 I^{-1} h^{-1}$ . However, industrial production of ethanol from seaweed would require an optimization of the extraction process to yield a higher ethanol concentration.

<sup>&</sup>lt;sup>51</sup> <u>http://www.springerlink.com/content/95c34ej9x1p8lumw/</u>


## Methane Fermentation of Seaweed Biomass<sup>52</sup>

2006

A field test plant was built for practical use of macroalgae to produce biogas in large scale. Maximum treating capacity of this plant is one ton-seaweed/day. The effective way to exchange biogas to energy has been researched at same time. A project of this field test is cooperated with new energy and industrial technology development organization (NEDO) in Japan. Seaweeds of Ulva sp. and Laminaria sp. were used as materials in this field test.

Methane fermentation process is proper to exchange seaweeds to fuel of gas because of the high concentration of water (about 90%). This field test plant consists of four parts (pre-treatment, fermentation, biogas storage and generation).

- In pre-treatment part, seaweeds are smashed and diluted with water to suppress the effect of salt and make appropriate slurry.
- In fermentation part, there are two processes (pre-fermentation and methane fermentation) for a higher efficiency of fermentation.
  - The seaweed slurry is treated by pre-fermentation (acid production) and use of methane fermentation as substrate. Capacity of a pre-fermentation tank is 5 kl.
  - In the methane fermentation process biogas is produced. Capacity of a methane fermentation tank is 30 kl.
- Biogas is refined (de-sulfur) and stored in a gasholder (30 kl). Residue of methane fermentation is dehydrated and used as fertilizer.
- Biogas is mixed with city gas (natural gas) and fed to the gas engine generator (a cogeneration system). A gas mixer of the engine was improved to mix with biogas and city gas.

An equipment of deodorization using microorganisms is set. Seaweeds of Laminaria sp. as test materials were continuously supplied (0.2 to finally 1 ton/day). Composition of the biogas was about 60 % methane and 40 % carbon dioxide. One ton-seaweed yields 22 kl methane gas. In this test biogas had been produced continuously for over 150 days. Seaweeds of Ulva sp. collected on seashore were also tested. Amount of 0.6 ton/day (TS=3%) of Ulva sp. was supplied. Conditions of the fermentation were same as the test of seaweeds of Laminaria sp. Composition of the biogas was about 60 % methane and 40 % carbon dioxide. Yield of methane gas was 17 kl/ton-seaweed. The yield was lower than the case of the seaweeds of Laminaria sp. Results of these tests show it is possible to produce biogas from seaweeds (Laminaria, Ulva sp.) in condition of practical use. Biogas after de-sulfur is used as fuel of gas engine for generating electricity in this field test plant.

<sup>&</sup>lt;sup>52</sup> http://aiche.confex.com/aiche/2006/preliminaryprogram/abstract\_73948.htm