Seaweed Biofuel Derived from Integrated Multi-trophic Aquaculture

Amita Jacob, Ao Xia, Daryl Gunning, Gavin Burnell, and Jerry D. Murphy

***Abstract*—Aquaculture contributed 23.8 million tonnes of aquatic algae globally in 2012. Increasing consumption of seaweed (as food, for the production of hydro-colloids, and for production of third generation biofuels) will lead to an upward trend in its production and cultivation. Aquaculture contributed 66.6 million tonnes of fish in 2012, 42 % of global production. Fish demand globally is rising to meet food and nutritional requirements; aquaculture for fish will grow. However fish farms are marred by criticism of pollution caused by discharge of waste. Integrated multi-trophic aquaculture can reduce pollution through co-culture of several species such as seaweed and mussels that utilise waste disposed from fish farms for their growth and development.**

A model is investigated which would provide 1.25% of energy in transport in the EU from seaweed. This would involve annual production of 168Mt of seaweed (in excess of present world harvest) integrated with 13Mt of farmed salmon. Themodel proposes 2603 anaerobic digesters, each treating 64,500 t/a of *Saccharinalatissima* in coastal digesters adjacent to natural gas infrastructure for downstream use in natural gas vehicles.

***Index Terms*—Bio-methane, gaseous biofuel, hydro-colloids, integrated multi-trophic aquaculture, seaweed.**

I. Introduction

A. The Market for Seaweed

Seaweed (macro-algae) is extensively used as a food in several countries including China, Japan and the Republic of Korea. In the last decade seaweeds have been used to produce hydrocolloids in the food processing and cosmetics industry. Recent applications of seaweeds include in the field of bio-catalysis, bio-plastics, pharmacology and textiles. The level of use of seaweed is excessive for natural stocks; hence close to 90 % of the seaweed used today comes from aquaculture [1]. There has been a significant increase in the production of farmed aquatic plants. The FAO reported a production of 15.8 million Tonnes (wet weight) of aquatic plants in 2008 from aquaculture; 99.6% of this production is seaweed and by 2013 the aquaculture harvest rose to 26.1 million tonnes of aquatic plants; again the majority of which is seaweed [2]. This is a 65% increase in 5 years. The seaweed industry is valued at US$ 5.5-6 billion annually of which human consumption accounts for US$ 5 billion [1].

Hydrocolloids are substances, which form gel in water. In the food industry they are used to bind food proteins in the dairy and meat industry. Seaweeds can be a vegetarian substitute for gelatine. The hydrocolloids industry produces alginates, agar and carrageen an from seaweed; this industry was worth US$ 600 million in 2003 and increased to US$ 1156 million in 2014 [1]. This is an increase of 92.6% in 11 years.

B. The Market for Seafood

By 2050 our planet will be home to close to 9.6 billion people. More food and nutrition will be required. Most importantly an adequate amount of protein will be necessary to prevent malnourishment. Meat protein is increasingly being used as a source of protein but it is unsustainable in the long run as the amount of CO_2 released per kg of edible meat is highest for cattle meat (30 kg CO_2/kg edible meat) and is the least for farmed fish (29 kg CO_2/kg edible meat) [3]. Globally around 158 Mt of food fish was produced in 2012 which includes finfish, crustaceans, molluscs, amphibians, sea squirts and edible jellyfish. Aquaculture contributed 42 % to the total production of food fish in 2012; the remainder was supplied by capture production [2]. Protein from fish contributed 16.7% to the global animal protein intake in 2010, with 150 g of fish being sufficient to meet more than half of an adult's daily protein need [2]. In 2012, 136.2 Mt of food fish was utilised for human consumption with an extra 21.7 Mt used for non-food uses, such as fish oil and fish feed used in aquaculture [2].

Global aquaculture (including food fish and aquatic plants) attained an industry value of US$144.4 billion in 2012 and produced 66.6 million tonnes of farmed food fish, with farmed finfish accounting for two-thirds of the production [2].

C. Role of Integrated Multi-trophic Aquaculture (IMTA)

IMTA is one of the most scientifically promoted methods of removing wastes from fish farms and has been used by Asian countries for centuries. It is now gaining importance as a method to reduce the ill-effects of fish farms (including inland and marine aquaculture) especially the discharge of inorganic nitrogen that is responsible for water eutrophication. The basic concept of IMTA involves two levels: the first trophic level involves species such as Salmon or Trout (usually a carnivorous species). This species is the primary product being cultivated and is generally fed with fish processing wastes or fish oil. The second level comprises of inorganic extractive species (such as seaweed) and organic

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extractive species (such as shellfish). The nutrient rich waste that is discharged by the fish farms is sequestered by these extractive species. The dissolved nutrients (containing nitrogenous compounds and phosphates) are absorbed by the inorganic extractive species (aquatic plants including seaweed). The floating and suspended particulate matter released is eaten by organic extractive species such as mussels, sea urchins and sea cucumbers [4], [5].

D. Requirement for Advanced Biofuels Such as Sourced from Seaweed

On the 24th February 2015, a press release from the Environment Committee of the European Parliament concluded that biofuels from seaweed or certain types of wastes should contribute at least 1.25 per cent of energy consumed in transport by the year 2020 [6]. Biofuels from seaweed is an emerging area of research for both liquid and gaseous biofuels. It could not be said that there is any consensus on what the seaweed biofuel system would look like. What would be the species of seaweed? Would it be cast seaweed, or sub tidal seaweed? Would it be sourced from natural or cultivated stocks? Would the biofuel be liquid or gaseous? Whatever the system is, it is a massive task to generate 1.25% of energy from transport by 2020 from seaweed.

This paper presents a perspective seaweed biofuel system based on co-location of farmed fish and seaweed in an integrated multi-trophic aquaculture system. An objective is to suggest the resource of seaweed required to satisfy 1.25% of energy from transport by 2020 in the EU.

II. Fish Farms, Seaweed and Gaseous Biofuel Production

A. Salmon Production and IMTA

Around 60 % of the global salmon production comes from salmon farms with farmed Atlantic salmon dominating the farmed salmon market with a share of more than 90 % and contributes more than 50% to the global salmon market with the total supply of farmed Atlantic Salmon in 2013 being 1.84 million tonnes HOG (head-on-gutted) [3], [7]. Atlantic salmon production is largely a function of seawater temperature and hence only selected coastal regions, where the water temperature is between 8 and 14 ℃ is considered optimal for salmon growth and production.

The main regions for production are around the coast of Norway, Scotland, Canada and Chile; in these areas certified licenses are required for farming as well as for catch production. A few studies have been carried out on bio-extraction by seaweed of carbon and nutrients excreted from fish farms.

Fig. 1 provides a concept of the proposed Fish to Fuel model. Depending on the composition (and hygiene) of the seaweed, it can be used for food and hydrocolloid production or biofuel. In some cases where the cost of fish feed is expensive, operators of salmon farms may prefer to use the produced seaweed as a major component of fish feed.

Table I gives an overview of results obtained at field scale as well as laboratory studies to determine the nutrient sequestration capacity of certain seaweeds. Various factors such as water temperature, currents, light hours, seeding and stocking density of the seaweed affect the productivity of such a system.

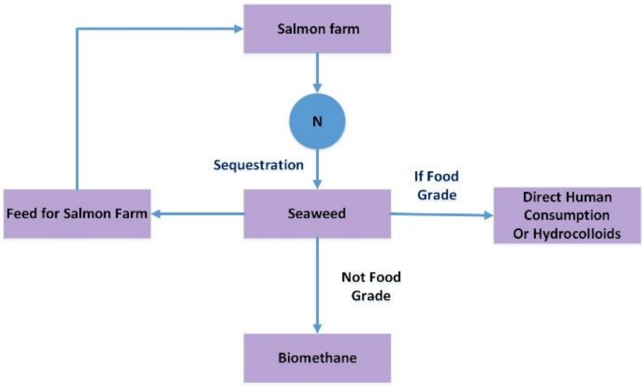

Fig. 1. Fish to fuel model.

TABLE I: Seaweed Cultivationin Integrated Multi-trophic Aquaculture

Fed Trophic level species	Seaweed cultivated
Sea bass (Dicentrarchuslabrax), Turbot (Scophthalmus rhombus), Senegalese sole juveniles (SoleasenegalensisKaup) [8]	A productivity of 23 $g/m^2/day$ (dry weight) for Gracilariavermiculophylla was achieved with a nitrogen removal capacity of 1.3 $g/m^2/day$
Atlantic Salmon (Salmosalar) [5]	Mean weight ratios of 6.7:1 and 12.9:1 for *Alariaesculenta* and *Saccharinalatissima* were required to sequester nitrogen excreted per unit weight of salmon
Salmon farms located near Chile [9]	A productivity of 53 $g/m^2/day$ (fresh weight) for *Gracilariachilensis* was achieved with a nitrogen removal capacity of 9.3 g/m for long line cultivation
Atlantic Salmon [10]	*Palmariapalmata* and *Saccharinalatissima* were grown at a productivity of 180 t/ha/a and 220 t/ha/a and removed ca 12 % and 5 % of nitrogen released by about 500 tonnes of fish over a period of 2 years

B. Bio-methane from Seaweed

Bio-methane can be produced from seaweed via thermochemical or biological processes The ash content of seaweed is higher (ca 15-30% dry matter basis) [11] than terrestrial biomass (ca 5-10 % dry matter basis) [12]. High ash content is a hindrance if used in thermal processes such as pyrolysis and gasification as ash causes fouling and slagging. Hence seaweed may be more suited to anaerobic digestion. Table II gives the bio-methane yields for a selection of seaweeds.

C. Potential Resource of Seaweed Biofuel Associated with a Fish Farm

The average weight of an Atlantic Salmon after two years of growth at sea is in the range 3.6-5.4 kg [19]. The amount of nitrogen excreted per kilogram growth of Salmon is 29.49 g; this can be sequestered by 12.9 kg of *Saccharinalatissima* (wet weight) [5]. Using a methane yield of 340 L/kg VS for *S latissima* (Table II) the resource of seaweed biome thane from a 5000 t salmon farm can be assessed as 79,216 GJ (Box 1).

TABLE II: BIOME THANE POTENTIAL OF SELECTED SEAWEEDS

Type of seaweed	Methane yield (L CH4/kg) Volatile solids (VS)
Ulvalactuca [13]	271
Laminariadigitata [14]	238
Saccharinalatissima [15], [16]	256
	340
Ascophyllumnodosum [17]	110
Gracilariavermiculophylla [18]	295

BOX 1: SEAWEED BIOFUEL SYSTEM ALLOWING PRODUCTION OF 1.25% OF ENERGY IN TRANSPORT IN THE EU

Relationship between salmon and seaweed

A **5000 t salmon fish farm** produces **150t of nitrogen**

[29.49g nitrogen excreted per kg of salmon]

150 t of nitrogen allows production of **64,500 t (wet weight) of *S. latissima***

[12.9 kg of S.*latisma* produced per unit weight of salmon]

Relationship between seaweed and biomethane

Biomethane production from 64,500 t (ww) of *S. latissma* = **2,212,737m_n^3 CH_4**

[64,500t (ww) *0.1009 (%VS)* 340 m^3/t VS)]

This scale is equivalent to a 1MW_e digester system (at 40% electrical efficiency).

Scale of industry required to satisfy 1.25% renewable energy in transport in the EU

Energy produced in seaweed biomethane from 5000 t of salmon = **79,216 GJ**

[2,212,737 m_n^3 * 35.8 MJ/m^3]

1.25% of energy in transport in the EU equates to 206 PJ

2603 seaweed digesters each digesting 64,500 t ww of *S. latissma*

The model proposes that seaweed is harvested in late summer when the biome thane potential is highest. The seaweed is ensiled on shore adjacent to a coastal digester and to the natural gas grid. The biogas from the seaweed is upgraded to biome thane (methane composition of 97% plus) and injected to the natural gas grid. In 2012 the total energy consumed in transport in the EU was of the order of 16.5EJ [20].

If advanced biofuels from seaweed are to satisfy 1.25% of this energy then 206 PJ of transport biofuel is required per annum. In Box 1 it is shown that 5000 t of salmon can generate 64,500t of *S.latisma* or 79.2TJ of biome thane. Based on this model, 168Mt of seaweed would need to be digested by 2020 in 2603 anaerobic digesters, each treating 64,500t ww of *S.latisma* per annum; at present the EU has approximately 9000 digesters operating on various substrates. The distribution system would be the existing natural gas grid.

Thus based on this model, the EU would need 13 million tonnes of salmon associated with the production of 168 Mt of seaweed. To put this in context the total supply of farmed Atlantic Salmon in 2013 was 1.84 million tonnes HOG (head-on-gutted). The world harvest of farmed fish was 66.6Mt in 2012 Aquaculture contributed 23.8 million tonnes of aquatic algae globally in 2012. A considerable ramping up of aquaculture is required for the EU to provide transport biofuel from seaweed.

D. Blue Growth and Blue Carbon

The nutrient load of the 5000 t salmon farm is equivalent to the sewage released by a community of 37,500 people; 4 kg of nitrogen is excreted by an average human being per year [21]. Implementation of IMTA can have the benefits of excessive nutrient extraction/sequestration; co-production of diverse products whilst only feeding the main species (the lower trophic levels live off the waste from the fish farm); and improved amenity of coastal habitat .

IMTA promotes high productivity of seaweed as there is a constant source of nutrients supplied. Similar to carbon credits, a nutrient credit system/trading is also implemented in countries (such as Sweden) for fish farms, thus increasing the total income generated by farmed fish aquaculture [8].The release of wastewater can be taxed, such as employed in Denmark where charges of €4 per kg of N released, are in place [22]. If similar charges are imposed on salmon farms the use of IMTA can reduce the burden of such taxes. The nitrogenous wastes can be compared to valuable nutrients; nitrogen based fertilizers cost ca €800/t [23]. Effective use of the coastal environment through IMTA concepts is classified as blue growth. Carbon sequestration in the marine environment is termed as blue carbon and is considered as an effective sink for carbon absorption.

III. SEAWEED: FOOD VERSUS FUEL DEBATE

A. Use of Seaweed for Food

Irrespective of the nature and method of cultivation or harvest of seaweed, there could be a competition for the resource. Asian countries are the largest producers and largest consumers of seaweed. Unlike in the West, seaweed forms an important part of the cuisine in many Asian countries. In food circles *Laminaria* is known as kombu, *Undaria* is known as wakame, *Porphyra*is known as Nori Kombu, Wakame and Nori are sold at US$ 2,800/dry tonne, US$ 6,900/dry tonne and US$ 16,800/dry tonne respectively[1].There is an increasing market in Europe for seaweed as food.

B. Use of Seaweed for Industrial Applications

Hydrocolloids from seaweed are a suitable alternative to synthetic gums, stabilisers, thickeners and gelling agents. Hydrocollids include for gelatin, xanthan, pectin, carboxy methyl cellulose, carrageenan, alginate, agar and guar; these are considered high value speciality chemicals. These are used in food products and pharmaceutical applications.

Seaweeds have an asset value in industrial applications. The world hydrocolloid market is expected to reach annual sales of US$ 7911 million by 2019 [24]. The hydrocolloid market is a competitor to seaweed biofuels.

C. Use of Waste Derived Seaweed as Fish Feed

Seaweed that is grown using waste streams from integrated multi trophic aquaculture is a suitable feedstock for biofuel, as it does not directly compete with natural or farmed resources. Its primary function is to sequester nutrients from the waste secreted from fish farms and as such may not be seen as a high value food for human consumption commanding prices such as for Kombu (*laminaria*) of US$ 2,800/dry tonne.

Fish feed and fish oil high in omega-3 fatty acids, are the preferred choice of feed for fish farms, especially for species such as salmon and trout. The prices of fishmeal and fish oil have seen an increase [25]. Alternative sources of fish food such as soymeal and corn meal have been used. Micro and macro-algae (seaweed) are also suggested to supplement the nutrient requirement of fish farms. Certain species of sea urchins, abalones and fish utilise seaweed as their source of food during the early stages of growth. Hence the seaweed produced from fish farms may partly be used as feed for the organisms being cultivated.

D. Further Research

Much research is required on seaweed and biofuel production from seaweed. Technical and economic feasibility of offshore and onshore based IMTA systems is required. Offshore systems will require new infrastructure to be built (such as structural rigs); onshore systems require land. Detailed composition of the seaweed produced using IMTA is necessary. Life cycle analysis including for sustainability analysis for seaweed biofuel is required to justify the benefits of this third generation biofuel as compared to first (food crops) and second (lignocellulosic biomass) generation biofuel systems. Biorefinery systems, which include for biofuel production from the residues obtained after alginate and other high value products have been extracted, should be assessed.

Moreover the sustainability of salmon farms may also be assessed. The production of farmed finfish is associated with many problems such as disease outbreak; that can also affect the wild species present in the natural water. Use of antibiotics, chemicals and steroids are damaging to the ecosystem, as are the high levels of nutrient discharge from the waste from fish farms [26], [27]. Regulations will come into force, which will ultimately improve on the shortcomings of aquaculture and may lead to IMTA and seaweed production becoming standard at fish farms [28], [29].

IV. Conclusion

Seaweed is a food and a versatile raw material. If advanced biofuels from seaweed are to satisfy 1.25% of energy in transport, the EU would need 13 million tonnes of salmon, generating 168 Mt of seaweed that would need 2603 anaerobic digesters. The world harvest of farmed fish was 66.6Mt in 2012; aquaculture contributed ca. 23 million tonnes of seaweed in 2012 .Natural stocks of seaweed cannot be involved in this increasing demand for seaweed IMTA can improve the sustainability of fish farms, clean the waters of excess nutrients and supply seaweed as raw material for industry and as biofuel.

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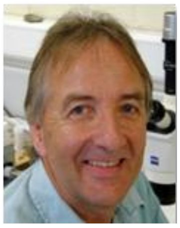

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