Aquatic biofuels for local development

Author: Rik Hoevers, for FACT

Date: 16 June 2011

ACKNOWLEDGEMENTS

Aquatic biomass is attracting a lot of interest for the production of biofuels. Algae are regularly in the news as the promising alternative for fossil fuels, providing feedstock for biodiesel and even jet fuel. Several water plants on the other hand are known for their vigorous growth to the extent that they are notorious invasive weeds. Properly managed these too may be a promising feedstock for biofuels. These plants might be an appropriate resource for local biogas for cooking and electrification, thus contributing to local development.

This report is the result of a study on feasibility of aquatic biofuels for local development. It is the result of many years of experience on the management of invasive floating and emergent water plants, and more recently on opportunities and challenges in algae production.

The study has revealed chances for aquatic biofuels in a local development context. It also showed that considerable progress is still to be made. There are interesting opportunities for community driven development and for local investments using floating and emergent water plants, and seaweed. Considerable research is still required for microalgae to become the biofuel of the future.

I am thankful to the staff at FACT and Wageningen University and Research Centre for their contributions and support. The preliminary field study by Otto Jandle on the use of floating invasive weeds in Ghana and Benin contributed greatly to assessing the feasibility of using these plants as a feedstock for local biogas. And so did the meeting held in December 2010 at Wageningen University and Research Centre contribute to the discussion and insights in using aquatic biomass. I am grateful to Winfried Rijsenbeek, Ywe Jan Franken and Bart Frederiks of FACT, René Wijffels, Bert Lotz and Willem Brandenburg of Wageningen University and Research Centre, Annelies Balkema of the Technical University Eindhoven, and many others. I particularly wish to thank Amoako ‘Digi’ DeGraft-Johnson, senior scientist and aquatic weed specialist in Ghana, and Peter Neuenschwander, emeritus scientist and former director of the IITA station in Cotonou, for 20 years of pleasant cooperation and thought provoking discussions.

For FACT,

Rik Hoevers

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1 INTRODUCTION

Reliable access to energy is an important prerequisite for local development. In general remote areas however are not connected to a grid. Communities in these areas depend on generating their own electricity for lighting, and on bottled gas, firewood or charcoal for cooking.

Aquatic biomass attracts substantial interest as a valuable feedstock for second and third generation biofuels. It is a possible source for a variety of biofuels: biodiesel, bioethanol, biogas, pellets and charcoal briquettes. Biofuels that are locally obtained from aquatic biomass may contribute to reducing the dependency on fossil fuels, and to preventing further deforestation or otherwise the degradation of the local environment.

Compared with terrestrial crops that are specifically grown for the purpose of biofuel aquatic biomass offers considerable advantages. Typical first generation terrestrial biofuel crops demand rather vast areas of arable land. Growing these plants for biofuels purposes comes at the expense of food crop production and natural ecosystems. The production of aquatic biomass on the other hand does not necessarily compete for arable land or other scarce resources, including fresh water. It is generally considered not to have an immediate impact on food and feed stock accessibility, nor on already fragile ecosystems such as tropical forests and peatland. An aquatic vegetation may also yield significantly higher than the most efficient biofuel crops such as the oil palm.

Sources for aquatic biomass are free floating plants, emergent (rooted) fast growing plants (reeds, cattail), and algae. These aquatic plants are characterized by their vigorous growth, to the extent that several species are listed among the world's worst weeds. The biomass can be harvested from 'nature' or it can be grown in dedicated facilities such as ponds and bioreactors. Harvest from nature is an option in particular when the relevant vegetation occurs abundantly and when harvesting does not affect the natural ecosystem. It is in particular an option when, at least part of, the vegetation has to removed on a regular basis as this vegetation affects the water body due to its invasiveness. The production in dedicated facilities is an option when controlled production is required, for example when the vegetation is also used for phytoremediation of waste water, for production under quarantine procedures, or for the production of microalgae in ponds and bioreactors.

Floating aquatic plants which can be valuable for biofuels and consequently for local development are water hyacinth (*Eichhornia crassipes*), water lettuce (*Pistia stratiotes*), water ferns (*Salvinia molesta* and several *Azolla* species), and duckweeds (*e.g.*, *Lemna minor*, *Lemna gibba*, *Spirodela polyrhiza*, *Wolffia arhiza*). Water hyacinth can also be used for phytoremediation of polluted water, and for handicraft (e.g. for baskets). Azolla is a well known 'bio-fertilizer' in irrigated rice farming. Duckweed is rich in proteins and has a potential as a source for animal feed. Water hyacinth, water lettuce and salvinia are notorious aquatic weeds due to their invasive character.

Cattail (*Typha spp.*) and reeds (notably *Phragmites australis* and *Arundo donax*) are important emergent aquatic plants. They can be dominant in wetlands and along the banks of rivers and lakes. Although indigenous, cattail in particular is a problem in irrigation programmes and it is hard to control. Cattail and reeds are recognized as multipurpose plants providing biomass for fuel as well as building material. Reeds are also used in helophyte filters for phytoremediation of waste water.

The production and processing of microalgae for biofuels receives most of the attention as a promising aquatic biofuel source. Microalgae are considered to become a major source for transport fuels eventually replacing current fossil fuels. Lipids extracted from microalgae might be used to produce biodiesel in particular and more recently also to produce aviation fuels. Microalgae can be grown in bioreactors or open ponds. In spite of the high production potential their feasibility for biofuels only is however questionable. Macroalgae (seaweed) have quite a potential as well. They can be grown in open marine systems, for example in conjunction with off-shore windturbine parks. There already is experience in growing macroalgae in particular for food purposes and for the industry.

This report deals with the opportunities and feasibility of aquatic biofuels, their limitations and associated problems and threats.

2 FLOATING PLANTS

2.1 General features of floating plants

Many floating plants are known for their prolific growth. A population can develop rapidly and cover a substantial surface of fresh water bodies including lakes, lagoons, ponds, rivers and canals. The total biomass production of a floating aquatic plant population is considerably higher then the production achieved by terrestrial crops. A biomass production of 40 tonnes per ha per year (dry weight) in open water bodies is not an exception. Several species are however very invasive outside their natural habitat due to their vigorous growth and the absence of natural antagonists that control population development. Consequently these alien invasive species seriously affect aquatic ecosystems, water management and navigation, and public health. They are among the world worst weeds.

Important floating plants from the tropical and sub-tropical regions are water hyacinth, (*Eichhornia crassipes*), water lettuce (*Pistia stratiotes*), water fern (*Salvinia molesta*, *Azolla spp.*), and duckweed (*e.g.*, *Lemna minor*, *Lemna gibba*, *Spirodela polyrhiza*, *Wolffia arhiza*). Water hyacinth, water lettuce and salvinia are notorious invasive weeds.

Figure 1: ***Eichhornia crassipes*** **(water hyacinth)**

Figure 2: Floating mat of water hyacinth on Lake Victoria

Figure 3: ***Pistia stratiotes*** **(water lettuce)**

Figure 4: ***Salvinia molesta***

Figure 5: Duckweed

Figure 6: Azolla filiculoides

2.1.1 Growth and proliferation of floating plants

Water hyacinth and salvinia are native species from South America, from the Amazon and from the coastal and inland water bodies of Brazil respectively. Water lettuce probably originates from South America as well although this is very speculative. Most literature on floating aquatic species and their uses is on water hyacinth. It is the most notorious invasive aquatic weed. It is widely distributed outside its natural habitat of the Amazon, it grows vigorously and it seriously affects fresh water bodies. This chapter focuses mainly on water hyacinth. Water hyacinth is the most interesting floating aquatic species as a feedstock for biofuel, in particular with respect to rural community-based biofuel supply.

Water hyacinth has been introduced into new areas of infestation as an ornamental in ponds. The first documented introduction outside its natural habitat was in North America in 1884 at the Cotton States Exposition in New Orleans. Since then it has been introduced as an ornamental throughout tropical and sub-tropical regions and it has become the worst invasive aquatic weed in North and South America, Africa, Asia, Southern Europe, Australia and New Zealand. Salvinia is mainly distributed as a plant for aquaria, and to a lesser extent (and similar to water hyacinth and water lettuce) as an ornamental for garden ponds. These plants escape and become a problem usually through deliberate release into nearby open water after the vegetation in the garden ponds or aquaria has become too abundant. Invasive aquatic weeds, water hyacinth in particular, are able to develop and spread rapidly thus invading and affecting fresh water bodies not only due to their already vigorous growth, but also because these ornamentals are distributed clean of their natural antagonists that could hamper their growth. Noting its attractive flowers and its impact as an aquatic weed water hyacinth is often called ‘the noxious beauty’.

Water hyacinth propagates vegetatively and can double its biomass in 7 to 14 days depending on local conditions. It is not restricted to a particular location but spreads with the water flow, tide and wind. Unlike a terrestrial vegetation spatial competition therefore is not an important limiting factor. This provides opportunities for further and less restricted population development which enables water hyacinth, as well as water lettuce and salvinia, to cover a water body within a relatively short time. Taking into consideration the wide distribution of water hyacinth throughout tropical and sub-tropical regions the climatic and water quality vary considerably and influence the growth rate. The estimates for total biomass production per ha of a water body consequently also vary considerably. The main factors influencing the growth rate and carrying capacity of water hyacinth are salinity, temperature, nutrients, disturbance and the presence of natural enemies of the plant. Water hyacinth does not tolerate a salinity above 0.2%. The optimum temperature is 30°C. With higher temperatures mortality increases. Below 13°C growth stops but damage and mortality only occurs due to frost. Water hyacinth grows vigorously in eutrophic water bodies rapidly forming dense mats. Growth is severely hampered by nutrient deficiencies. Wave action reduces the growth rate and mats of water hyacinth may break up due flooding and rapid water flow. New mats subsequently build up downstream. In areas with heavy wave action water hyacinth can only persist in sheltered areas. Obviously natural enemies limit the growth of water hyacinth. To control water hyacinth natural enemies have to be introduced and form a strategic ingredient of integrated control strategies.

When water hyacinth is harvested repeatedly the production can be 40 to 47 t/ha/year DM. A production level of 80 t/ha/year or more may be possible. The actual production depends on the growth rate and therefore on the environmental conditions that limit growth. It also depends on the harvesting capacities and strategies to control the water hyacinth population and to prevent its further proliferation. These actions in turn also facilitate regrowth. Studies in Mexico over a growing season of 244 days in a eutrophic dam indicated that a production of approximately 134 t/ha/year could be possible, with a growth rate of 0.551 t/ha/day. Earlier studies from Louisiana and the Nile basin suggest that a production of 110 to 150 ton could very well be possible. Other studies estimated yields from eutrophic water bodies that are even considerably higher with a growth rate of 0.29 t/ha/day up to 0.72 t/ha/day in waste water effluent, and an annual production of 194 t/ha/year up to 269 t/ha/year. Gunnarsson and Mattsson Petersen (2007) emphasize not to overestimate yields and assume that the maximum production is 140 t/ha/year.

These very high results from extrapolation and growth simulation corresponds with a logistic growth model in which the biomass ideally doubles in 7 to 14 days, with a maximum biomass of 40 t/ha and weekly harvesting of approximately 30 to 50% of the total biomass which corresponds to about 4 to 7 t/ha/week. In that case the total biomass per ha would be stable at about 11 to 17 t/ha. This however does not take into account the reduction in biomass due to environmental conditions and biological control agents which may result in a more realistic yield figure of 40 to 50 t/ha/year DM.

2.1.2 Possible use of floating plants

Floating plants can be used for a variety of purposes. In addition to being a feedstock for biofuels, they are also a source for handicraft, fertilizer and soil improvement, bioremediation of waste water, animal feed, and even medicinal purposes are sometimes mentioned.

- Biofuel

Floating plants are viable sources for biofuels, in particular for biogas. The residual digestate can composted and used as organic fertilizer. Water hyacinth and duckweed are also gathering interest as a source for bioethanol.

- Fertilizer and soil improvement

Several floating species are appreciated as a source of biofertlizer and mulch. Best known are the *Azolla* species, small free floating ferns. Azolla is widely appreciated and introduced in rice farming because of its symbiosis with nitrogen fixing cyanobacteria (*Anabaena azollae*). Water hyacinth is occasionally used as an organic mulch. Plants removed from infested water bodies are then applied to crop fields. The mulch contributes to improving soil properties and to reducing weed growth in the crop.

Residual digestate from biogas fermentation can be composted and used as organic fertilizer. Thus valuable nutrients are recovered from the water and returned to the crop land. Obviously the water should not be polluted with toxic components that could contaminate the crop and create a health hazard.

- Phytoremediation

Water hyacinth and duckweed are used for phytoremediation of waste water. Other floating species may be used for the same purpose. The biomass can in turn be a source for biogas and soil improvement. Water hyacinth may also be used for reclamation of polluted water bodies. Notably, water hyacinth effectively takes up heavy metals such as lead and mercury. Even dried hyacinth roots are very effective in removing arsenic. Obviously the biomass should be treated with care to prevent contamination of farm land with toxic components such as lead, mercury and arsenic as well as pesticides that remain in the residual plant material.

- Animal feed

Azolla and duckweed are used as a fodder crop. Important duckweed species are *Lemna minor*, *Lemna gibba*, *Spirodela polyrhiza* and *Wolffia arhiza*. The protein content of duckweed is 35% with a similar composition as soy bean meal.

- Medicine

Water hyacinth is occasionally mentioned as a source for traditional medicine and food supplements. In India root and leaf extracts are used to cure certain swelling, burning, haemorrhage, and goitres, and it is also used to treat certain inflammatory conditions of animals. Water hyacinth may also contain antioxidants and other components.

- Handicraft

In South and Southeast Asia in particular, and increasingly in Africa, water hyacinth is harvested from infested water bodies for handicraft purposes. It is a popular source for amongst others the weaving of baskets. Handicraft from water hyacinth is not only used locally but is increasingly finding its way into the international market.

- Ornamentals

Many floating plants are known for their beautiful appearance. They are consequently appreciated in garden ponds and aquaria. Water hyacinth is a popular ornamental because of its beautiful flowers. It is widely used in garden ponds throughout the tropical and sub-tropical regions even though it is the most notorious floating aquatic weed. Water lettuce and salvinia are also appreciated for garden ponds, whereas salvinia is also a popular plant for tropical aquaria and terraria.

2.1.3 Impact of floating plants

Floating aquatic weeds are a serious problem in fresh water bodies. They are known for their vigorous growth. Outside their natural habitat they are among the world worst weeds because of their invasive character. The most important invasive aquatic weeds in tropical and sub-tropical regions are water hyacinth, water lettuce and water ferns (salvinia, azolla). There are however many more, also in temperate regions.

Invasive floating weeds affect fisheries and aquaculture based activities, navigation, water supply schemes, (hydro-electric) power generating facilities, drainage and irrigation. Abundant growth affects biodiversity in and around fresh water bodies. The water flow in drains and canals may be severely obstructed, affecting drainage and irrigation in agriculture and aquaculture. In urban areas household waste accumulates in canals and stagnant water increases the breeding opportunities and incidence of vectors for human and animal diseases such as malaria, dengue and schistosomiasis.

Figure 5: Water hyacinth blocking landing site at Jewi Wharf, Tano Lagoon, Ghana

Aquatic weed complexes have caused the drying up of shallow lagoons and water reservoirs, and increased siltation and eutrophication. The average water loss due to evapo-transpiration by water hyacinth is an estimated 3.5 times higher than that of a free water surface. Thick mats of water hyacinth deplete dissolved oxygen. Aquatic weeds, and water hyacinth in particular, may consequently have a considerable impact on the ecology of lagoons and fresh water bodies, endangering fish and crustaceous populations and sub-merged vegetation. The dark, anoxic conditions under thick floating-plant cover leave little opportunity for animal or plant life. Wildlife populations related to the aquatic environment, such as water fowl, are known to have reduced significantly due to the water hyacinth infestation on the Tano lagoon system in Ghana.

Eutrophic systems facilitate the growth of invasive floating plants and reduce the resilience of freshwater systems against a shift to floating-plant dominance. This can be a self-stabilizing ecosystem state, hence its notorious persistence. A single drastic harvest of floating plants may however induce another, permanent, shift whereby by rooted, submerged plants become dominant. Invasive weed control strategies that focus on a swift eradication of large floating mats may consequently result in new problems with affected fresh water bodies due to such probable vegetation shift in shallow water bodies. It should also be noted that a fast decomposition of the floating biomass resulting from the large scale use of herbicides will reduce DO levels which will further affect he aquatic ecosystem.

Observations on vegetation shifts from shallow lagoons in Ghana

The disturbance of the biodiversity and ecological balance, due to the presence of large floating mats of alien invasive aquatic weeds, has proven a constraint in itself to effective control programmes. With an effective reduction of the alien plant population, the subsequent ecological niche that occurs is occupied by indigenous emergent plant species such as *Vossia cuspidata*, that do not pose a problem under normal circumstances. As the natural wetland ecosystem is destabilized, such species however tend to develop invasive properties. A serious threat can be controlled, but it will consequently be replaced by another problem, if population dynamics of disturbed ecosystems are not adequately anticipated upon through strategically planned and locally sustained management programmes.

The first known introduction of water hyacinth outside its natural habitat was in North America at the Cotton States Exposition in New Orleans in 1884. It was a botanical curiosity due to its size, floating growth habit and the beauty of its flowers. It was introduced to Florida in 1890. Because of its excessive growth it was thrown into a river which it covered from bank to bank in just a short time. In the following 60 years water hyacinth had covered more than 50,000 ha of Florida's freshwater habitat. From the US in the early 20th century water hyacinth has spread throughout the tropical and sub-tropical regions of the world as an ornamental where it became a serious problem as well. Several countries including the USA, South Africa, Ghana, India and Australia developed strict regulations and control schemes to prevent further spreading of this weed.

Throughout Africa, South and Southeast Asia, Australia and Southern Europe fresh water systems are affected by water hyacinth. In West Africa the entire lagoon system is invaded even hampering navigation near the ports of Abidjan and Lagos. Large catchments including the Nile, Niger and Volta basins are covered with dense mats of water hyacinth creating health hazards, obstructing navigation and fisheries and hampering water supply, drainage and irrigation. A similar situation occurs in Asia and Australia. Water hyacinth has also become a problem closer to its origin, in South and Central America. On the other hand the sale and distribution of water hyacinth and other invasive species continues in other countries, including in areas that are prone to severe invasions.

2.2 Opportunities for the use of floating biomass

There is an obvious need to control invasive floating plants. Any integrated control strategy ideally consists of biological control, physical removal and barriers, preventive measures and eventually chemical control through herbicide applications. Efforts to control these plants often only have marginal success. The economic advantage provided by harvested biomass, in particular as a reliable energy feedstock for biogas production for rural electrification and cooking, can be an important incentive for successful physical removal of the vegetation or at least to reduce the dominance of this vegetation. Harvesting of the floating biomass can be embedded in community-driven weed control and wetland co-management programmes. Taking into consideration that a water surface covered with water hyacinth can produce as

Control options of floating invasive weeds

- Biological control

The restoration of the ecological balance of affected water bodies is the primary target in biological control. The establishment of a complex of biological control agents results in a gradual but continues decline of the vegetative cover, preventing the rapid changes and further disturbances of the aquatic ecosystems.

- Chemical control

Chemical control is not an option for effective large scale aquatic weed control. Many weeds escape treatment and are a source for re-establishment. The rapid decomposition of the vegetative mass following large scale herbicide application will lead to the rapid depletion of dissolved oxygen, further affecting the aquatic ecology. Chemical control may thus only be an option for clearing of landing stages to facilitate other, more appropriate, control activities on the affected water bodies.

- Physical control

Physical control of floating weeds is necessary to ensure access to water bodies, to reduce the population size and to eradicate new and small infestations, and to prevent further spreading of the weeds. Locally constructed barriers protect landing sites from becoming obstructed. Physical barriers can be made from for instance bamboo and raffia palm. These barriers are effective but tend to collapse during heavy weather. They should therefore be repaired on a regular basis. Floating weeds are removed from the water surface using a variety of tools, including rakes, mowing buckets and aquatic weed harvesters.

Removed weed biomass can be used for various purposes. It can be converted into biofuels, in particular biogas, and it can be used for soil improvement applied as mulch or as compost.

much as 40 to 50 t/ha/year regular harvesting of a floating mat of water hyacinth provides enough biomass to generate biogas for a rural community. In addition, the residue from biogas production can be a valuable source for compost.

Floating plants can be grown as an aquatic crop, in association with another crop such as azolla in irrigated rice, and in basins for example for phytoremediation of waste water. Species that are potentially invasive should not be introduced in open water bodies where they can affect the aquatic ecosystem. Invasive plants should therefore only be grown in contained ponds and under strict regulations to prevent their spread.

Although in tropical areas duckweed can be harvested from large lakes the most appropriate is cultivating duckweed in contained systems. Azolla can be invasive. Its cultivation should therefore be restricted to contained systems, similar to other potentially invasive species, and care should be taken that it does not escape to open water systems.

2.2.1 Harvest and transport of floating aquatic biomass

Harvesting floating aquatic biomass which is grown as a biofuel crop is not necessarily different from removing invasive floating weed biomass from an infested water body as a means of physical control of the weed. Generally the harvesting of a floating aquatic crop is less difficult than the harvesting/removal of a floating weed vegetation. A floating aquatic crop is grown under controlled conditions, preferably in contained ponds. The floating weeds typically grow under uncontrolled natural conditions, with varying water depth and with natural shores and vegetation. Removal of floating weed biomass is a means of physical weed control and a component of integrated control strategies. It has the advantage that superfluous nutrients in eutrophic systems are removed and can be recovered for agricultural practice.

Figure 6: Manual harvesting of floating plants, Ghana

Floating plants can be harvested manually from narrow streams and canals, from landing stages to ensure access to the water, or from relatively small ponds where the plants are cultivated. The floating plants are pulled from the water using rakes. On large water bodies manual harvesting is a tedious activity. As invasive floating plants propagate vegetatively through stolons they form dense mats with the plants connected through their root systems. In addition large floating mats attract silt as well as seed from other plants thus enabling colonization by other macrophytes. Various reeds, sedges and even shrubs and small trees have been observed establishing on floating islands of water hyacinth.

To enable manual harvesting of the biomass from such floating mats the vegetation has to be cut and separated into parts resulting in smaller floating mats of approximately 1 to 2 m2. In most remote and low income areas, cutting of the floating vegetation is generally done using a machete (cutlass) or similar tools. The biomass is then brought ashore by pulling it into a boat or barge using rakes, by dragging it alongside a boat or by dragging it while wading through the water. Usually typical small fisher boats are used such as a canoe or piroque that may be navigated by manual labour or equipped with an outboard engine. Moving near a mat of floating plants may however cause the propeller of the outboard engine to get entangled in the roots.

Manual harvesting can be facilitated by using motorized equipment to cut the floating vegetation. A hedge cutter would be an appropriate tool as it can be handled from a boat or barge and can be maintained at the community level. Care should be taken when manually harvesting floating plants for example for snakes. The water may be infested with parasites such as schistosomiasis.

A wide range of machines has been developed for mechanical harvesting of floating plants. Tractor mounted mowing buckets are used for the clearing of drains, canals, and landing stages. To enable the clearing of large water surfaces the use of aquatic or even amphibious weed harvesters is an option. Such equipment is suitable for maintaining access to and manoeuvrability in ports, and for clearing operations on relatively deep and large lakes such as Lake Victoria and large wetlands such as the Everglades. Taking into consideration the initial investment as well as the operating and maintenance requirements of large weed harvesters they are not likely to be suitable for remote and low-income communities. Typical aquatic weed harvesters are based on cutting the mats of floating vegetation and simultaneously pulling it into the collection area of the boat by a special conveyor belt. When the loading area is full the harvester will have to unload it on the shore or into a barge that transports the biomass to the shore. To address large surfaces often additional equipment may be required such as (tipper) trucks with a loading crane, trailers, and barges. In less accessible and shallow areas such as most of the coastal lagoons as well as many inland wetlands, catchments and major rivers such aquatic weed harvesters may not be able to efficiently clear large surfaces. Their size and often limited manoeuvrability restrict their effective use. To operate in less accessible areas smaller and more appropriate harvesters are required that can be operated may be operated and maintained locally. Locally adapted equipment include weed screens with continuously moving rakes that can be mounted on small vessels and locally built barges with a hand powered winch to harvest water hyacinth.

Figure 7: Aquatic weed harvester

Once the harvested biomass is on the shore it has to be transported to the biogas digester or another facility for biofuel production. Grinding or manually chopping the biomass to pieces of a few centimetres increases the contact surface for the bacteria in the digester. Consequently the digesting process takes place faster. As the fresh biomass has a low dry matter content (6 to 10%) it represents a considerable weight to transport to the biomass chopper and the digester. The sludge from the digester also high a low dry matter content. It can be composted before applying to the crop field. To limit the transport requirements it is advantageous to locate these treatments close to where the biomass is brought to the shore or the ponds where the plants are grown.

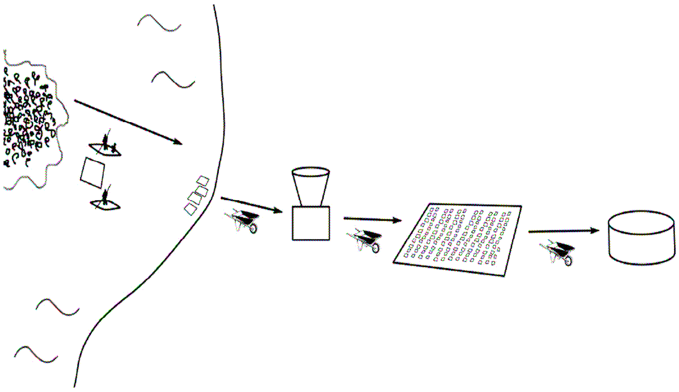

Figure 8: Schematic view from harvesting floating weeds, to grinding and drying the biomass and feeding the digestor

2.2.2 Biofuels from floating plants

Floating plants are viable source for local biogas production. Operating a unit for anaerobic digestion of floating biomass is not different from other fresh (green biomass), eventually through co-fermentation with manure. Small floating plants such as the water ferns (salvinia, azolla) and duckweeds can be fed directly to the biogas digester. The biomass can be left to sundry to a dry matter content of about 15%. It is recommended to reduce the size of the biomass of large plants such as water hyacinth and water lettuce. This can be done by manually chopping the plants or, preferably, by grinding them. Thus the specific surface of the substrate in the digester is increased enhancing access of the microbes to the plant material and consequently facilitating the digestion process. The optimum particle size is approximately 6 mm. Under local village conditions the biomass from large plants such as water hyacinth and water lettuce is reduced to parts of approximately 40 cm x 40 cm. Using a grinder the biomass is further reduced the particle size to approximately 2 cm x 2 cm before feeding the biomass to digester.

Biogas production from floating plants is 180 to 290 litres per kg dry weight, with a possible harvest of 40 to 50 t per ha per year. The annual biogas yield per ha can therefore be 10 million litres. The methane content from floating plant biogas is 55 to 80%. Even with a residence time of only 8 days biogas production from water hyacinth of 143 to 190 litres per kg dry weight has been reported.

	Biomass yield (t/ha/year)	Biogas yield (l/kg DM)	Methane content (%)
Water hyacinth	40-80	190-290	60-70
Azolla	4-50	180-560	80
Duckweed	20-45	~ 180	55-65

For household and community use digesters should be easy to operate. Plug-flow type of digesters are therefore the most appropriate, bag digesters in particular. They can be installed and operated by people with little background in biogas technology. The biomass feedstock is fed in one side of the digester. The digester is fed daily. The digestate leaves the system on the other end where it is contained in a basin. The digestate can then be fed to a composting unit.

The gas is taken from the bag through a gas connection on top. From there it is taken to the user through a system of pipes and hoses or to a generator for local electricity supply.

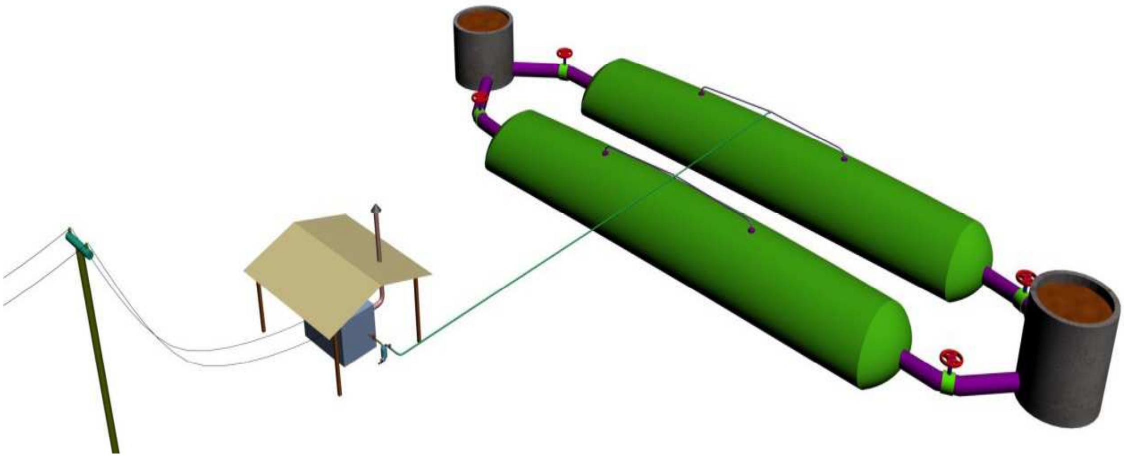

Figure 9: Plug-flow digester feeding biogas to a local electricity plant

Other biofuels that can be obtained are bioethanol, and fibre (eventually converted into pellets or charcoal) for direct combustion. The pre-treatment for hydrolysis and fermentation to produce bioethanol from the plant material requires high temperatures, acids and pressurized reactors to make the sugars available. As the energy balance is likely to be

Community biogas from water hyacinth in Ghana and Benin

Field observations in Ghana and Benin show that the use of water hyacinth for community biogas generation close to water bodies infested with water hyacinth is feasible. In Ghana the observations focussed on remote and resource-poor communities harvesting water hyacinth from the Tano Lagoon. Other observations include harvesting a complex of aquatic weeds consisting of water hyacinth, water lettuce and grasses on the Kpong headpond of the Volta river. In Benin the observations were done near Porto Novo and also included water hyacinth from basins for phytoremediation of effluent. Preliminary results from these field observations in Ghana and Benin also suggest that it may be interesting for private investors to operate local biogas systems based on water hyacinth.

For a community with 100 households and 6 persons per household it may be possible to run a local biogas system, assuming limited electricity needs for a fridge and energy saving lighting (i.e. LED) and biogas for cooking. This is based on a water hyacinth production of (only) 30 t/ha/year, an average biogas yield of 240 litre/kg DM, and 5 working days per week for harvesting the water hyacinth biomass, transporting, grinding and feeding the digester. Considering the electricity need of such a community of 33 kWh/day, a generating power of 25 kW would be required, and an overall biogas need for both electricity and cooking of 93 m3/day. With a fresh weight of 50 kg/m2 with 5% dry matter content the community would have to harvest 9.8 t fresh water hyacinth per working day, and equivalent of 197 m2. Considering 1.9% population growth in 5 years the harvest objective could increase to 10.9 t/working day (217 m2). Given natural regrowth a water surface covered by water hyacinth of 4.28 ha which is harvested continuously could guarantee the biogas needs for cooking and electricity. 12 persons are needed for harvesting, transport, grinding and feeding the digester.

negative bioethanol production from floating plants is only feasible when liquid fuel is needed. Direct combustion of floating biomass, and the production of pellets or charcoal, is not an option due to the high water content of the plant material.

2.2.3 Synergy with other uses of floating plants

The production of biogas can be combined with the use of floating aquatic plants for soil improvement and for phytoremediation. Eutrophication is a problem in many surface waters. Harvesting (invasive) aquatic plants plays a role in lowering the nutrient content of eutrophic water, providing opportunities to recover nutrients fro the water. Dried sludge from the biogas digester and compost made from the digestate can be applied to crop fields. Obviously, once nutrient levels in the water decrease productivity of the floating vegetation also decreases.

Floating weeds are used for phytoremediation of waste water. Nutrients may be recovered from effluent. Water hyacinth in particular is for phytoremediation of water contaminated with heavy metals such as lead, mercury and arsenic. The biomass can be used for the production of biogas. This biomass and the digestate should however be treated with care to prevent contamination of farm land with toxic components such as these metals as well as pesticides that remain in the residual plant material. In fact, the residue from the digester should be considered toxic waste and be treated accordingly.

Figure 10: Water hyacinth ponds for watse water treatment at the Centre Songhai, Porto Novo, Benin

Residual plant material from water hyacinth can not be used for handicraft or similar uses of the fibrous material. Excessive plant material for biogas production from harvesting operations may however still be used for that purpose and contribute to the harvesting feasibility.

2.2.4 Feasibility using floating plants for biofuels

Floating plants can be used for the generation of biogas. To locally assess the feasibility the following activities have to be taken into consideration:

- harvest and chopping of the floating biomass
- transport of the biomass to the grinder and the digester
- operation and maintenance of grinder and the digester
- collection and treatment of the residual sludge (digestate)
- collection and distribution of the biogas
- operation and maintenance of the biogas generator

These activities require labour and investments in equipment. The choice for the equipment also depends on the local capabilities and access to spare parts for its operation and maintenance. In particular in remote areas this is very important yet it is often overlooked. The equipment includes amongst others hedge cutters or similar tools to facilitate harvesting the floating biomass, boats or barges preferably equipped with appropriate (outboard) engines, tool to chop the harvested biomass (cutlasses or similar), grinder, digester, reservoir to collect the digestate. Piping for the gas to the households and/or the biogas generator which supplies electricity to the community. Earlier studies showed that when the hyacinths are close to the shoreline, one person can harvest approximately 200 kg of fresh water hyacinths per hour using only simple tools such as rakes to collect the plants. This confirms the recent studies in Ghana and Benin showing that 12 persons are needed to provide basic gas and electricity to a 100 household rural community based on harvesting and converting water hyacinth.

For the situation in Ghana the savings on cooking (firewood, charcoal, LPG) and lighting (kerosene, batteries) during the first year can already exceed the investment and the pay back period can be less then 2 years. A biogas facility based on using waster hyacinth would then not only be feasible for a remote community, the studies also suggest that it may be interesting for a small investor. Noting the labour requirement harvesting and/or cultivating floating plants for biogas may thus also contribute to employment generation in rural areas.

The situation for water ferns (azolla and salvinia) and duckweeds is similar to the larger floating plants water hyacinth and water lettuce. As the plants are however considerably smaller the need to chop the biomass and eventually grinding before feeding it to the digester will be less prominent.

Assessing the feasibility of a biogas facility several major aspects are not taken into consideration. These nevertheless further improve the economic viability. In open water systems water hyacinth and other floating plants are a serious hazard. Aquatic weed control is therefore necessary. The costs related to removal (harvest) of the floating mats, embedded in an integrated control strategy, have to made also if the biomass is not used. Consequently, the investment should only refer to labour and specific equipment for ensuring regular supply of biomass and for operating the biogas facility. The residual digestate represents value as a source for biofertilizer. The sludge can be composted and brought to the crop field, thus improving soil conditions and yields. Grown in basins floating plants can be used for phytoremediation of effluent. If the effluent is not contaminated wit toxic compounds such as pesticides and heavy metals, the plants can recover nutrients which can be returned to the crop fields as compost. If the effluent is however contaminated the digestate may be contaminated as well and should be treated as toxic waste which represents costs. It should on the other hand that a biogas facility reduces the cost of a waste water treatment facility through the biogas output.

2.3 Challenges associated with the use of floating plants

The production of floating biomass does not necessarily plants require valuable land resources. Many floating plants species are however a possible a nuisance due to their prolific growth, invading open water systems, affecting the stability of aquatic ecosystems, and being a hazard to public health and to the use and management of water systems. Opportunities for the production and use of these therefore provides challenges related to he prevention and control of these plants as possible invasive weeds.

2.3.1 Use of invasive aquatic weeds vis-à-vis weed control

The popularity of floating plants is attributed to their beautiful appearance, notably water hyacinth, and other useful properties such as an associated crop for biofertilizer, in particular azolla. These plants are consequently spread around the world and due to introductions into open water and uncontrolled growth they have developed into invasive weeds. The popular and useful properties of these plants are beyond doubt. The growth is such that they produce an interesting potential as a feedstock for biofuels.

In already infested water bodies biomass can be harvested from mats of floating plants. As such it is a component of aquatic weed control. Due to the prolific growth of these plants there is an abundant source for biomass. In these circumstances local harvesting strategies can be designed that both reduce the impact of floating weeds and provide a constant supply of biomass for biogas.

In areas with only a short growing period for example because of seasonally low temperatures, harvesting of floating invasive weeds only provides a temporarily supply of feedstock for biofuels.

If an infestation with invasive floating plants is recent the priority is to maintain the population at a small level (and preferably eradicate it) and to prevent further spreading of the aquatic weeds. The supply of feedstock for biogas after successful control of an invasive aquatic weed problem should then be complemented by supply from other sources. The cultivation of floating biomass in contained basins is an option.

Azolla is widely used as an associated plant in irrigated rice farming. As it spreads into open water it however develops as an invasive plant. Regular harvesting of azolla from infested water bodies is required. Together with azolla harvested from the irrigated fields it provide a regular supply of biomass, eventually complemented from cultivation in contained basins.

2.3.2 Use of resources

In general the production of floating plants does not compete for resources with terrestrial (food) crops. Instead, these plants are a source of nutrients recovered from eutrophic water bodies or effluent. When the plants are specifically cultivated for biogas in contained systems nutrients from the residual sludge and can be returned to crop fields as compost. Contained basins for cultivating floating plants can constructed on land that is not considered valuable. As a consequence the production of floating biomass does not compete with land and nutrient resources and may even be a source for nutrients.

Water loss increases substantially due to the evapo-transpiration by floating plants, up to threefold, compared with an water surface free of these plants. Shallow water bodies are therefore prone to siltation and drying up. Consequently water demand has to be taken into consideration when growing floating plants in contained basins.

2.3.3 Invasiveness, hazards and legislation

The invasiveness of floating plants is well known as are the hazards caused by floating mats of invasive alien plants. This knowledge has not prevented these plants from being introduced into new areas. This is due to their popularity as an ornamental or associated crop in irrigated rice farming or otherwise. Similar to these experiences the potential of floating plants as a viable feedstock for biogas presents a new threat of floating plant invasions.

Floating plants have the potential to contribute to sustainable development through local power generation and reducing the dependency on fossil fuels. This presents a new popularity of these plant as well as a new threat for further spreading of these plants as invasive weeds. Recognizing the potential care should be taken that the plants are not introduced in hitherto unaffected water bodies. Farming of floating plants should therefore be limited to situations where complete quarantine can be ensured. For areas prone to infestation appropriate regulation for growing these plants is required as well as its enforcement.

Growing floating plants for phytoremediation care should be taken that toxic compounds such as heavy metals and pesticides are not brought back into the environment or on crop fields, or that they leach to the water table thus contaminating fresh water supply. If the residual digestate is contaminated it should be treated as hazardous waste

3 EMERGENT WATER PLANTS

3.1 General features of emergent water plants

Emergent water plants typically occur near the shores and in shallow water. They usually are pioneer species that are the first to firmly establish. Due to their prolific growth are able to develop a dense vegetation. Emergent water plants are rooted in the soil, i.e. the bottom of the water body, but they are also known to establish on floating islands that mainly consist of floating (invasive) plants such as water hyacinth. Taking into consideration their prolific growth and their tolerance to a wide range of environmental conditions which is common to such pioneer species they are attractive as biofuel feedstock. These traits however are also characteristics for potential invasive species. Important emergent plants are reeds, in particular *Phragmites australis* (common reed) and *Arundo donax* (giant reed), as well as other grasses such as *Vossia cuspidata* (hippo grass), and *Typha domingensis* (typha, cattail, bulrush). The annual production of reeds and typha can be as much as 20 t/ha. Reeds can be grown in constructed wetlands for phytoremediation purposes of effluent water. Noting its similar properties typha can be used for the same purpose. Residual biomass from rice can also be used as feedstock for biofuel, compressed into charcoal briquettes of as a feedstock for biogas.

Reed and typha are common species in natural fresh water wetlands. When they are however introduced as alien species they rapidly become invasive. In man-made water systems such as in irrigation programmes or in situations where water properties change they may also become invasive even though they are indigenous in the area.

3.1.1 Reed and typha

Reeds and cattails occur naturally in most fresh water systems. *Phragmites australis* (common reed) is a common species in fresh water throughout tropical and subtropical regions. Giant reed (*Arundo donax*) is well known from temperate and subtropical regions including the Mediterranean. A common species in tropical fresh water systems is *Typha domingensis* (typha, cattail or bulrush) which however may be better known by many by its synonym of *Typha australis*. Typha species are generally grouped together with the reeds due to its similar appearance and habitat although taxonomically it is a different family.

Figure 11: ***Typha domingensis*** **(typha, bulrush, cattail)**

Figure 12: ***Phragmites australis*** **(giant reed)**

Typha and reeds can form dense wetland vegetations (reed beds) in shallow fresh water systems. *Typha domingensis* grows abundant in water with a depth of up to 2 and even 2.5 metres. Above ground biomass production of typha and *Phragmites australis* of respectively 22 and 23 t/ha DM is documented in Moroccan wetlands with a water depth of 0 to 0.6 m. These plants have extensive rhizomes and their root shoot ratios are less than 50 %: total biomass accumulation exceeded 52 t/ha DM. Typha and reeds are typical fresh water pioneers; typha does not tolerate salt concentrations above 2%.

3.1.2 Possible use of emergent water plants

Typha and reeds can be valorized in several ways and are therefore an appreciated local resource. The stems are widely used for construction purposes, in particular for roofing, for reinforcing clay walls, and for fencing. They can also be a resource for animal feed. Reed and typha are often used in constructed wetlands as helophyte filter for phytoremediation purposes of effluent. Typha, reeds and other emergent aquatic plants are a raw material for the paper industry. Reeds and smaller grasses are used for handicraft, such as for basket weaving and furniture. The raw biomass may be brought to crop fields for mulching purposes.

Reeds and typha have attracted the interest of rural development initiatives as a potential resource for biofuels. The stems are a feedstock for:

- Charcoal, for cooking
- Direct combustion of the woody stems, for cooking and electricity generation
- Biogas, for cooking and electricity generation

Typha in the Senegal river basin

In the Senegal river several dams are built to provide an impulse for irrigated rice farming in the river basin. Following the construction in 1985 of the anti-salt intrusion dam in the delta, the Diama dam the delta has become a fresh water reservoir. A shallow lake has been formed between the dams. Due to the dams the fluctuation in the water level and the stream velocity has reduced and eutrophication of the water took place due to increasing fertilizer application in the expanding irrigated rice farming. These changes in the aquatic created a favourable environment for native emergent water plants, in particular typha (Typha domingensis) as well as common reed (Phragmitis australis).

The dominant typha vegetation that was able to develop causes serious problems in the lower valley of the Senegal river. The area with a dominant typha vegetation in the delta upstream the Diama dam already covers about 140,000 ha. It is also dominant in nearly all “marigots” feeding water for irrigated agriculture and along the banks of the river and in all inundated areas up to a water depth of 2,0 – 2,5 meter. Dense typha vegetations obstruct access to these marigots and the Senegal river for fishermen and cattle farmers. The water flow is hampered and siltation occurs. The abundant growth of typha near villages has a negative impact on the health situation for people and livestock depending on the water. Reduced flow and the development of marshes and the incidence of diseases such as malaria and schistosomiasis has increased.

The people in the affected areas recognize typha as a useful resource. It is amongst others appreciated as a building and fencing material. It has attracted the attention of rural development initiatives as a potential energy resource.

Typha is a potential substitute for firewood. Using reed and typha biomass for local energy supply thus reduces the dependency on firewood and charcoal. It is an important advantage that both the production of charcoal and the plants are already known locally by riverine communities. Noting its potential as a biogas resource it also reduces the dependency on fossil fuels. The production of biogas will require additional effort, similar to the use of floating biomass for biogas production. Residue is a valuable resource for soil improvement. Ashes from direct combustion and charcoal are typically rich in potassium and phosphate. Digestate from biogas production can be composted and applied as biofertilizer.

3.1.3 Impact of emergent water plants

Various agricultural development programmes contributed to the proliferation of typha as an unwanted vegetation posing a threat to the welfare of riverine communities. This is due to the construction of dams to prevent salt intrusion and to reduced natural flooding resulting from water management and irrigation schemes. Vegetation shifts consequently occur which are dominated by typha. In the Senegal river delta already a surface of 140,000 ha is occupied by typha. Problems associated with typha are the obstruction of water flow and siltation. It affects irrigation and drainage systems, wetland ecosystems, agriculture and fisheries. Abundant typha vegetations consequently also constitute a health hazard increasing the incidence of waterborne diseases such as malaria, dengué and schistosomiasis.

Figure 13: Typha hampering fisheries in Northern Nigeria

3.2 Opportunities for the use of emergent water plants

Whereas dense typha and reed vegetations near shores and in shallow water can be troublesome and need to be controlled, the biomass can be used for a variety of purposes. Typha has a high growth rate. The production of typha and reed can be 20 t/ha DM or more depending on water depth, which exceeds the production of commonly planted trees for community-based firewood production such as eucalyptus and *Leucaena leucocephala*. This yield provides interesting opportunities for local biofuel production, and in particular to substitute firewood (including charcoal). Harvesting typha and reeds however requires a different strategy than weed control as the objective is not to prevent regrowth of the typha or reed vegetation but to attain a sustainable production while ensuring adequate management of the water system.

3.2.1 Harvesting of emergent water plants

To ensure rapid regrowth the stems have to be cut 20 cm above the water surface to maintain air exchange with the lower parts of the plant. For weed control the stems are cut under the water surface. Studies in the Lac de Guiers in Senegal showed that cutting typha stems 20 to 50 cm below the water surface led to a vegetation shift towards submerged species. Typha almost disappeared and was partly replaced by *Potamogeton* species.

To ensure sustainable production advantage has to be taken of the rapid regrowth. This means that the harvesting strategy has to be different from a weed control strategy. Typha (and reeds) can be harvested manually and mechanically. The stems should be cut at senescence to maintain sufficient reserves for re-growth in the rhizomes, but before the seeds spread. One harvest per year appears to be the optimum.

Figure 14: Typha harvest in Senegal

For manual harvesting the stems can be cut using tools such as a cutlass and a scythe. Harvesting the stems in inundated wetlands care has to be taken because of the presence of waterborne diseases like schistosomiasis. The stems will float and have to be collected using rakes. Manual harvesting is easier in areas which are temporarily dried out, either naturally or purposely. After harvesting the area can be flooded again and the plants re-grow from their rhizomes.

Mechanical harvesting is generally done in flooded conditions using a mowing boat equipped with a mowing bar. For collecting the stems the boat has to be equipped with a rake. The mowing bar therefore has to be replaced or a second boat collects the stems. It should be noite that these boats are generally designed for clearing waterways in temperate zones. In the tropics typha stems are much thicker and the engine may overheat. Another option is the use of an amphibious vehicle with a larger loading capacity. Alternatively the area can be dried and conventional equipment such as for the harvesting of sugarcane or rice can be used.

Figure 15: Mowing boat with rakes attached for removing typha and reed stems

Before the stems can be converted into pellets or charcoal they have to be dried. In semi-arid and sub-humid conditions the biomass can be air dried in about a day. Under humid conditions the drying process may take considerably longer depending on the season. Many areas in Africa where typha grows abundantly are however located in arid and semi-arid regions, in West Africa notably in the Sahelian basins of the large rivers such as the Niger and the Senegal river.

3.2.2 Biofuels from emergent water plants

Recurring typha and reed vegetations provide a interesting opportunity for local biofuel production. The production can be more than 20t/ha which exceeds crop and wood production under local marginal circumstances. This also provides opportunities for community based wetland (co-)management initiatives that contribute to controlling the aquatic vegetation and to protecting fragile ecosystems.

Typha and reeds biomass can be burned as a substitute for wood, eventually after pelletizing the stalk and it can turned into charcoal for cooking purposes. Pellets are produced by compressing the biomass using a binding agent. The biomass can also be a source for biogas production. To convert typha and reed biomass into pellets or charcoal it has to be dried. Under semi-arid and sub-humid climatic conditions sun drying can be done which requires a day. A large area has to be reserved for the drying process.

Harvesting typha in Senegal

Studies carried out in the Senegal river delta have shown that manual harvesting of typha, i.e. clearing an area, is considerably slower in a flooded area and/or when typha has formed a dense vegetation (20 m^2/h) than in dry areas and when the vegetation is less dense (40 m^2/h). For the conversion of the biomass in charcoal the weight of the harvested biomass is important. As typha grows tallest and heaviest in inundated areas the lower harvesting speed in m^2/h is thus compensated by the typha biomass.

A mowing boat can cut a typha stand at a speed of approximately 400 m^2/h. The time needed to replace the mowing bar by the rake to remove the stems (about 50 minutes) and the speed with which the stems are removed from the water should also be taken into consideration. A mowing boat may thus clear 1 ha in 35 hours.

Charcoal can be produced at the village level using small reactors. Carbonizing the fibrous material results in charcoal dust, but to enable the use of the charcoal it has to be in the form of briquettes. There are two options for producing charcoal briquettes:

- Compression of the biomass after which it is carbonized.
- Carbonization of the biomass without compression. This results into charcoal dust which needs to be turned into briquettes using a binding agent, agglobriquetting.

Figure 16: Typha charcoal briquettes, Senegal

In Senegal a small mobile charcoal reactor was designed by PERACOD that can be built by local craftsmen. A team of 2 persons can operate 5 or 6 of these charcoal reactors. It can convert 100 kg typha biomass into 20 kg charcoal dust in a cycle of about 4 hours. In an agglomerator and adding a binding agent the briquettes are formed.

Figure 17: PERACOD Charcoal reactor '3 fûts', Senegal

Similarly to the floating plants typha and reed biomass can be used for the production of biogas which is subsequently used for cooking and electricity generation. Both plug-flow and batch digesters are an option, depending on the availability of the biomass.

3.2.3 Synergy with other uses for emergent plants

A constructed wetland (using reeds or typha) for phytoremediation can be combined with a plug flow digester in an integrated water, energy and sanitation approach to treat household residues (organic waste and waste water). Through such a system access to water is improved and biogas is obtained. The sludge from the digester can be composted and returned to crop land to improve agricultural production of depleted soils. Biomass harvested from the constructed wetland can also be used for construction and handicraft purposes.

3.2.4 Feasibility using emergent water plants

Studies were carried out in Senegal on the feasibility and acceptability of typha based charcoal briquettes for rural energy supply. Wood and charcoal account for 60% of the energy supply of Senegal and nearly 85% of household energy consumption. Charcoal briquettes produced using the agglobriquetting may count on a wide acceptance to replace firewood and regular charcoal. The typha biomass supply is abundant. A 2003 satellite estimate over 40 km from the Diama dam on the Senegal river suggests that more than 500,000 tonnes of dry biomass can be harvested. There is however a deficit in charcoal supply which is supplied from the from Kolda and Tambacounda forests.

The charcoal selling price increased from €0.31/kg in 2006 to €0.38/kg in 2007. The production costs for typha charcoal briquettes, which includes harvesting, drying, carbonization, agglobriquetting and transport is €0.08 to €0.11. From a costs and availability perspective charcoal briquettes are feasible. The production of charcoal briquettes could also be interesting for small investments, rural entrepreneurship, and supply towns in the region.

The calorific value is less than regular charcoal: 17Mj/kg against 29Mj/kg. This was not considered a problem. The traditional and improved charcoal stoves function well, and the briquettes even last longer. The briquettes may have a slight odour due to the binding agent, but this too was not considered a problem.

4 ALGAE

4.1 General aspects of algae

The production and processing of algae currently receives most attention as an source for biofuels. Algae production is the most efficient method to benefit from solar radiation in the production of biomass. Algae have a higher production then any other organism. They further do not necessarily occupy arable land. Many algae can be produced in saline water conditions, thus limiting the need for fresh water. Production can take place in a rather small scale open pond system, or in sophisticated closed systems in an industrial process.

Algae are a source for a wide range of products, including biofuels (biodiesel, bioethanol), food supplements, pharmaceuticals, and a variety of compounds for the chemical industry. Production and processing for biofuels usually focuses on biodiesel, and to a lesser extent on bioethanol. The production of biogas from algae receives relatively little attention. For many centuries algae are an appreciated food ingredient.

The focus for biofuel as far as algae are concerned is on biodiesel. Various algae are also an interesting source for amongst others food supplements and pharmaceuticals. These attract a more interesting price than biodiesel or ethanol. The challenge for algae-based biofuel production is the competition with low priced fossil fuels. A smart production combining both bulk (biofuel) and high value production objectives may be economically feasible. Other possibilities are the use of algae for bioremediation, providing an bulk value output for the production of biofuels.

Figure 18: ***Ulva sp.*** **(sea lettuce, a green seaweed)**

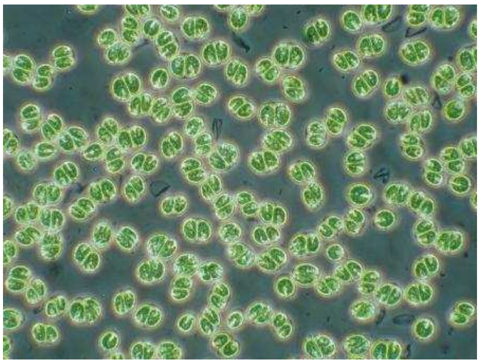

Figure 19: ***Tetraselmis suecica***

4.1.1 Microalgae and macroalgae

Two kinds of algae can be distinguished, macroalgae and microalgae. Macroalgae (seaweed or kelp) are well known from their appearance as “aquatic plants” attached to rocks and shallow sea bottom or floating in the sea. They can be cultivated in the sea, attached to solid structures like poles and rafts. Occasionally they may be kept in suspension in agitated ponds as small individual plants. Microalgae are very small plant-like organisms, usually as a single cell or in colonies of single cells. Their size ranges from 1 to 50 µm. In this context prokaryotic cyanobacteria (commonly referred to as blue-green algae) such as spirulina are treated with the microalgae although taxonomically they are considered to be bacteria.

In general, microalgae are cultivated in open ponds and photobioreactors whereas macroalgae are cultivated in natural environments. Macroalgae are produced for their content of gelling substances (agar, alginates and carrageenans) and for food. The annual global production of seaweed is several million tons. There is a growing interest in macroalgae as a feedstock for biofuel production. Microalgae are produced for their unique products such as carotenoids, antioxidants, fatty acids, enzymes, polymers, peptides, toxins and sterols. Over 15,000 novel compounds originating from algal biomass have been chemically determined. It has been estimated that about 200,000-800,000 species exist of which about 35,000 species are described.

4.1.2 Possible use of algae

Algae represent a resource with significant potential for practical exploitation. Algae and algae products are, or can be, used for:

- Food and feed
- Food and feed supplements
- Pharmaceuticals
- Industrial purposes
- Phytoremediation
- Biofuels

Algae are widely used as a food ingredient and as food supplement. Seaweed is both harvested from natural saline waters and cultivated. It is particularly popular in East Asia where it is used in soups and to wrap sushi. Seaweed is cultivated for the extraction of alginates, agar and carrageenans. These are amongst others used as food additives and preservatives. Alginates also have pharmaceutical uses and agar is used as a culture medium in microbiology research.

The cyanobacteria *Arthrospira platensis* and *Arthrospira maxima* (commonly known as spirulina) are an important food source for many native Central and South American and African cultures. Spirulina has for ages been gathered from alkaline lakes such as Lake Chad in Central Africa. It was first identified in Central Africa in the 1930s where it was regarded an important food and sold on the local markets as dried cakes (dihé). Similarly the Aztecs used it as a daily food supplement and appreciated its medical properties (tecuitlatl). As a health food and natural food supplement spirulina is now consumed by millions of people worldwide.

Lipid content of some microalgae species

Microalgae species	Lipid content (% dry biomass)
Chlorella sp.	28–32
Crypthecodinium cohnii	~20
Cylindrotheca sp.	16–37
Dunaliella primolecta	23
Isochrysis sp.	25–33
Monallanthus salina	> 20
Nannochloris sp.	20–35
Nannochloropsis sp.	31–68
Neochloris oleoabundans	35–54
Nitzschia sp	45–47
Phaeodactylum tricornutum	20–30
Schizochytrium sp.	50–77
Tetraselmis sueica	15–23

Many microalgae have a high lipid content of 30% up to 60% of the dry biomass, or depending on the circumstances and species maybe even more. These lipids can be converted into biodiesel through a transesterification process which makes microalgae an interesting source for the production of biofuels. Algae lipids are esters of glycerol and, in general, polyunsaturated fatty acids (PUFAs). Algae a therefore a popular feedstock for food supplements, and for feed in aquaculture resulting in fish which is rich in ω−3 fatty acids. In fact the expansion of fish production will only be possible if sufficient PUFA sources are available. – *Botryococcus braunii* does not produce lipids but isoprenoids, alkane like C32 to C38 compounds, comprising 25–70% of the biomass which can be directly used in existing oil refineries. *Botryococcus braunii* is however difficult to grow. – Microalgae are further rich in carbohydrates, pigments, vitamins, aromatics, proteins and other compounds. These make them interesting in an industrial context. Some compounds may be interesting as potential new energy carriers.

Algae can be important for CO_2 mitigation, O_2 supply to aquaculture, recovery of nutrients from water bodies and phytoremediation. For the production of 1 ton of dry biomass about 1.8 tons of CO_2 is used, and algae produce about 1.6 tons of O_2-rich gas per ton of dry biomass that can be supplied to fish in aquaculture. Microalgae can be used in phytoremediation processes. In wastewater treatment algae contribute to the recovery of nitrogen compounds and phosphates. Because of possible contaminants biomass from phytoremediation facilities may not be suitable to serve as a feedstock for nutrition or pharmaceutical purposes and care should be taken with its use for soil improvement, but lipids extracted from harvested algae biomass are suitable for biodiesel production.

4.1.3 Impact of algae production

The production algae for biofuels is a popular alternative for food crops such as maize as a biofuel feedstock. Arable land is not required and algae can be cultivated in saline water. The ecological impact of algae farming is nevertheless underestimated. Microalgae farms are in general located on land. Although the land may not be arable or otherwise considered as valuable by the general public and policy makers, this land may still be of ecological significance. Alien algae and effluents from the farms, in particular related to harvesting and processing of the algae, can have an ecological impact in natural water bodies. Algae production systems should not replace natural wetland ecosystems or jeopardize wetland ecosystem services. An microalgae trial project in Hawaii, positioned in a coastal wetland area, appeared to have a significant impact. Up-scaling such production models which indiscriminately release farm effluent into the environment would be devastating to fragile mangrove ecosystems as well as brackish water aquaculture.

4.2 Opportunities for algae-based biofuel

The high productivity of algae suggests that these organisms are ideal sources for biofuels. Their photosynthetic efficiency contributes to the high production opportunities. In flat panel reactors a photosynthetic efficiency of 6.5% is realized, and 7.5% may be possible. The theoretical maximum photosynthetic efficiency is approximately 9%. In open pond systems a photosynthetic efficiency of 2 to 3% is realized. For terrestrial crops it is less than 2%. Noting this high productivity combined with high lipid content, microalgae have attracted attention as the most promising future energy crop. The biofuel prospects have become a major driver in research and development on algae production and processing. On the other hand, commercial applications of microalgae have concentrated on high value compounds such as carotenoids, and the use of microalgae as a food supplement and feed ingredients for aquaculture.

A common concern related to biofuel crops is that competition for arable land required for food production increases with increased production of biofuel crops. Closed algal bioreactor systems have the advantage that they can be sited on non-arable land, eliminating competition with food crop production and opening up new economic opportunities for arid regions. Another important advantage of algae production is that many algae can be cultivated in a saline environment, thus limiting the need for fresh water. In addition conventional crops used for biofuel production require significantly more (fresh) water than algae production.

4.2.1 Production of algae

Seaweed is cultivated in marine and brackish conditions at relatively low costs and technological input level. Thus agro-production can be brought to the marine environment through seaweed cultivation. There already is considerable experience in marine seaweed cultivation. It has been collected from, and cultivated in, natural marine environments for centuries, mainly for food purposes such as an ingredient for example for salads and wraps (*e.g.*, sushi), in particular in East Asia. Seaweed is also cultivated for the extraction of alginates, agar and carrageenans. Madagascar for example produces seaweed for agar. Seaweed production can be located in big estuaries and semi-arid areas: seaweed is harvested near desert lands, e.g. the Northern Libyan coast. Few seaweed species are free-floating; most species require a firm attachment point. Large scale cultivation of seaweeds can thus be combined with off-shore wind energy parks and platforms. The production can be twice as efficient as terrestrial biofuel crop production. A large scale park has production costs comparable with maize but with a considerably higher yield.

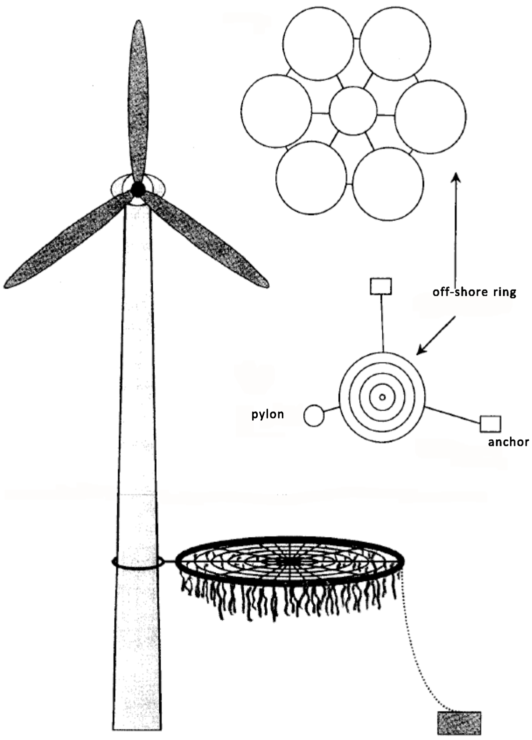

Figure 20: Schematic view of integrated windenergy and seaweed production

Seaweed can be cultivated land-based (in open ponds), in shallow natural water bodies such as estuaries, or off-shore. In open ponds and shallow estuaries seaweed is commonly produced attached to ropes, floating rafts or nets. It often is an artisanal production system and harvesting is labour intensive. Off-shore seaweed production is an industrial activity. It can be designed as floating, anchored, or as a combination of both. Floating system drift but may well withstand storms. Most production systems are anchored to the sea bottom, and/or they are attached to off-shore wind farms or platforms. The seaweed is attached to longlines, grids or nets. A variety of designs is possible to best accommodate the local production opportunities. In multilayer cultivation and the application of the variation of photoreceptor pigments (green seaweed vs. red and brown seaweeds) solar radiation is used optimally. In large scale production the harvesting can be mechanized using harvesting vessels or a platform that pulls in the lines or nets to gather the attached seaweed. Seaweed can yield as much as 60t/ha/year DM in the North Sea. In the tropics the production can be up to 100t/ha/year.

Microalgae can be cultivated in open and closed systems. Open pond systems, usually raceway ponds, are the most frequently used production systems in particular for the production of spirulina. In these systems a photosynthetic efficiency of 2 to 3% is realized. This is more than the photosynthetic efficiency for terrestrial crops which is less than 2%. Other open systems are natural lakes and open basins. Closed photobioreactors (PBRs) include flat panel systems and tubular, horizontal or stacked, systems. In flat panel reactors a photosynthetic efficiency of 6.5% is realized, and 7.5% may be possible. – The theoretical maximum photosynthetic efficiency is approximately 9%. – The high photosynthetic efficiency contributes to high production opportunities. Tubular systems may produce about 60 t/ha/year and flat panel systems about 100 t/ha/year. Open systems (race way ponds) produce about 20 t/ha/year. The chemical composition of microalgae depends on species and cultivation conditions: temperature, CO_2 supply, photosynthetically active radiation (PAR), pH, salinity, O_2 level, and nutrient supply or deprivation of specific nutrients. The production of large amounts of photosynthetic algae requires large amounts of CO_2. The CO_2 supply to algae cultures is however a technological challenge. Algae also produce large amounts of O_2. As high O_2 levels inhibit growth the culture need s to be degassed which is another technological challenge.

The investment costs for open raceway pond systems are low. The CO_2 supply depends on atmospheric CO_2, the number of species that can be used is limited, harvesting is expensive and the biomass concentration is less than 0.5 g/l. Because it is an open system it is vulnerable for contaminations. Raceway ponds are therefore used for the production only a few species that can grow in selective environments such as *Dunaliella salina* in high salinity and *Arthrospira platensis* and *A. maxima* (spirulina) in high alkalinity.

Figure 21: Raceway ponds for microalgae production, Seambiotic

Closed, tubular and flat panel, systems are aseptic and CO_2 can be applied mixed with air. The water demand is less for closed microalgae production systems than for terrestrial crops: 1.5 litre water/litre biodiesel compared with 1000 litre/litre biodiesel for terrestrial crops. Tubular systems in particular are scalable. The biomass concentration can be 3 g/l for tubular systems and more than 5 g/l for flat panel systems. An important constraint is the accumulation of O_2, and consequently the degassing of the system, and the investment costs are higher than for open systems.

Figure 22: Closed tubular photobioreactor, Wageningen University

Microalgae are small and usually they consist of individual cells. Harvesting therefore requires specific technologies different from harvesting aquatic macrophytes (floating and emergent water plants) and macroalgae. Pumping water with the suspended microalgae from the production facility and centrifugation is the most common harvesting method. The diluted streams with an algae concentration which is generally less than 3 g/l requires a large-capacity centrifuge. This makes the harvesting expensive and very energy demanding. An alternative would be flocculation of the algae, followed by sedimentation and flotation, before centrifugation or filtration would substantially reduce the harvesting costs and energy requirements. After harvesting the algae follows the extraction of the lipids. This is done using organic solvents or more environmentally benign but also more expensive solvents such as supercritical CO_2. The algal oil can then be converted into biodiesel by transesterification with methanol or by hydrogenation of fatty acids into linear hydrocarbons.

4.2.2 Biofuels from algae

Algae are a feedstock for several biofuels, notably biodiesel and biogas. They accumulate solar energy as lipids, hydrocarbons and polysaccharides. The lipids can be converted into biodiesel. Algae biomass can be converted to biogas through anaerobic fermentation. Fermentation of algae biomass can result in bioethanol, but the energy balance may not be positive. Through gasification syngas, a gas mixture of CO and H_2, can be produced. Pyrolysis of algae biomass results in biocrude and hydrocarbon gas mixtures.

Microalgae are considered the most promising future feedstock for biodiesel and they have attracted interest as a feedstock for jet fuel. Biodiesel is obtained through the conversion of algal lipids through a transesterification process with methanol. Also, linear hydrocarbons can be obtained through hydrogenation of the fatty acids. Growing microalgae a production of 20,000-80,000 litre/ha/year oil can be realized compared with 6,000 litre/ha/year for palm oil. Even in open raceway pond systems which are common for the production of for example spirulina this superior production level of algae oil compared with terrestrial oil crops is justified. With the technological capabilities presently available it is possible to replace the transport fuels in Europe with algae based fuels, representing about 400 million m3 of lipids. A surface area 9.25 million ha would be required, the equivalent of the surface area of Portugal.

Research is paying some attention to the direct production H_2 by microalgae. The most appropriate approach for H_2 production suggested so far is hydrogenase-based indirect biophotolysis rather than H_2 production by nitrogen fixing microalgae (i.e., cyanobacteria). The microalgae can be produced in open raceway ponds, similar to those used for spirulina farming and waste water treatment, and concentrated by settling. After transfer to an anaerobic dark fermenter the hydrogenase enzyme is induced and H_2 production is initiated. The remaining H_2 is released after transfer of the microalgae to a PBR. The depleted cells are returned to the open pond where the cycle starts again.

Macroalgae biomass is considered to be a more suitable substrate for anaerobic fermentation to biogas than terrestrial plant biomass. Macroalgae contain complex polysaccharides which are less resistant than lignin. Findings from research on gasification has shown that the net energy generation from macroalgae exceeds that of microalgae (11,000 MJ/t compared to 9500 MJ/t). Seaweed can yield as much as 60t/ha/year DM in the North Sea. In the tropics the production can be up to 100t/ha/year. A feasible large scale cultivation of seaweeds in conjunction with off-shore windturbine parks in the North Sea would cover a surface area of approximately 5000 km^2 and produce 350 PJ, an equivalent of 10% of the current (2009-2010) Dutch energy consumption.

4.2.3 Synergy in algae production

Algae can be cultivated for a variety of reasons. Smart combinations of these production objectives may result in a synergy that contributes to the feasibility of algae production for biofuels. This synergy can be distinguished at several levels, both in algae growing and in algae processing and usage of the biomass.

Algae can be cultivated with a specific objective such as the production of raw material for the food and feed industry, the production of biodiesel or waste water treatment. The objectives can also be integrated. The CO_2 supply is a limiting factor in microalgae production whereas high O_2 levels inhibit production. Production facilities for microalgae can play a role in CO_2 mitigation, and supply O_2 to aquaculture. A production facility can also take advantage of residual heat, thus providing opportunities for cogeneration. Microalgae are already used for phytoremediation in wastewater treatment facilities. There the microalgae are a resource for biodiesel, biogas and eventually H_2.

Algae can play a significant role in nutrient recovery from wastewater and natural (eutrophic) water bodies. Thus after extraction of relevant components, anaerobic digestion for biogas and composting, residual microalgae biomass is a source for soil improvement or otherwise for nutrient amendments. In wastewater treatment CO_2 may be recycled internally and H_2 may become a biofuel output through indirect biophotolysis.

The sea is a CO_2 as well as a phosphate sink. The sea also contains substantial nutrient deposits. These can be used by seaweeds. Taking into consideration a projected phosphate shortage for terrestrial crops, seaweed farming may contribute to phosphate recovery. It will be an interesting challenge to manage these nutrients in open sea systems. Seaweed farming in open sea can be integrated with other off-shore activities such as windturbine parks. Under low-input production conditions seaweed can be farmed in shallow estuaries or ponds for a combination of biofuels, high value products such as food products, alginates and agar, and nutrient recovery from residual algae biomass for improving crop land.

Algae produce a broad spectrum of interesting chemicals for example for food, feed, various materials such as coatings, pharmaceuticals, and energy. These are high value components such as proteins and pigments and low value bulk chemicals such as lipids for the production of biodiesel. Through biorefinery these components can be co-produced and obtained from the algae biomass. The bulk chemicals for bioenergy attract a low price as they have to compete with other (fossil) energy sources. Through an integrated biorefinery process, and taking into consideration the high value of various fine chemicals, a reasonable value could still be realized for the total biomass.

4.2.4 Feasibility of algae production for biofuels

The competition with low priced fossil fuels is a major challenge in the development of (micro)algae-based biofuel production. In spite of the high production potential of microalgae, the economic feasibility is doubtful if the production objective focuses on biofuel only. It should also be noted that food and feed supplements, feed for aquaculture, pharmaceuticals and other special algae products attract a far more interesting price than bulk chemicals such as biodiesel and bioethanol. For biofuel purposes microalgae production should therefore be smart enough not only to be economically feasible but also to be economically interesting. Biorefinery offers opportunities combining bulk and high value production objectives. Other possibilities are the use of algae for phytoremediation, providing a bulk value output for the production of biofuels. Macroalgae may be farmed at sea at relatively low costs for example integrated with windturbine parks.

It is already possible to replace the transport fuels in Europe with microalgae based fuels, representing about 400 million m^3 of lipids. This would require a surface area 9.25 million ha, the equivalent of the surface area of Portugal. In addition about 400 million tons of proteins would be produced, which is 40 times the amount of soy protein imported in Europe. Algae biomass is also a source for chemicals and aquaculture, sugars and oxygen. This contributes both to the feasibility of algae production for biofuels and to a more sustainable supply of food and feed proteins. The current production costs are however too high to compete with fossil fuels.

Biorefinery offers opportunities to provide additional value to microalgae biomass and integrate microalgae production for both high value chemicals and bulk value chemicals for the production of biofuels. By-products add value to the biomass in a sense that the costs for the production of biofuels can be brought down: e.g., O_2 can be supplied to fish cultures. The biorefinery processes are however still a challenge and not suitable for village level implementation. Taking into consideration production and biorefinery costs and technological requirements microalgae production for biofuel purposes should focus on large scale production but even then the production costs are still too high. It should however be noted that innovations in algae production started because of the demand for biofuels. Considering the production potential compared with terrestrial crops innovations are likely to continue and production costs to drop. In the future the production costs may go down from €4.15/kg DM to €0.70 for tubular systems, and from €5.95 to €0.68/kg for flat panel systems. For open systems (race way ponds) the costs may be reduced from the current €4.95 to €1.28 per kg. More improvements are still needed to further bring down the costs. To compete with fossil fuels the production costs should be reduced to €0.40 if the production focuses entirely on biofuels. In a biorefinery context, recycling of O_2 and recovery of nutrients (nitrates and in particular phosphates) the costs may be higher, approximately €1.65/kg DM, but the revenues may be higher as well. Future closed stand alone production systems in which the algae are milked, may not require fresh water, N and P fertilizers, and use atmospheric CO_2. Those systems could be applied in remote areas with high solar radiation.

The CO_2 supply for microalgae production through carbon capture farming contributes to CO_2mitigation. This is particularly interesting in combination with nutrient recovery from eutrophic water phytoremediation of effluent. Studies carried out in the USA in the 1980's and updated in 2000-2002 suggest that it may be feasible to install raceway ponds for desalination and nutrient recovery of eutrophic water bodies. The ponds would be similar but much larger than the ponds used for spirulina cultivation. They would have earth bottom, not lined with plastic. Harvest would be by flocculation and settling of the algae. Costly centrifuges would not be required. The biogas obtained from the system could be used in a gas power generating facility, whereas the flue gas from the power plant is the CO_2 source for the algae. It should be noted that the gas transfer is a major energy input into the microalgae production system. The microalgae production on the other hand contributing to CO_2 mitigation by fixing the flue gas CO_2. Contrary to typical water treatment facilities there are no CH_4 and N_2O emissions. Nutrients from the saline eutrophic water are recovered in the algae biomass. The sludge resulting anaerobic digestion biogas production from the algae biomass can be composted and

Feasibility aspects of spirulina cultivation for biodiesel

Spirulina is often grown for the production of food and feed supplements in small-scale low-input production systems in the Sahel area and in Southeast Asia. Usually small basins of 20-30 m^2 are used and paddles are used to manually stir the algae suspension. The algae are harvested by filtering the mixture through cheesecloth. The algae paste is sun dried and sold on the local market or, if the production is well organized, on the international market.

These systems can be important for the production of food and feed supplements and for generating rural income. They are promoted by many rural development agencies. Growing spirulina at small scale, of for that matter other microalgae, is however not (or not yet) interesting for the production of biofuels. The production and processing is generally considered to be too complicated for community-based initiatives, and the price of spirulina as a feedstock for biofuels can not compete with the price obtained for spirulina as a raw food or feed supplement. For biodiesel the price of the raw biomass should not exceed €0.40 per kg DM. As a food and feed supplement spirulina attracts 10 to 50 times that amount, and there is sufficient demand for the product to further increase production. Some microalgae used for aquaculture feed are even valued at €250 per kg dry biomass.

is a valuable source for organic fertilizer rich in N, P and K. Adding up these advantages, including CO_2 credits, the system would be feasible for such a large-scale implementation. Noting the growth of microalgae and the possibility of cultivation in saline water, it might also be worthwhile to study such a system for small-scale implementation with limited investment similar to the use of other aquatic plants for integrated phytoremediation, nutrient recovery and biofuel purposes.

The production of hydrogen and bioethanol from microalgae does not seem to feasible for local biofuel and development. Notably the energy balance does not appear to be positive. The systems also require considerable investment and technological input.

It is important to note that the raw biomass of many microalgae already represent a high value as a food supplement and an ingredient for aquaculture and poultry feed, and as a source for many fine chemicals for the industry. Unless biorefinery is a reasonable alternative it is more interesting to venture into microalgae farming to supply to the food, feed and industrial market than for biofuels and other bulk chemicals.

Figure 23: Small-scale spirulina farming near Maroua, Cameroon

Figure 24: Spirulina harvesting in small-scale production

From a local development point of view it appears more feasible to produce biofuels from macroalgae than from microalgae. Seaweed is grown in marine and brackish conditions, in a range of systems: open sea, estuaries, and open saline or brackish ponds. There already is ample experience in low-input cultivation. Seaweed is are easier to grow, harvest and process than microalgae. It is an interesting source for the production of biogas as well as bioethanol because of the high levels of carbohydrates. Large-scale bioenergy production is feasible at an annual production of production of 500,000 tonnes DM. Depending on the production system this represents an area 100 to 170 km^2. Preliminary studies in Malaysia suggest that seaweed can be a feasible source for bioethanol to at least partly replace fossil transport fuels. Small-scale seaweed cultivation is possible for the production of biogas for local energy supply and

Opportunities for bioethanol production from seaweed in Sabah

A preliminary study was carried out to assess the opportunities for bioethanol production from seaweed harvested from the sea in Sabah, Malaysia. The assessment was based on line method cultivation of *Eucheuma spp.* and 5 harvests per year. The annual seaweed harvest is 3 kg/m^2 DM (30 t/ha/year). of seaweed One line represents 5 m^2 and yields about 30 kg of fresh seaweed (3 kg dry weight). The potential seaweed farming are is 102,413 ha. *Eucheuma spp.* contains 70% of carbohydrates. 56.2% of galactose can be extracted from these carbohydrates which can be fermented to bioethanol. Thus 1.18 kg of galactose can be derived from 1 m^2 of cultivation area annually. Based on a fermentation efficiency of 0.39 the total third generation bioethanol production from seaweed in Sabah is estimated 241 ktons. With future improvements in galactose extraction fermentation this quantity can increase.

The net calorific value for ethanol is of 27 GJ/ton. The total energy potentially available from seaweed based bioethanol therefore is 6.50 x 10^6 GJ. In 2007 the total energy consumption of the Sabah transport sector was 7.41 x 10^6 GJ. Bioethanol from seaweed can therefore fulfil more than 88% of the transport fuel (petrol) demand, and 35.5% of the country's energy demand can be fulfilled with a cleaner and sustainable renewable energy.

cooking purposes. This is similar to the use of floating macrophytes such as water hyacinth for local biogas production.

Multiple usage of the area for seaweed cultivation is possible. This includes amongst others nursery of fish, reduction of waves and other measures of climate proof coastal defence. In particular in the tropics the cultivation of seaweed may be combined with brackish water agriculture, for example on the Sahara Atlantic shores. The sea is phosphate sink, as well as a CO_2 sink. Through seaweed cultivation in open sea systems substantial amounts of nutrients, in particular phosphates can be recovered. Nutrients such as phosphates can also be recovered from residual seaweed biomass from phytoremediation of effluent in estuaries and open ponds. Other smart combinations with seaweed cultivation lead to a more beneficial exploitation of off-shore wind energy parks and wave energy initiatives. Seaweed cultivation in the North Sea in combination with off-shore windturbine parks covering a surface area of approximately 5000 km^2 could an equivalent of 10% (350 PJ) of the current (2009-2010) Dutch energy consumption.

Seaweed cultivation can be further valorized through biorefinery. This is similar to biorefinery of microalgae, by integrating protein, pharmaceutical and bioenergy production. It should also be noted that algae proteins are of similar value as meat proteins. Seaweed and microalgae can replace soy protein used by the food and feed industry, thus reducing the dependency on soy by the industry and contributing to more sustainable land-use.

5 SUMMARY

Aquatic biomass constitutes a valuable resource for local biofuels. The production by aquatic plants exceeds terrestrial biofuel crop production such as oil palm. Aquatic biomass production does not necessarily compete with agricultural (food crop) production for arable land, with fisheries or with nature preservation. Production can take place in ponds, bioreactors, coastal waters, and even in the open sea. It can also be harvested from water bodies (e.g. lakes, rivers, wetlands) where excessive growth affects the ecosystem, navigation, fisheries or public health. This is the case with various invasive plants, alien or not, floating or emergent.

Local aquatic biomass is a source for biogas, charcoal, bioethanol and biodiesel. These biofuels contribute to reducing the dependency on fossil fuels, to reducing environmental degradation caused by firewood gathering, and to CO_2 mitigation. Residual biomass, in particular the digestate after fermentation for biogas, can be turned into compost and applied to crop fields. Thus plant nutrients are recovered and soil properties of crop fields are improved.

Floating plants are a potentially important source for local biogas production, thus reducing the dependency on firewood, charcoal and fossil fuel for cooking and lighting. The biomass production can be 40 to 50 tonnes per ha annually, or more. The biogas yield can be 180 to 290 litre/kg DM with a methane content of about 60%. The most important floating plants in tropical areas are notorious invasive weeds: water hyacinth (*Eichhornia crassipes*), water lettuce (*Pistia stratiotes*) and the water fern salvinia (*Salvinia molesta*). Other important floating plants are the water fern azolla (*Azolla spp.*) and duckweed (*Lemna minor*, *Lemna gibba*, *Spirodela polyrhiza*, *Wolffia arhiza*).

Floating biomass can be harvested from open water bodies or from contained basins. Most floating plants can be notoriously invasive, notably water hyacinth, water lettuce and the water fern salvinia, but also the water fern azolla which is a popular biofertilizer and widely introduced to grow in association with rice. Harvesting from open water is a component for aquatic weed control and can provide a constant supply of biomass. Harvesting and processing the biomass contributes to reducing the costs of weed control. Floating plants can also be grown in contained basins under low-input conditions, including for phytoremediation of effluent. Considering their invasiveness regulatory measures must be taken to prevent these plants from escaping to open water and invade hitherto unaffected water bodies. This includes strict adherence to national and international agricultural and environmental pest prevention and control regulations.

Nutrients can be recovered from eutrophic water bodies and effluent. Residual digestate from biogas production can be valuable source for compost thus improving the crop fields' soil properties. Residual biomass from azolla is particularly interesting as a source for compost because of the symbiosis of azolla with nitrogen fixing cyanobacteria. Care should be taken that toxic compounds such as heavy metals and pesticides are not brought into the environment, applied on crop fields or leach to the water table. Contaminated digestate should be treated as hazardous waste.

In addition to nutrient recovery form eutrophic water and phytoremediation of effluent, other uses also contribute to the feasibility using floating biomass. Water hyacinth is used for handicraft such as basket weaving. Duckweed may be a valuable resource for animal feed. With a protein content of 35% it is competitive to soy bean meal.

For small communities the investment to facilitate weed harvesting in remote areas (e.g., hedge cutters, rakes) and a biogas facility is economically feasible. It provides opportunities for local development, including local investments in biogas and electricity production and supply, and may also contribute to employment generation in rural areas.

Dense vegetations of emergent plants, typha and reeds in particular, are a problem in irrigated agriculture, may affect navigation and fisheries, and constitute a health hazard due to increased incidence of waterborne diseases. Typha and reeds are common in shallow fresh water, wetlands and along rivers and lakes throughout the tropics. The most important *Typha domingensis* (typha, cattail or bulrush) *Phragmites australis* (common reed) and *Arundo donax* (giant reed). Their abundance has increased following the construction of dams to prevent salt intrusion and to reduce natural flooding for large scale irrigation programmes. Instead of applying a weed control strategy which aims at eradicating (if possible) the abundant vegetation, it can also be managed to the benefit of local communities. Typha and reed are already appreciated for construction, fencing, and handicraft purposes.

Typha and reeds produce up to 20 t/ha annually which can be converted into charcoal briquettes and biogas. Thus the dependency of forest based firewood and charcoal is reduced, as well as the dependency on fossil fuels for electricity generation. Harvesting and processing the biomass also contributes to reducing the costs of the typha or reed vegetation control. Sludge from the digester can be composted and returned to cop fields for soil improvement. Typha and reeds fit very well in integrated water, energy and sanitation approaches to treat domestic organic residue and waste water, and as a result enhance access to water, energy and biofertilizer.

Algae are generally considered very promising as a source for bioenergy, for biodiesel in particular. An important advantage growing algae is that cultivation can take place using saline (sea) water.

The high photosynthetic efficiency contributes to the high production opportunities of microalgae. Tubular systems may produce about 60 t/ha/year and flat panel systems about 100 t/ha/year. Open systems (race way ponds) produce about 20 t/ha/year. Growing microalgae a production of 20,000-80,000 litre/ha/year oil can be realized compared with 6,000 litre/ha/year for palm oil. In closed systems water demand is less than for terrestrial crops: 1.5 litre water/litre biodiesel compared with 1000 litre/litre biodiesel for terrestrial crops.

Seaweed (macroalgae) can yield up to 100 t/ha annually in the tropics. It is mainly a feedstock for biogas and eventually for bioethanol production. Seaweed can be cultivated in coastal waters and estuaries, and it can be combined with brackish water agriculture in arid and semi-arid areas. Considerable amounts of seaweed are already being harvested near desert lands. Seaweed production in open sea can be combined with windturbine parks, wave energy initiatives and other off-shore activities. There is ample experience with marine seaweed cultivation in the tropics, e.g. for agar.

The sea is a phosphate sink. Taking into consideration possible future phosphate shortages, phosphate may be recovered from seaweed which cultivated at sea or in coastal waters such as estuaries. The phosphates can be returned to crop land as compost, produced from the residual biomass for example after anaerobic fermentation for biogas. Nutrients can also be recovered from eutrophic water and effluent through a phytoremediation concept. These algae may be used a as source for biofuel production. The integration with water treatment may provide feasible opportunities.

The sea is also a CO_2 sink and algae need CO_2 for their photosynthesis. Cultivating microalgae and seaweed in open ponds, and in particular microalgae production in closed systems, requires CO_2 supply into the water. Flue gas from a power plant is an important CO_2 source. Thus algae farming can be an interesting contribution to CO_2 mitigation. The CO_2 supply into a closed photobioreactor system is however a serious technological challenge.

Taking into consideration production costs and technological requirements microalgae production for biofuels has to focus on large scale applications. The introduction of microalgae cultivation for biofuel production in a (small-scale) local development context is not yet likely to be feasible. Small-scale microalgae production for food and feed purposes, such as spirulina farming, and eventually for industrial purposes on the other hand is very feasible. Biofuels can however not compete with these products. Raw microalgae biomass can have a value of up to €250 per kg.

With the current production and refinery costs microalgae production for biofuels only is not yet feasible. To compete with fossil fuels microalgae production costs have to be reduced to €0.40 per kg. In the future the production costs may go down from €4.15/kg DM to €0.70 for tubular systems, and from €5.95 to €0.68/kg for flat panel systems. For open systems (race way ponds) the costs may be reduced from the current €4.95 to €1.28 per kg. An important cost factor is the harvesting of the microalgae and extraction of the components. High value components such as proteins and pigments and low value bulk chemicals such as lipids for the production of biodiesel can be co-produced from the algae biomass. Through an integrated biorefinery process a reasonable value could still be realized for the total biomass. These processes however still have to be further developed and are not likely to be suitable for small-scale local development but only for larges scale and high technological input. In the future stand alone production systems are foreseen in which the algae are milked. These could be applied in remote areas with high solar radiation, such as desert lands, and may not require fresh water, N and P fertilizers, and use atmospheric CO_2.

Seaweed can be successfully cultivated for biofuels, for biogas and for bioethanol production. It can be feasible for large scale bioenergy production in the North Sea. A production of 500,000 t/year DM can be realized, representing an area of approximately 5000 km^2 and producing 350 PJ. Under tropical conditions the production would be considerably higher. Preliminary studies from Malaysia suggest that bioethanol from seaweed can, at least partly, replace fossil transport fuels. On a smaller scale seaweed biomass can be a feedstock for local biogas production for lighting and cooking, similar to the use of floating plants. Seaweed cultivation may be feasible for biofuel production. But if the biomass attracts a better price when used for industrial or food purposes, that may be more interesting than a primary focus on biofuels from a local development, income generating, perspective. Seaweed cultivation can be further valorized through biorefinery similar to biorefinery of microalgae, by integrating protein, pharmaceutical and bioenergy production.

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