Proposal full title:
Algae and aquatic biomass for a sustainable production of 2nd generation biofuels

Proposal acronym:
AquaFUELs

Type of funding scheme:
Cooperation
Theme 5 - Energy

Deliverable 3.4
Impact on developing countries

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REV	Date		Organisation	Beneficiaries involved	Dissemination level
Rev 0	30 May 2011	Chiara Zanasi	EBB	EBB	PU
Rev 1	16 June 2011	Raffaello Garofalo	EBB	EBB	PU
Rev 2	14 July 2011	Pierre-Antoine Vernon	EBB	EBB	PU

Table of contents

1 Introduction

The biofuel programs in many countries such as Ethiopia, Kenya, Madagascar, Mozambique, and Tanzania (and possibly others) are in part export driven and prompted by investment from external agencies such as European companies. Therefore, it is legitimate to include the impact on developing countries to the overall sustainability assessment of algae biofuels, carried out under the project's Work Package 3.

Many developing countries have advantages over developed countries in the temperate zones in that biomass production potential is much higher and production costs can be lower. The tropics have also been targeted as having the more arable land area to meet the growing demand for biofuel crops (Field et al. 2008). As such the biofuel policies of developed countries such as the EU and USA are also partly driving and defining biofuel programs in the developing world, particularly Africa. Biofuels have been described as a chance for developing countries for their potential positive impact, as they create a market for biomass which can benefit the least advanced economies through increased demand for agricultural products in large quantities.

In addition, many developing countries have promoted biofuels motivated by security of energy supply, support to agriculture and fighting climate change, which can have meaningful consequences for certain developing countries. Bioenergy has also been used in developing countries to replace firewood use and the related environmental (deforestation, desertification) and health (indoor air pollution) concerns. The objective of this report is to address whether the potential production of algae in developing countries can bring these positive effects to developing countries. Indeed, "*the potential for algae-based technology is clear, but their developing status also presents a number of barriers to be overcome*" (FAO, 2010).

2 Economic and technological challenges

The picture for developing countries is not homogeneous or straightforward, as some developing countries are the only countries in the world having successfully developing a large-scale algae production sector, while economic conditions in other countries would seem to prevent the development of algae production as a whole. As algae technology is widely regarded as in its nascent phase, continued investment and research and development requiring a high level of scientific expertise will be needed to unlock the full potential, which is typically not favourable to developing countries. With the exception of countries like China and Brazil, the top ten largest economies are also the leaders of technology intensity.

2.1 Existing algae production in developing countries

As pointed out by several studies (Lee 1997) (FAO 2010) as well as by the AquaFUELs report on main stakeholders, forming deliverable 1.3, there are significant algae producers and stakeholders outside the EU, in particular in developing countries. In this respect, the work done by EABA after the completion of the AquaFUELs deliverable confirmed that Asian stakeholders are numerous and well-established. In addition to China, whose long-standing algae sector has been active since the 1950s, UTAR microalgae provided its database of stakeholders to AquaFUELs, revealing many producers that had not been mapped out initially. Generally, it is an accepted fact that transparence and access to information is lacking to have an accurate picture of the state of the art of algae cultivation in Asia.

Technological bottlenecks are applicable to the world as a whole and thus also apply to developing countries. These bottlenecks are described in the report on technological bottlenecks, forming AquaFUELs deliverable 3.2. Technological challenges are important and concern all production steps, from cultivation to final product. In the case of developing countries, more specific variables need to be analysed in order to properly evaluate the economic viability of any project.

In addition, experiments have been launched to cultivate *Spirulina* in remote areas, where this algae can represent a valuable input in the protein diet of local populations. Though promising, it is not certain that these experiments can be extended to energy production as oil extraction and processing would require a further step. Harvesting, however, proves feasible due to the nature of Spirulina as a filamentous algae, which naturally flocculates.

2.2 Choice of algae and culture method

Algae can be grown either on land or offshore, depending on the kind of algae concerned.

Large-scale microalgae culture can be carried out through open ponds or photo-bioreactor. Previous studies showed that open ponds require less economic investment, technical skills and maintenance than photo-bioreactors. However, they both require the availability of land surfaces (that can be unproductive land). Open ponds have been considered as a favourable option for developing countries not only because of their low cost, but also because of their ability to use the benefits of tropical climate on plant growth.

Macro algae, on the other side, can be grown offshore but need available locations not already used for other purposes (i.e. shipping routes), cultivation structures that allow easy harvesting and replantation, as well as the possibility of pre-treating the biomass already offshore (reducing transport expenses). Some projects suggested also inundation of deserts as a possibility to cultivate macro algae, but those projects are still at the scenario phase. Both kind of algae (micro and macro) as well as both culture methods would be possible in certain developing countries, where the availability of unproductive land is greater and where costal surfaces are available.

It has been emphasized that two approaches would be possible for developing countries:

- the large-scale industrial approach, intended to achieve long-term profitability and for which technological bottlenecks currently form the greatest challenge
- the small-scale approach, intended to provide decentralised food and energy, for which the initial investment would represent the greatest challenge

2.3 Availability of nutrients

The biggest challenge in order to make algae biofuels economically viable is to augment the productivity while reducing the costs. The growth rate can be influenced by modifying the availability of nutrients, bringing to an increased productivity.

In the case of microalgae cultivation, light, CO2 and other nutrients can be controlled both in open ponds and in photo bioreactors: light can be artificially provided, as well as other nutrients. Ambient CO2 can be captured, concentrated and dissolved into the water, while CO2 from combustion gas can be cleaned and transported directly to the culture sites. However, these activities are costly and energy-consuming, and achieving an overall positive CO2 balance is very challenging.

Of course, in the case of macro algae cultivated offshore, it is more difficult and costly to influence nutrients, and growth rate is then more connected to structural choices (i.e. location) rather than modifiable variables.

In the case of developing countries, geographical situation is a comparative advantage over the culture of algae in developed countries, as the availability of sunlight and temperature allows a structural higher growth rate.

2.4 Availability of capitals and technology

Local examples show that growing certain strain of algae is not particularly difficult and can be done in rural areas with limited instruments (Flower E. Msuya), and that seaweed farming can become the major source of labour and income.

However, algae cultivation for biofuel production requires a scale and technologies that cannot apply to local/rural farming and that requires a structured organization that cannot rely on social arrangements and village leaders.

In order to produce biofuel from algae (biodiesel, bioethanol etc.) it is important to cultivate the right type of algae and to harvest a biomass sufficient for carrying out the extraction process. This requires lands (for microalgae) or sea surfaces, as well as adequate investments and technologies.

As already highlighted, the algae industry is still in its nascent phase, so investments and technology requested cannot be precisely quantified and identified. However, both capitals and technology would not be available at local level, and it is possible to forecast that both elements would reach developing countries through foreign companies, element that would influence the final destination of this industry's revenue.

2.5 Biomass use

Algae can produce a various range of product with different characteristics, and biofuels must be considered just one among others in order to reach the economic viability of algae cultivation. The price of algae biofuel, indeed, has to be competitive with other biofuels, as well as with common fossil fuels, and this result can be achieved only by creating an integrated industry able to fully use the potential of algae: biofuels, high value co-products (for pharmaceutical and other industry use), food and feed.

It can also be forecasted that in the initial phase, biofuels would be part of the co-products group, taking more and more space according to the technology development. In the case of developing countries, the creation of an algae industry could contribute to tackle some major problems: unemployment, gender inequality, malnutrition.

3 Food security implications (food vs. fuel debate)

Biofuels development is often linked to unintended negative effects on global food commodity prices. These effects are determined by the direct and indirect land use changes generated by the large crop surfaces needed for biofuels production on global scale.

One of the main advantages of algae based biofuels, especially if based on marine water, is to unlock the cap represented by the limited availability of earth's available agricultural surfaces.

Algae based biofuels can be grown using unproductive lands where production systems (open pond, bio-reactors, others) can be set or using water surfaces, especially from marine coastal areas. As 43 percent of the earth's landmass is arid or semi-arid and 97 percent of the Earth's water is seawater, the potential for algae cultivation (without any direct or indirect competition with food) can be considered as relevant.

If developed on a world-wide scale algae based biofuels could represent a twofold opportunity to improve the food security implications of biofuels, eliminating the competition with traditional food agricultural surfaces and increasing the availability of high value proteins, carbohydrates and other nutritionals contained in most micro and macro-algae species.

3.1 Algae potential as a protein-rich food for developing countries

The portion of algae biomass that can be converted in a biofuels (biodiesel, bioethanol, etc.) is, in average, much lower than the portion of the algae biomass, both in weight and in volume, that is left for other applications. Algae biomass can contain proteins, carbohydrates, carotenoids, amino acids, vitamins and trace minerals as shown in the table below. Very often these are extremely good nutrients.

Algae Strain	Lipids	Protein	Carbohydrates
Anabaena cylindrica	4–7	43–56	25–30
Aphanizomenon flos-aqua	3	62	23
Arthrospira maxima	6–7	60–71	13–16
Botryococcus braunii	86	4	20
Chlamydomonas rheinhar.	21	48	17
Chlorella ellipsoidea	84	5	16
Chlorella pyrenoidosa	2	57	26
Chlorella vulgaris	14–22	51–58	12–17
Dunaliella salina	6	57	32
Euglena gracilis	14–20	39–61	14–18
Prymnesium parvum	22-38	30-45	25-33
Porphyridium cruentum	9-14	28–39	40–57
Scenedesmus obliquus	12–14	50–56	10–17
Spirulina maxima	6-7	60-71	13-16
Spirogyra sp.	11–21	6–20	33–64
Spirulina plantensis	4–9	46–63	8–14
Synechococcus sp.	11	63	15

Table : % of Dry Matter; Edwards, 2009

Considering the large amount of production that is to be achieved in an algae-to-biofuels scenario in any case the most important outlets that could absorb such quantities would be the animal feed markets and the production of human food and nutrients.

Algae (and mainly algae proteins) as animal feedingstuff are being increasingly considered as a very valuable option in order to find additional and alternative protein sources to the record growing demand for meat and animal proteins at world level and mainly from developing areas of the world (as reported by the FAO). The European Union is, since years, suffering from a structural vegetable proteins deficit that amounted in the last years to more than 20 million tonnes of soybean meals equivalents, which today are imported from South America. In this sense the fact that Europe has already reviewed its rules for listing animal feedingstuffs including in its positive list several entries for algae represents a very positive signal for the development of a feed usage of algae protein, in Europe of course, but especially in developing countries.

Although there is very little tests yet about feed usage of algae nutrients for rearing cattle in developing countries, the frame is already set for larger consumption and availability in the next years should algae to biofuels production pathways start to deliver a large scale production.

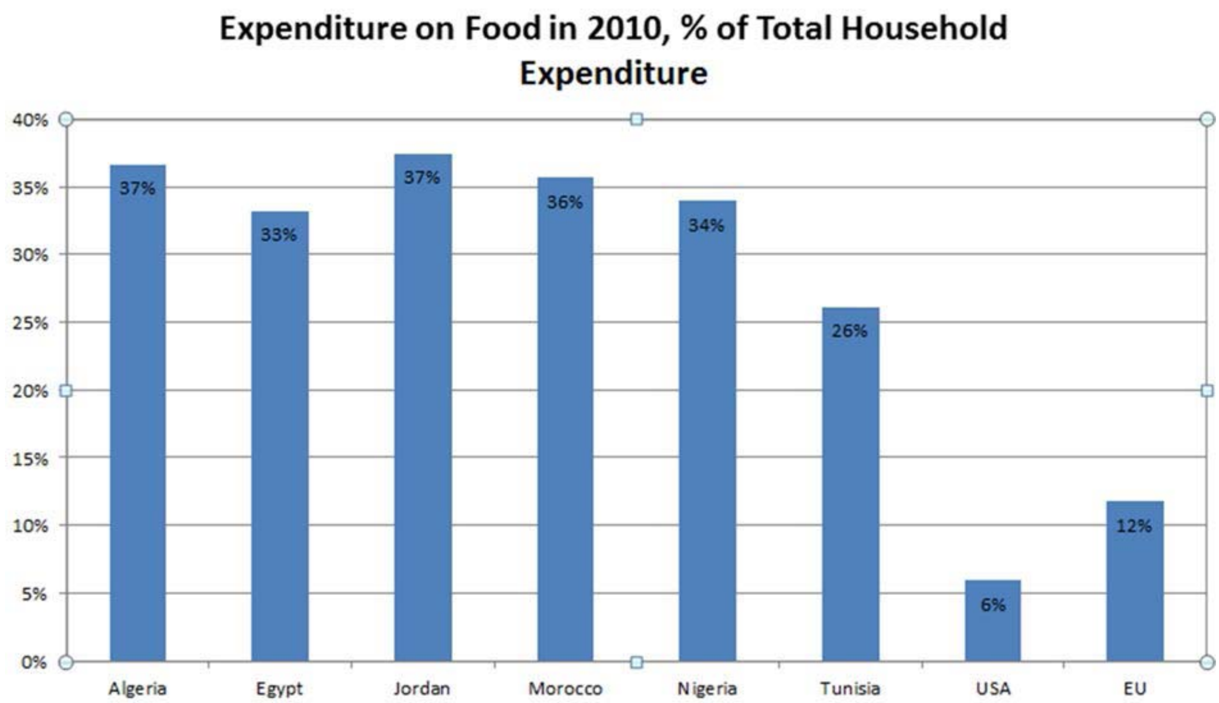
Live cattle nutritional improvement via the availability of local algae proteins (if the production of algae was to be achieved locally) could be of course a very interesting opportunity for ensuring a higher availability of meat in many developing countries.

On the side of food use of algae co-products derived by biofuels production, the picture is similar. It continues on historical human nutritional habits, since the consumption of algae by humans may go back as far as the Aztec times in South America.

The species of algae that has attracted the most attention so far as food for developing countries is Spirulina but in the next decades algae biofuels co-products could become a major source of highly valuable proteins and other nutrients for the global markets and improve quality food and nutrients availability for developing countries.

The mass production of certain protein-rich micro-algae can be considered as a possibility to close the predicted so called “protein gap”. Comprehensive analyses and nutritional studies have demonstrated that these algal proteins are of high quality and comparable to conventional vegetable proteins. However, due to high production costs as well as technical difficulties to incorporate the algal material into palatable food preparations, the propagation of algal protein is still in its infancy. Although to date, the majority of micro-algal preparations are marketed as health food, as cosmetics or as animal feed the perspective of an emerging algal food market is algae to biofuels production pathways were to generalize would be particularly interesting.

As one could expect that an important part of algae biomass grown for biofuels application could be produced in developing countries the positive impact on the economies of these areas would be proportionally higher than in others. Additionally given that the pro-capita expenses linked to nutrition are exponentially higher in developing countries that in Europe or North America (see table below), the overall positive impact of the use of algae to biofuels could be greater than it is currently witnessed in developed countries.



Co-products for food application could even be multiplied in countries where the average availability of high protein and meat food is very low.

3.2 Indirect food security impacts for large scale land based algae applications

Number of projects of large scale open ponds or large surface inundation for algae growth may have micro-climatic impacts with important consequences on local availability of food and water.

Irrigating large tracts of desert land with saltwater can have an unintended anthropomorphic effect turning adjacent desert into farmland. The evaporating water from these planted tracts may modify the local weather pattern, resulting in condensation, and change dry climates to wetter climates.

This could build up a dynamic based on the exact reverse fact-chain of what is happening in large tracts of land next to the Sahara desert, where the desert absorbs the moisture and expands into the adjacent farmlands. For instance such an event has been a critical issue in Beijing for the last few decades. Because of the immediate effects of deforestation, the Gobi desert has been expanding towards Beijing for the last few decades, where the climate is becoming now much drier and sandier than it used to be.

Putting large amounts of water into the desert for the water to vaporize can potentially make places where like Sahel areas a little better and promote vegetation growth, e.g. on super-saline water, which will in turn put more water in the atmosphere. Ultimately, it has the possibility of improving agricultural production and food availability in developing countries areas by halting or outright reversing desert expansion.

4 Social and labour implications

Economic growth in all countries is highly dependent on an inexpensive energy supply. In this respect, it should be borne in mind that the prices of fossil energy will rise significantly in the coming years, leaving many developing countries with shortage that might impede both their economic growth and their socio-economic well-being. Increases in price for fossil fuels have an indirect impact on alimentation, transport, lighting, heating, agriculture (festilisers, crop protection, etc.), and many other products. In many countries, where lighting and transport are currently used in small quantities, a significant increase in energy price could lead directly to decreased mobility, malnutrition and famine. On the opposite, securing energy supply though algae biofuels in developing countries could allow developing countries to support their economic development by keeping financial resources inside the country rather than buying from oil producing countries.

Low-technology algae cultivation for energy carried great hopes for many developing countries, as shown by the existing algae cultivation for food. Given the recent evolution of developing countries in the field of research and technology, algae cultivation could induce gains in terms of employment and also in terms of know-how transfer to countries in need for economic development.

5 Interactions with global warming and other sustainability implications in developing countries

In this section is detailed an overall analysis on the potential interaction of both micro and macro-algae large scale production systems with climate change and other sustainability issues. The objective is to try to find few initial answers about the way in which algae could interact with climate change consequences as well as with other sustainability indicators in developing countries.

5.1 Climate change, coastal planning and algae biomass production in developing countries

According to IPPC report global climate change may raise sea level as much as one meter over the next century and, in some areas, increase the frequency and severity of storms. Hundreds of thousands of square kilometers of coastal wetlands and other lowlands could be inundated.

Beaches could retreat as much as a few hundred meters and protective structures may be breached.

Flooding would threaten lives, agriculture, livestock, buildings, and infrastructures. More importantly in coastal areas saltwater would advance landward into aquifers and up estuaries, threatening water supplies, ecosystems, and agriculture in some areas.

As far as coastal areas are concerned, the IPPC has defined a range of strategies which should serve in order to approach the new reality produced by climate change.

The two main reference strategies are grouped around the two logics of retreat or accommodation. The “Retreat” strategy involves no effort to protect the land from the sea, as the coastal zone is abandoned and ecosystems shift. In these areas to be abandoned there is no potential for algae development. However much more interest - and potential - comes for algae biomass deployment in developing countries under the “Accommodation” strategy. Such strategy implies that people continue to use the land at risk but do not attempt to prevent the land from being flooded. This option includes erecting emergency flood shelters, elevating buildings on piles, converting agriculture to fish farming, or growing flood- or salt-tolerant crops.

In order to structure the "Accomodation strategy" International experts contributing to the IPPC have defined long term guidelines for national coastal planning under which coastal nations should implement "comprehensive coastal zone management plans". The plans include technical assistance for developing nations and stimulation of co-operation efforts. The IPPC also highlights in its reports that institutions offering financial support should recognize the need for technical assistance in developing coastal management plans. This could easily include fundings for new micro or macroalgae production sites to be realised in these areas, which will be along the years to come increasingly adapted for this kind of activities.

Algae farming and production could contribute in this sense to give a new added value to semi-inudated areas which otherwise would be considered as lost. A major work will be needed in order to build up a systematic mapping and resource assessment of coastal zones to identify functions and critical areas at risk.

The overall World coast areas length is of 1,634,700km, 629,421 km of which are in developing countries. Coastal lines where solar incidence is the highest, i.e. Middle East, African and Central America/Caribbean coasts, including also South Asian and Oceanian coasts account for more than one fourth of global coasts and in average, as lower coast lines, are much more exposed to climate change threats.

Clearly adaptation efforts to climate change could coincide in the medium to long term with the opportunity of developing algae based biofuels within an overall algae economy deployment as a part of climate change accommodation strategy, via the funding of projects implying the controlled flooding of unproductive areas, the creation of pillow surfaces where sea water could be used to grow various species of macro or micro-algae as well as salicornia like kind of salt-resistant plants.

As a result, provided that a global regulatory framework for adaptation is drafted containing ad hoc indication on the role of algae, algae biofuels could substantially develop as a direct effect of implementation of adaptation strategies to climate change on a world wide scale.

6 Conclusions

Developing countries play a specific role in the future of algae biofuels, as potential producers, consumers or suppliers to the developed economies. It should also be borne in mind that several developing countries, incluing China and India as well as other economies in Southeast Asia, can actually be regarded as more advanced than developed countries when it comes to large-scale algae cultivation, in particular macro-algae.

However, the development of algae production facilities for food or feed had so far avoided the issue of harvesting and extraction, which represents a significant bottleneck for developing countries as well as for developed countries. In this respect, developing countries may have an advantage over developed countries, as low labour costs allows more labour-intensive harvesting and extraction techniques, which could contribute to a less energy-intensive process and therefore improve both economic and environmental sustainability.

Although tropical climates can be considered as an asset, in particular for low-cost open ponds technologies allowing to use the temperature and sunlight from the environment, the limited investment and R&D capacities can represent an issue for an industrial process where technological bottlenecks can be expected to play a major role for market development in the coming years.

Similarly to other biofuels, algae biofuels could help fighting the forthcoming energy scarcity, which will affect developing countries to an even greater degree than developed economies. In this respect, algae biofuels could represent the only way to maintain effective transport systems in countries in lack of infrastructure and to allow continued agricultural development. Algae cultivation in developing countries could allow mitigating or using the potentially negative effects of pollution and global warming by removing pollution from algae blooms or using water supply created by floods related to the rising sea level.