Promising technologies for biodiesel production from algae growth systems

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Abstract: *Biodiesel is considered as a renewable fuel because it can be obtained from the transformation of vegetable oils, cooking greases or animal fats. Currently, oleaginous plants like rapeseed, sunflower, palm oil and soybean are the most important sources of biodiesel. However, the productivity of some of these crops are considered relatively low and they require long extension of lands.*
In this context, microalgae has been emerged as a source of natural oil due to its lipids, starch and hydrocarbon contents. Microalgae produces about ten times more oil than oleaginous plants and it can be grown in systems like open ponds and photobioreactors. Open raceway ponds are well known because they have been used to grow algae for food, nutritional complements and others. Their construction is less expensive compared to photobioreactors, but their productivity is lower. Photobioreactors can be found with different configurations (e.g. tubular, annular, plastic bags) and they have numerous advantages over open raceway ponds: superieur control of nutrients, light exposition and carbon dioxide absorption, as well as contamination avoidance with other microorganisms. These culture systems receive special attention because they can use carbon dioxide from flue gases and nutrients from wastewater to perform microalgae growth.
The most common species to be found in literature and experimental studies are Chlorella sp., Spirulina sp. and Dunaliella sp. Several universities, organizations and governmental departments have been working in microalgae production systems, their design as well as the factors that influence microalgae growth.
In this context, this study develops a review about current systems, microalgae species, their requirements and their oil production. Also, the potential production of algal biodiesel is compared with the current biodiesel production.

Keywords: *biodiesel, microalgae, photobioreactors, ponds.*

Introduction

The increases of world energy demand and greenhouse gas emissions have been concerning all sectors since last decades. The individual is realizing that both have harmful effects over the environment and human being. In this context, there is the need to produce a fuel that can be categorized as a renewable fuel.

Today biodiesel is produced from vegetable oils that come from oleaginous plants. These vegetable oils are transformed using transterification process, resulting in the so-called (m)ethyl esters or biodiesel. Biodiesel can be used in cars and airplanes, as it is blended with fossil diesel.

However, biodiesel has been strongly criticized because vegetable oils require cultivation of crops like rapeseed, palm, sunflower and soybean, which involves long extension of lands. In this sense biodiesel production encourage competition for the land as well as for the final use of cultivated crops. In addition, deforestation of forests has been in a constant increase (like in Indonesia, Malaysia and Brazil) as a consequence of longer extensions of lands required for biofuels production.

For several decades, algae has been used in the production of food, feed and nutritional supplements due to the presence of carbohydrates, proteins and naturals oils in its composition. It has been employed in wastewater treatment in order to remove nitrogen, phosphorus and metals. Recently, algae has been considered as a potential source for CO_2 capture and biofuels production.

Algae have numerous advantages over terrestrial plants: 1) they use solar energy with efficiencies 10 times higher compared with terrestrial plants, fixing higher quantities of CO_2 (Skjanes et al. 2007); 2) they can grow in fresh, salty waters and even in wastewaters; 3) they can be used as a metal absorbers (e.g. Cu, Cd) in wastewater treatments; 4) algae harvesting can be performed after a few days once the culture has started, which does not occur with crops; 5) flue gases from power plants can be directly used in algae culture, recovering carbon and nitrogen dioxides; 6) algae production systems can be installed in surfaces next to industries and in non-cultivable surfaces, avoiding competition for the lands (Skjanes et al., 2007); 7) several studies affirm that more quantities of oil can be obtained from microalgae compared from oilseeds. (AlgaLink, n.d.; Sazdanoff, 2006)

Three types of aquatic plants have been considered for energy production: macroalgae, emergents and microalgae. Macroalgae or "seaweeds" are plants that can grow in marine and fresh waters, achieving sizes of 60 meters. They have been considered as a feedstock in thermochemical processes like liquefaction, supercritical CO_2 and pyrolysis for oil production (Aresta et al., 2005).

Emergents are aquatic plants that have direct contact with water and air because they are partially submerged in wetlands, like bogs and marshes. Microalgae are microorganisms that can grow in marine and freshwaters. They have a high surface-volume ratio, which implies a large surface of exchange with the environment (Van Harmelen and Oonk, 2006).

According to NREL report, macroalgae and emergents are organisms that storage carbohydrates as primary energy compounds, and lipids (in form of triacylglycerols (TAGs)) in cell membranes. In the case of microalgae, lipids are the primary energy of the plant and their quantities are higher (Sheehan et al., 1998).

Microalgae is the preferred group of aquatic plants used in ponds and bioreactors cultures. A part from their high lipids contents, they allow to design simple systems due to their practical size. On the other hand, their reproduction is faster compared to macroalgae and terrestrial plants (Sheehan et al., 1998; Van Hermelen et al., 2006).

For these reasons, microalgae is considered today as a potential source for biodiesel production. Currently, universities, enterprises and governmental departments are proposing several technologies to cultivate microalgae with high biomass productivity. Numerous pilot projects and tests have been performed and positive results have been obtained. In this sense, the following document presents a general description of these technologies, their respective limitations and potentials as well as a comparison between algal oil and traditional oil production.

Current microalgae production systems

Requirements for microalgae growth

As photosynthetic organisms, microalgae require solar energy, carbon dioxide, water and nutrients. The provision and the efficiently control of these parameters will define the final production of the system (Van Hermelen et al., 2006).

Solar energy is a variable that determines the geometry and the materials of the reactor. Transparent materials like glass and plexiglas have been used in order to improve collection efficiency in reactors.

Solar light has been replaced for artificial light in experimental studies performed indoors, using fluorescent lamps, strip lights, halogen lamps and others (Pulz, 2007).

Carbon dioxide can be obtained from flue gases of fossil fuel combustion. Some algae production systems obtain CO_2 from flue gases coming from coal and natural gas power plants. In power plants CO_2 concentrations usually range between 10 and 20%, with an average of 13%. (Sheehan et al., 1998; GreenFuels, 2007). In addition, nitric oxide from flue gases can be a source of nitrogen for microalgae growth (Nagase et al., 2001).

Depending on the microalgae specie, water medium can be fresh or marine. One of the most discussed points is the utilization of wastewater as a growth medium in algae culture. For example, municipal wastewaters and wastewaters coming from power plants can be used. These waters usually contain nitrogen, phosphorus, nitrates, phosphates and metals like chromium, lead, iron, zinc, which can be used as nutrients for microalgae. At the same time microalgae help to purify wastewaters reducing the concentrations of these elements. For example, *Chlorella vulgaris* has been used as a single organism and in combination with bacteria (like *A. Brasilense*) to remove ammonium and soluble phosphate ions from municipal wastewater. Metals like iron, zinc, manganese, chromium, nickel, cadmium and cobalt have been removed by *Chlorella vulgaris* and *Scenedesmus* in a range of 64-100% in a continuous system (De-Bashan et al., 2004).

In laboratory experiences, nutrients concentrations have been manipulated in order to vary microalgae compositions. For example, nitrogen has been reduced in order to obtain higher lipids concentrations and higher calorific values. Sulfur has been reduced to increase starch, which can be extracted and fermented for ethanol production (Illman et al., 2000; Skjanes et al., 2007). In some experimental studies, microalgae has received carbons from glucose or acetate in order to increase its lipids concentrations, which is the so-called heterotrophic growth (Borowitzka, 1999; Miao and Wu, 2006).

Microalgae species considered for oil production

Microalgae is classified as diatoms (bacillariophyceae), green algae (chlorophyceae), goldenbrown (chrysophyceae) and blue-green algae (cyanophyceae). More than 200,000 microalgae species exist in the world and just a certain number can be considered for biodiesel production (Sheehan et al., 1998). According to the Solar Energy Research Institute (SERI) rapport, the most promising species for fuel production are *Botryococcus braunii* due to its important quantities of hydrocarbons, *Nannochloropsis salina* with its high quantities of ester fuel production and *Dunaliella salina* due to its high quantities of fatty acids (Feinberg, 1984). The National Renewable Energy Laboratory (NREL) in United States affirms that *Spirulina*, *Dunaliella*, *Scenedesmus*, and *Chlorella* are the most popular strains that have been produced at commercial or large scale (>0.1 ha) (Sheehan et al., 1998). A more recent rapport explains that for a sustainable production of algal biomass, the species *Spirulina platensis*, *Dunaliella salina* and *Chlorella*, are the most suitable (Huntley and Redalje, 2006).

On the other hand, some microalgae species have been grown under stress in order to increase their quantities of lipids. This stress refers mainly to nitrogen deficiency. The following table shows the most common species found along the literature and their respective lipids concentrations.

Table 1. Microalgae species considered for oil production

Species	Stress	% Lipids (Dry weight)	References
Cyclotella Cryptica	Nitrogen deficiency	18	Feinberg, 1984
Dunaliella salina	Osmotic stress and nitrogen deficiency	18.5	Feinberg, 1984; Borotwizka, 1999
	Nitrogen deficiency	14.4	Feinberg, 1984
	Non environmental stress	6	Spolaore et al., 2006
Nitzschia sp.	Non environmental stress	45-47	Chisti, 2007
Phaeodactylum tricornutum	Non environmental stress	20-30	Molina et al., 2003; Acién et al.[1], 2003; Chisti, 2007
Botryococcus Braunii	Nitrogen deficiency	54.2	Feinberg, 1984; Sawayama et al., 1995.
	Non environmental stress	25-75	Chisti, 2007
Chlamydomonas sp.	Non environmental stress	23	Feinberg, 1984
Chlorella sp.	Non environmental stress	20.7	Feinberg, 1984
	Non environmental stress	28-32	Chisti, 2007
Chlorella vulgaris	Nitrogen deficiency	18	Illman et al., 2000; Huntley and Redalje, 2006
	Non environmental stress	14-22	Spolaore et al., 2006
Nannochloris sp.	Non environmental stress	20-35	Chisti, 2007
Nannochloropsis sp.	Nitrogen deficiency	33.3-37.8	Huntley and Redalje, 2006
	Non environmental stress	31-68	Chisti, 2007
Nannochloropsis salina	Nitrogen deficiency	54	Feinberg, 1984
	Non environmental stress	28.6	Feinberg, 1984
Spirulina platensis	Non environmental stress	16.6	Feinberg, 1984
Tetraselmis sueica	Nitrogen deficiency	20-30	Huntley and Redalje, 2006
	Non environmental stress	15-23	Chisti, 2007
Isochrysis sp.	Nitrogen deficiency	26-45	Feinberg, 1984
	Non environmental stress	25-33	Chisti, 2007

Installations and testing systems for microalgae growth

Capture and injection of CO2 to microalgae culture

Microalgae are observed as potential organisms that can absorb important quantities of CO_2 from flue gases of power plants. These flue gases can be sent directly to microalgae culture or CO_2 can be first separated from flue gases before being injected.

In the first case, microalgae culture can have problems with high temperature and high concentrations of CO_2, NO_x and SO_x, but that will depend on microalgae specie. As an example, *chlorella sp.* has been grown at different conditions of CO_2 (around 15% in concentration), NO_x and SO_x, showing resistance to harsh ambiances (Maeda et al., 1995). In power plants, a solvent like monoethanolamine (MEA) is usually used in order to separate CO_2 from flue gases. The separated gas contains a high percentage of CO_2 (more than 90%), nitrogen, carbon monoxide, hydrogen and small quantities of methane and hydrogen sulfide. According to several authors, it is possible to inject flue gases directly to the system. (Acién et al.[2], 2007; APS, 2007)

Flue gases or pure CO_2 are usually injected into photobioreactors or ponds in form of bubbles (Van Harmelen and Oonk, 2006; Acién et al.[2], 2007). Authors affirm that fixation of CO_2 will improve in the system if it is injected in the liquid phase and not spread directly into the microalgae culture (Acién[2] et al., 2007).

Several studies establish that around 80-90% of carbon dioxide can be removed from flue gases (Sazdanoff, 2006; Acién et al.[2], 2007). A 1000 ha of algae cultivation system can transform about 210 mt/year of CO_2 (Kadam, 2002).

Algae production systems

Open raceway ponds

Open ponds have been the most simple, old and common system to produce algae. Through the history, they have been considered as the less expensive system to construct. They can be found as large open ponds, circulating ponds with a rotating arm and raceway ponds. (Borowitzka, 1999).

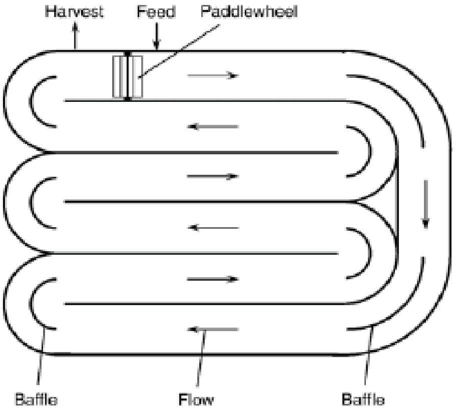

Figure 1. Open raceway ponds (Chisti, 2007)

Open raceway ponds (Figure 1) consist in a racetrack that contains microalgae mixture, which is in a permanent circulation. The cover surface is usually between 1000 and 5000 m^2 (Travieso et al., 2001). The water is kept shallow (at around 30 cm deep) in order to give a proper exposition of the microalgae to sunlight. The flow is produced by a mechanical mixer, usually a paddlewheel. While the algae is flowing, nutrients like phosphorus and nitrogen are supplied into the system in form of fertilizers or by wastewaters (Sheehan et al., 1998; Van Harmelen and Oonk, 2006). Ponds can be designed as opened or enclosed ponds. In the first case, undesirable contamination with other microorganisms is avoided, however building costs are higher. Usually, ponds are opened in order to increase sunlight exposure.

Carbon dioxide is injected in form of bubbles and in counter-current flow by diffusers and sumps (Van Harmelen and Oonk, 2006). Microalgae is harvested when the flow finishes the loop, just before the paddlewheel (Chisti, 2007).

Tubular photobioreactors

Tubular photobioreactors consist in a set of transparent pipes made of glass, acrylic or plexiglas installed in array. The system works in a close-loop where the microalgae culture flows continuously. Generally microalgae, nutrients, CO_2 and water are fed to a vessel, from where they are pumped to the tubes. A harvesting system is installed at the end of the circuit, usually constituted by a filter, where algae are collected according to its maturity.

An example of these reactors is the horizontal and flat tubular photobioreactors commercialized by AlgaLink. They work with different capacities: 1, 10, 25, 50, 75 and 100 ton of dry biomass per day.

The circuit works as follows: In the feeding vessel, nutrients, water and microalgae are fed. A set of sensors measures pH, temperature, conductivity and flow level. According to the values, these sensors activate the appropriate pump. The pumps are in charge of controlling pH, nutrients and to send the flow to harvesting system. Carbon dioxide is injected in a valve of the feeding pump, just before the flow enters to the reactors. Oxygen and dissolved oxygen are monitored in order to avoid microalgae damage. The oxygen produced is released in the feeding vessel. Also, a cell density sensor is installed in order to determine the appropriate moment for harvesting (AlgaeLink, n.d.).

Another example of an industrial tubular photobioreactors system is the installation of GreenFuel Technologies at the Cogen Power Plant in Massachusetts. Tubular photobioreactors were installed and tested in a triangle shape, exposing the hypotenuse to the sunlight and the other two sides to the shadow. The pipes were made of polycarbonate with lengths ranging from 2 to 3 cm and diameters from 10 to 20 cm. Flue gases from the power plant were injected as a countercurrent flow into the system, from which microalgae obtained CO_2 and NO_x. CO_2 concentration from flue gases was around 13%. The clean gases exited the systems by the highest point of the triangle.

Other configurations include the disposition of reactors as a wall or panel, where one tube is disposed over another.

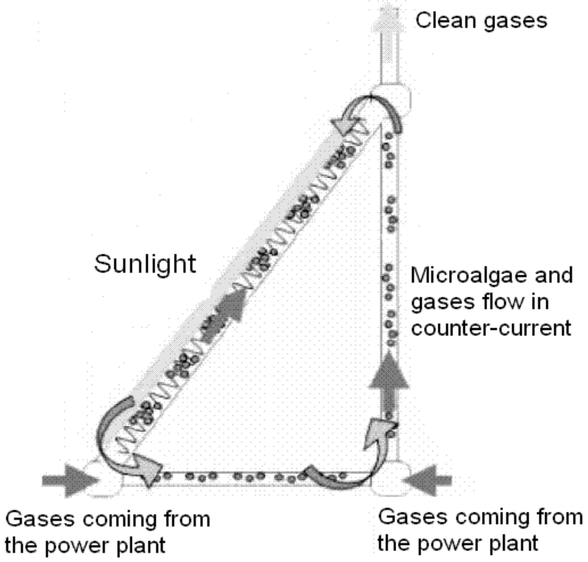

Figure 2. Triangular photobioreactors. Scale 1/100 (Vunjak-Novakovic et al., 2005)

Their purpose is to increase the area exposed to sunlight; however these systems usually produce less algal biomass compared to the last ones.

Also, photobioreactors have been arranged forming a helical coil. The Murdoch University in Australia created a pilot scale helical tubular photobioreactor called BIOCOILs with a capacity of up to 700 liters. The reactor consists into plastic tubes with diameters between 2.4 and 5 cm, to which the mix is sent by pumps (e.g. centrifugal, diaphragm or lobe pumps). Species like *Tetraselmis sp., Isochrysis galbana, Phaeodactylum tricornutum* and *Chaetoceros sp.* as well as *Spirulina* were growing in this system (Borowitzka, 1999).

Plastic bags photobioreactors

These photobioreactors consist of a set of plastic bags hanging along a metallic support. The system usually works in a semicontinuos batch mode. GreenFuel Technologies created a matrix called 3DMS Engineering Scale Unit (ESU) in order to test these plastic bags at Redhwak power station in Arizona, United States. The system obtained the carbon dioxide (with concentrations between 2 and 4%) from the flue gases of the natural gas power plant. The average productivity was 98 g/m²/d of algal biomass, being 174 g/m²/d the highest value reached.

Once the microalgae was harvested, ethanol was produced from the starch and biodiesel from the oil, both contained in the algae. Finally, the proteins were used as food livestock (Pulz, 2007).

Vertical column photobioreactors

They are characterized as vertical columns with relative large diameters (>0.1 m) that can work as bubble columns or airlift bioreactors. In airlift photobioreactors, there are three main parts: the riser (dark side), in which the gas is injected into the liquid mix creating a turbulent flow; the downcomer (side exposed to light) in which the liquid might have fractions of gas and finally, the gas separator. The mix and the gas have a defined circulation along the reactor, following the tubes designed for this purpose. (Vunjak-Novakovic et al., 2005).

In bubble columns, the gas is injected from the bottom of the reactor creating bubbles in the liquid microalgae culture. These bubbles promote culture mixing, agitating algae cells and exposing them to light and nutrients.

Annular photobioreactors

Annular photobioreactors consist in a two concentric cylinders forming an annular culture chamber. As it was designed by the University of Florence, the cylinders are made of plexiglas having diameters of 50 and 91 cm and a volume of 115-150 liters. If they are placed outdoors, the external cylinder surface is exposed to sunlight. Indoors, the internal cylinder receives the energy coming from artificial light (fluorescent tubes and metal halide lamps), as the light is placed inside the cylinder. Carbon dioxide and pH are controlled automatically (Chini Zitelli et al., 2003).

Two combined systems: photobioreactors and open ponds

The University of Hawaii and the University of Southern Mississippi designed a system consisting in a set of four photobioreactors partially immersed followed by open ponds. The goal was to control culture conditions in photobioreactors, allowing the desirable microalgae reproduction and then, to deprive nutrients in the ponds, promoting higher oil quantities in cells and astaxanthin (carotenoid pigment) (Huntley and Redalje, 2006).

Microalgae harvesting systems

Techniques such as flocculation, microstraining, filtering, sedimentation and centrifugation are usually employed in microalgae harvesting. Depending on microalgae sizes and the quality of the desired products, these techniques can be combined to have higher efficiencies.

Chemical flocculation and bioflocculation are employed to create a dense mass of microalgae easier to remove. In bioflocculation, microalgues start to attach themselves forming flocks as a certain conditions in the system are appearing. Also, it can be promoted by the use of non-algal microbial cultures. In chemical flocculation, chemicals like ferric chloride, aluminum sulfate, ferric sulfate, polymeric flocculants, chitosan are used to promote the formation of the flocs. The main disadvantage of chemical flocculation is the costs for acquiring chemicals. (Sheehan et al., 1998 ; Molina Grima et al., 2003). Both flocculation techniques are usually followed by sedimentation, filtration or centrifugation. In sedimentation, suspended microalgae are deposited by the action of the gravity, creating a certain concentration of mass easier to remove (Johnston, 1976)

Centrifugation is a common method used to recover microalgae in large volumes. Its efficiency depends on the type of microalgae, the settling deep and the residence time of the cell slurry. Usually a paste of 20% algae can be obtained. Compared to the other techniques, it has the highest energy consumption. (Molina Grima et al., 2003)

Filtration can be performed under pressure or vacuum if algae sizes do not approach bacteria sizes. Microstrainers (typically 25 to 50 µm openings) can be used for species like *spirulina* or *anabaena*, which are filamentous bacteria easier to remove. If flocculation is performed before, higher filtration efficiency will be reached. (Sheehan et al., 1998; Molina Grima et al., 2003)

Techniques for oil extraction

Three techniques are commonly found for oil extraction: mechanical pressing, solvents and supercritical fluid extraction. Using mechanical pressing, algal oil can be extracted in a range from 70 to 75%.

Chemicals like n-hexane, benzene, ethanol, chloroform and diethyl ether can be used as solvents to extract the fatty acids. The most common solvent used is n-hexane, which first is added to the algae paste and then is distilled to obtain the algal oil (Sazdanoff, 2006). If n-hexane is added after mechanical pressing, 95% of algal oil can be obtained (AlgaeLink, n.d.). Another example is the extraction of hydrocarbons from *Botryococcus sp*. using ethyl acetate.

In supercritical fluid extraction, CO_2 is first heated and compressed until it reaches the liquid-gas state. Then, it is added to the harvested algae, acting like a solvent. This technique has been used to obtain hydrocarbons from *Botryococcus braunii* and lipids from *Skeletonema* (Mendes et al., 1995)

Comparison between microalgae production systems.

As it has been discussed, microalgae production systems can be divided into open raceway ponds and photobioreactors. Photobioreactors are considered as higher productive systems because:

- Parameters like gas injection, nutrients concentrations, temperature of the growth medium and microalgae cell sizes are better monitored and controlled;
- Microalgae can be maintained isolated of other microorganisms and elements, considered as undesirable contaminants;
- The production of algal biomass is measured in terms of volume (due to the geometry of the reactor and its exposition to light) while in ponds is measured in terms of surface;
- The water losses due to evaporation are less than in open ponds;
- The algae cell densities are higher (AlgaeLink, n.d.; Borotwizka, 1999).

However, photobioreactors are more expensive respecting to construction, installation and maintenance. In open raceway ponds it is easier to release the oxygen produced from photosynthesis, while in a photobioreactor tube it cannot be released. A degassing zone has to be included in order to remove oxygen and dissolved oxygen and thus avoiding inhibition of photosynthesis (Chisti, 2007).

On the other hand, vertical columns bioreactors have a biomass production comparable to tubular photobioreactors. Contrary to tubular photobioreactors, columns easily release the oxygen produced by photosynthesis, avoiding its inhibition.

The table 2 presents examples of microalgae systems production with their respective biomass concentrations and productivities.

Table 2. Microalgae systems production. Biomass concentrations and productivities

Type of reactor	Biomass concentration grams / liter	Biomass productivity grams / liter / day	References
Open raceway ponds	0.1 to 0.5 0.5	0.028-0.046	Borotwizka et al., 1998 Radmann et al., 2007 Sazdanoff, 2006
Horizontal tubular photobioreactors	1.5	0.51-0.587	AlgaeLink, n.d. Spolaore et al., 2006
Horizontal tubular photobioreactors - Airlift	0.37	1.9	Molina et al., 2003
Tubular photobioreactors with an open raceway pond	Photobioreactors: 0.377 Ponds: 0.26		Huntley and Redalje, 2006
Helical tubular photobioreactor	0.4	1.5	Travieso et al., 2001 Acién et al.[1], 2003
Annular photobioreactor		0.225	Chini Zittelli et al., 2003
Cascade system (Open system)	10		Borotwizka et al., 1998
Vertical columns bioreactors : Airlift	4		Chisti., 2007
Vertical columns bioreactors : Bubble	4		Chisti, 2007

Biomass productivity is higher in photobioreactors than in open raceway ponds. Tubular photobioreactors disposed as helicoids or in horizontal-flat way, definitely affects biomass productivity. It is clear that biomass productivity depends strongly on the environmental conditions where the system was installed as well as the microalgae specie selected.

Biodiesel production from crops and microalgae

Once the oil is extracted from microalgae or oleaginous crops, the next step is to perform "transterification" to produce biodiesel. Transterification is a chemical reaction in which triglycerides of the oil reacts with methanol or ethanol to produce (m)ethyl esters and glycerol. In this reaction, 1 ton of vegetable or algal oil produces 1 ton of biodiesel (Chisti, 2007).

The worldwide production of biodiesel comes mainly from rapeseed (84%), sunflower (13%), palm oil (1%), soybean (2%) and others (1%). Currently, the European Union is the highest biodiesel producer and it is obtained from rapeseed and sunflower oils. In United States, biodiesel is produced from soybean while in Malaysia and Indonesia is obtained from palm oil (Demirbas, 2007; Tan et al., 2007).

The next table presents oil productivities that are usually obtained from certain crops and microalgae.

Table 3. Oil productivity from crops and microalgae

	Oil productivity		
Source	**t/ha**	**l/ha***	**References**
Microalgae	47.3	52569	Sazdanoff, 2006
	52.8	58700	Chisti, 2007
Oil Palm	5.4	5950	Chisti, 2007
	4.2	4667	Tan et al., 2007
Coconut	2.7	2996	Sazdanoff, 2006
	2.4	2689	Chisti, 2007
Jatropha	1.9	2113	Sazdanoff, 2006
	1.70	1892	Chisti, 2007

	Oil productivity		
Source	**t/ha**	**l/ha***	**References**
Rapeseed	1.2	1333	Tan et al., 2007
	1.49	1656	Poitrat, 2007
	1.2	1325	Sazdanoff, 2006
Sunflower	1.129	1254	Poitrat, 2007
	0.9	1041	Sazdanoff, 2006
Soybean	0.4	444	Tan et al., 2007
	0.6	652	Sazdanoff, 2006
	0.4	446	Chisti, 2007

*A density of 0.9 was employed to convert oil productivity from t/ha to l/ha and viceversa

As several authors affirm, microalgae produces higher quantities of oil compared to traditional crops. Companies and universities agree that an oil production between 47 and 185 ton/ha/year (5000 to 20000 gal/acre/year) can be obtained from microalgae culture.

According to Van Harmelen et al., one goal is to reach a production of 100 ton/ha/year of dry algal biomass. Assuming that microalgae contains 60% of oil in weight and 90% can be extracted, the oil production will be around 54 t/ha/year. Comparing this value with the results showed above, it seems this production should be possible in relatively short-term.

Conclusions

Until nowadays, several systems for microalgae culture have been proposed with eyes into oil production and biodiesel. Each system has its own particularities, advantages and disadvantages.

It is well known that open raceway ponds require low investment but they have low productivity. Generally, photobioreactors imply high investment and maintenance costs due to the materials of construction and mechanical equipments. These disadvantages can be recompensed by better control of nutrients, light and carbon dioxide concentrations, resulting in higher algal biomass productivity.

On the other hand, microalgae specie has to be well selected. The selection will depend on bioreactor design, the environmental conditions and the desired biomass quantities. Studies show that species like *Chlorella sp.*, *Spirulina sp.* and *Dunaliella sp.* are resistant to a certain range of conditions, which make them more profitable for commercial scale. The quality of the oil will depend on its calorific value, which is determined by the lipids accumulation in the microalgae.

As it has been discussed, higher quantities of oil can be obtained from microalgae than from oleaginous plants. Microalgae can produce ten times more oil than palm oil, which is considered the highest oleaginous producer. This means that less land is required for biodiesel production, which will reduce land competition.

Microalgal biomass can be also used in other energy generation process, once the oil has been extracted. Depending on the final biomass composition, it might be valuable to produce biogas employing an anaerobic digester or it can be gasified if it is sufficiently dried. Authors affirm that, after anaerobic digestion, the residues can contain quantities of nitrogen and phosphorus valuable as fertilizers.

The feasibility of microalgae cultures requires a deeply study of climate conditions, land availability, resources as well as positives and negatives environmental impacts that the system could cause. In this sense, it is important to evaluate the energy consumption of the system and the nutrients required. The utilization of fertilizers might imply high investments as well as the treatment of wastewaters. On the other hand, wastewaters might contain important quantities of microorganisms that can affect the environment if they are not properly handled. The manipulation of microalgae species and their utilization in different places require high control if it is desired to avoid any negative environmental impact.

It is important to remember that microalgae have been first cultivated for nutritional, pharmaceutical and cosmetics purposes. This new opportunity of producing biodiesel should not enter in competition with the production of other goods from microalgae.

Finally, it is essential to evaluate all these variables and to develop an economical feasibility study in order to estimate the required investments, maintenance costs, as well as the final revenues.

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