Development of algae for the production of bioethanol, biomethane, biohydrogen and biodiesel

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Abstract
Microalgal biofuels are a viable alternative for clean, economical and sustainable sources of energy. The research and development of microalgae needs a massive boost to ease the technical difficulties to overcome the large cost advantage of other biofuel feed stocks. It is a large source of biomass on non-arable lands and capture of CO₂. Lipids produced from algae contain saturated and polar lipids, which are suitable for use as a fuel feedstock and it exceeds the best producing oil crops. It has been found that representatives of green and diatom microalgae are the most promising producers of TAGs, the highest content of which (40–60%) has been found in diatom microalgae. This paper discusses current knowledge on different techniques for microalgal biomass production, harvesting and lipid extraction methods. The paper also discusses biodiesel production via transesterification of the lipids and other biofuels like biomethane, biodiesel, bioethanol and biohydrogen depending on the species as well as the biorefinery approach. Besides lipid extraction, the byproducts of processed algae can be utilized for many other purposes.

Key words: biofuel, bioethanol, biodiesel, bioenergy, microalgae cultivation, harvesting, lipids

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Introduction
The concept of using microalgae for energy production is not new. Algae require much less water than the traditional cereals, produce more biomass (Table 1) as well as it can be grown in salt water or in sewage water. Microalgae do not belong to the category of traditional raw food materials. One of the possible ways in which the cost of biofuel obtained from microalgae can be reduced is by adopting biorefinery approach and using wastes from other production processes for cultivating them. With the latest technologies it has become possible to cultivate the biomass of algae on a large scale all year round, not only under the conditions of tropical and subtropical climate, but also in zones with moderate climate, even at negative temperatures of outdoor air in winter. There is potential to effectively reduce the amount of carbon dioxide and nitrogen oxides released into the atmosphere from many stationary emitters by feeding the carbon-rich flue gas to the algae (Ackman et al., 1968; Adey and Loveland, 2007). Algae are able to fix approximately 1.8 kg of CO₂ for every 1 kg of algae biomass produced (Antoni et al., 2007). Approximately 40 ha of algae ponds are required to fix the carbon emitted from one MW of power generated from a coal plant (Becker, 1994). Treated wastewater rich in nitrogen and phosphorus can be utilized by algae, thereby providing the co-benefit of producing biofuels and removing nitrogen and phosphorus (Bilanovic et al., 1988; Benemann and Oswald, 1996; Bigogno et al., 2002).

Algae cultivation
The necessary technology for developing profitable algae-based fuel is still in various states of development and the final configuration is yet to be determined and demonstrated at the industrial scale. The high capital cost associated with
producing microalgae in closed culture systems is the main challenge for commercialization of such systems.

**Table 1.** Biomass yields of microalgae versus conventional crops. Source: Richmond (1986)

<table>
<thead>
<tr>
<th>Crops</th>
<th>Annual yield (tons/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sugar cane</td>
<td>54-125</td>
</tr>
<tr>
<td>Sweet sorghum</td>
<td>35-70</td>
</tr>
<tr>
<td>Soybean</td>
<td>1.1-4.0</td>
</tr>
<tr>
<td>Sweet potato</td>
<td>10-40</td>
</tr>
<tr>
<td>Trees</td>
<td>20-50</td>
</tr>
<tr>
<td>Microalgae</td>
<td>800-1600</td>
</tr>
</tbody>
</table>

Two methods of cultivation are used for realizing the biosynthesis abilities of natural and modified strains of autotrophic microalgae: in photobioreactors (PBRs) and in open cultivators. Cultivation can be conducted in batch, semi-batch, and continuous systems. In a continuous system, two types can be used: turbidostat and chemostat culture. Algae can be produced in closely-controlled laboratory methods to less predictable methods in outdoor tanks.

**Open pond systems**

Open pond systems are shallow ponds in which algae are cultivated. Nutrients can be provided through runoff water from nearby land areas or by channelling the water from sewage/water treatment plants. The water is typically kept in motion by paddle wheels or rotating structures, and some mixing can be accomplished by appropriately designed guides. Algal cultures can be defined (one or more selected strains), or are made up of an undefined mixture of strains (Borowitzka, 1988; Chaumont, 1993; Boichenko and Hoffmann, 1994).

**Indoor culture / Closed culture**

Vessels such as tubes, flasks, carboys, bags, etc. or ponds covered with green house or usually a photobioreactor which allows control over illumination, temperature, nutrient level, contamination with predators and other competing algae can be used. Researchers also took the path of creating heterotrophic strains of algae from obligate photoautotrophs due to inadequate illuminance. Heterotrophic cultivation of microalgae for lipids production does not involve CO₂ mitigation and wastewater treatment programme along with production of algal biofuel.

A photo bioreactor is equipment that is used to harvest algae. Photo bioreactors can be set up to be continually harvested (the majority of the larger cultivation systems), or by harvesting a batch at a time (like polyethylene bag cultivation). Some photo bioreactors types include: tubular photo bioreactors, flat-plated photo bioreactors, an inclined triangular tubular photo bioreactor, rectangular tanks, continuous stirred tank reactors (CSTR), helical coils made of plastic tubing placed across a column-like structure, square tubular reactors consist of plastic tubing arranged in a series of squares.

**Algal Turf Scrubber (ATS)**

In addition to the open ponds or photo bioreactors, an attached algal culture system such as an algal turf scrubber (ATS) can be used in which benthic algae grow on the surface of solid support for removing nutrients from animal wastewater (Bridgwater et al., 1999; Bosma et al., 2003).

**Harvesting Algae**

Conventional processes used to harvest micro-algae include concentration through centrifugation (Briens et al., 2008), foam fractionation (Brown et al., 1997), flocculation (Chaumont 1993; Canakci and Van Gerpen, 2001), membrane filtration (Chisti, 2007) and ultrasonic separation (Chynoweth et al., 1993). However, most harvesting methods still involve economic or technical drawbacks, such as a high energy cost, flocculant toxicity, or non-feasibility of scaling-up. The harvesting of algal cells by flocculation is more convenient than centrifugation or gravity filtration, because it allows large quantities of culture to be treated. A variety of chemicals have been tested as flocculants and the most effective was found to be aluminum sulfate followed by certain cationic polyelectrolyte (Conover, 1975). The flocculating reactions of an algal biomass are particularly sensitive to the pH, properties of the cellular surface, concentrations of the flocculants and divalent cations, ionic strength of the culture solution and other factors (Craggs et al., 1996; Csordas and Wang, 2004). High-density algal cultures can be concentrated by either chemical flocculation or centrifugation.
Froth flotation is a method of separating algae from the medium by adjusting pH and bubbling air through a column to create a froth of algae that accumulates above liquid level. Ultrasound based methods of algae harvesting are currently under development, and other, additional methods are currently being developed. Dissolved Air Flotation (DAF) separates algae from its culture using features of both froth flotation and flocculation. It uses alum to flocculate an algae/air mixture, with fine bubbles supplied by an air compressor. Alum is a common name for several trivalent sulfates of metal such as aluminum, chromium, or iron and a univalent metal such as potassium or sodium, for example AlK(SO$_4$)$_2$.

**Algal drying**

Dewatering/drying process reduces the water content of the algae prior to oil extraction process. The algae paste obtained from filtration/centrifugation contains as much as ca. 90% water content. Drying algae to ca. 50% water content is necessary to produce a solid material that can be easily handled. Solar drying, a popular and inexpensive method, is used commercially in grains and timber drying. However, it requires a considerable area of land. A more efficient method would make use of the low grade waste heat from the power plant to dry the algae contained in a vessel. The biomass harvested from the attached culture system is paste-like pulpy slurry having a water content to that of the cell pellet centrifuged from the suspension culture system. This implies a great advantage of the attached algal culture system in terms of ease of biomass harvesting (Das and Veziroglu, 2001).

**Fig. 1. Energy production pathway**

Energy production from algae

Algal lipids (so-called pseudo vegetable oil or PVO) are much more heterogeneous than the seed-oil lipid. Therefore makes it difficult to characterize algae-derived fuel products and treated analogous to vegetable oil. Energy production pathway can be expressed diagrammatically as shown in figure 1.

**Microalgae as biological sources of lipids and hydrocarbons**

Algae are far more oil-rich and offer a higher yield of oil per unit of land in a year compared to terrestrial crops (Table 2). Lipids are one of the main components of micro algae (2-60% of total cell dry matter) depending on the species and growth conditions (Dote et al., 1994). Microalgae contain lipids and fatty acids as membrane components, storage products, metabolites and sources of energy. Microalgal strains with high oil or lipid content are of great interest in the search for a sustainable feedstock for biodiesel. A few micro algal species, including some Chlorella species (FAO, 1997; Fukuda et al., 2001) Dunaliella species (Gaffron and Rubin, 1942; Gerpen, 2005) Nannochloris sp. (Gordillo et al., 1998; Ghirardi et al., 2000), Parietochloris incisa (Haesman et al., 2000) and Botryococcus braunii (Harris, 1989; Johnson and Wen, 2010), have been reported to have the capacity of accumulating large quantities of lipids in cells under favorable conditions. Lipid content also varies with season as tested in Chlorella vulgaris, Euglena gracilis and Chlamydomonas sp. (figure 2 Unpublished data).

**Table 2. Oil output of different biofuel feed stocks** Source: Khan et al. (2009)

<table>
<thead>
<tr>
<th>Crop</th>
<th>Oil yield (gal/acre-yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn</td>
<td>18</td>
</tr>
<tr>
<td>Cotton</td>
<td>35</td>
</tr>
<tr>
<td>Soybean</td>
<td>48</td>
</tr>
<tr>
<td>Canola</td>
<td>127</td>
</tr>
<tr>
<td>Jatropha</td>
<td>202</td>
</tr>
<tr>
<td>Oil palm</td>
<td>635</td>
</tr>
<tr>
<td>Microalgae (15% oil)</td>
<td>1,200</td>
</tr>
<tr>
<td>Microalgae (50% oil)</td>
<td>10,000</td>
</tr>
</tbody>
</table>

Lipids can be used as a liquid fuel in adapted engines as Straight Vegetable Oil (SVO). In comparison with SVO, algal oil is unsaturated to a larger degree making it less appropriate for direct combustion in sensitive engines (Table 3), however,
some members of these algal group like *Chlorella* is known for containing shorter-chain fatty acids (16 to 18 carbon length) which are ideally suited for biodiesel production (Kadam, 2002; Khan et al., 2009). *Neochloris oleoabundans* is a freshwater species that produces up to 80% triglycerides of its total lipids, and most of its fatty acids are saturated fatty acid in the range of 16-20 carbons (Gordillo et al., 1998), ideal for biodiesel production. However the triglycerides produced by *P. incisa* is rich of polyunsaturated fatty acid (Haesman et al., 2000), making them less desirable for biodiesel production.

**Table 3.** Fatty acid composition of microalgae oil [Source: Meng et al. (2009)]

<table>
<thead>
<tr>
<th>Fatty acid</th>
<th>Chain length:no. of double bonds</th>
<th>Oil composition (w/total lipid)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Palmitic acid</td>
<td>16:0</td>
<td>12–1</td>
</tr>
<tr>
<td>Palmitoleic acid</td>
<td>16:1</td>
<td>55–7</td>
</tr>
<tr>
<td>Stearic acid</td>
<td>18:0</td>
<td>1–2</td>
</tr>
<tr>
<td>Oleic acid</td>
<td>18:1</td>
<td>58–60</td>
</tr>
<tr>
<td>Linoleic acid</td>
<td>18:2</td>
<td>4–20</td>
</tr>
<tr>
<td>Linolenic acid</td>
<td>18:3</td>
<td>14–30</td>
</tr>
</tbody>
</table>

**Factors affecting oil production in algae**

Taxonomic groupings, stage of growth, and environmental factors (e.g., seasonal changes such as temperature and light intensity, and media composition) affect the quantity and types of lipids as well as fatty acids compositions (Klass, 1998; Lee et al., 1998; Knuckey et al., 2006) as shown in figure 2. The effects of growth conditions, growth stage of algal cultures and the taxonomic position of algae, on both lipid content and lipid type, are discussed (Piorreck and Pohl, 1984; Li et al., 2008). Lipid accumulation in algae typically occurs during periods of environmental stress, including growth under nutrient-deficient conditions. The average lipid content of algal cells varies between 1% and 70% but can reach 90% of dry weight under certain conditions (Livansky, 2005; Liu et al., 2008). Under unfavorable conditions of growth, *Botryococcus* enters a stage in which its unsaponifiable lipid content increases to a level of 90%.

**Figure 2.** Changes in lipid content in different algae

The total amount and relative proportion of fatty acids can be affected by nutritional and environmental factors e.g. nitrogen limitation as in case of *Neochloris oleoabundans* (Maeda et al., 1995). The effect of nitrogen on the lipid fraction and on cell growth of the strain *Nannochloris* cultured under saline conditions is summarized in Table 4. At the lower temperature ranges, an increase in fatty acid unsaturation has been observed. Light enhances the formation of polyunsaturated C16 and C18 fatty acids as well as mono- and di-galactosyl-diglycerides, sphingolipids and phosphoglycerides in *Euglena gracilis* and *Chlorella vulgaris* (Melis et al., 2000).

**Figure 3.** Energy conversion processes from microalgae

**Extraction of algal oil**

While more efficient processes are emerging as shown in figure 3, a simple process is to use a press to extract a large percentage (70-75%) of the oils out of algae. The remaining pulp can be mixed with cyclo-hexane to extract the remaining oil content.

**Chemical methods:** Algal oil can also be extracted using chemicals. Benzene and ether have been used, oil can also be
separated by hexane extraction, which is widely used in the food industry and is relatively inexpensive.

Three chemical methods are hexane solvent method, soxhlet extraction and supercritical fluid extraction method.

**Hexane solvent method:** Hexane solvent extraction can be used in isolation or it can be used along with the oil press/expeller method. After the oil has been extracted using an expeller, the remaining pulp can be mixed with cyclo-hexane to extract the remaining oil content. The oil dissolves in the cyclohexane, and the pulp is filtered out from the solution. The oil and cyclohexane are separated by distillation. These two stages (cold press and hexane solvent) together may derive more than 95% of the total oil present in the algae.

**Table 4.** Effect of nitrogen concentration (as KNO₃) on lipid production [Source: FAO (1997)]

<table>
<thead>
<tr>
<th>KNO₃ con. (mM)</th>
<th>Cell growth (g/L)</th>
<th>Internal lipid content (g/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9</td>
<td>0.39</td>
<td>42.4</td>
</tr>
<tr>
<td>9.9</td>
<td>2.5</td>
<td>32.9</td>
</tr>
<tr>
<td>9.9 + feeding</td>
<td>2.6</td>
<td>33.6</td>
</tr>
</tbody>
</table>

**Soxhlet extraction:** Soxhlet extraction is an extraction method that uses chemical solvents. Oils from the algae are extracted through repeated washing, or percolation, with an organic solvent such as hexane or petroleum ether, under reflux in special glassware.

**Supercritical fluid extraction:** In supercritical fluid / CO₂ extraction, CO₂ is liquefied under pressure and heated to the point that it has the properties of both a liquid and a gas, this liquefied fluid then acts as the solvent in extracting the oil.

**Other lesser-known extraction methods**

**Enzymatic extraction** - Enzymatic extraction uses enzymes to degrade the cell walls with water acting as the solvent, this makes fractionation of the oil much easier. However, the cost of this extraction process is estimated to be much greater than hexane extraction.

**Osmotic shock** - Osmotic Shock is a sudden reduction in osmotic pressure, causing pressure in a solution to rupture. Osmotic shock is sometimes used to release cellular components, such as oil.

**Ultrasonic-assisted extraction** - Ultrasonic extraction can greatly accelerate extraction processes. Using an ultrasonic reactor, ultrasonic waves are used to create bubbles in a solvent material, when these bubbles collapse near the cell walls, it creates shock waves and liquid jets that cause those cells walls to break and release their contents into the solvent. The need to subject biomass to filtration and chemical extraction of oil from it can be avoided using the method which consists of treating algal suspension in an alternating electromagnetic field with varying the pH value by adding CO₂ resulting in the cell wall destruction of algae thereby causing the floating up of oil. The method developed on the basis of acid catalysis allows the processes of extracting lipids from microalgae and obtaining biodiesel fuel to be combined in a single stage (Meng et al., 2009). The culture can be kept alive during the extraction of lipids from it by using mesoporous nanoparticles that extract oils from live cells of algae.

**Biodiesel from algal oil**

Raw microalgal oil is high in viscosity, thus requiring conversion to lower molecular weight constituents in the form of fatty acid alkyl esters. Transesterification is the process of converting raw microalgal lipid (triacylglycerols / free fatty acids) to give renewable, non-toxic and biodegradable biodiesel. Transesterification is a reaction of the parent oil with a short chain alcohol, usually methanol, in the presence of a catalyst. Products of the reaction are fatty acid methyl esters (FAME) and glycerol. The use of acid catalyst has found to be useful but the reaction rates for converting triglycerides to methyl esters are too slow (Meng et al., 2009). Acid catalysis is suitable for transesterification of oils containing high levels of free fatty acids (Metzger and Largeau, 2005). Alkali-catalyzed transesterification is about 4000 times faster than the acid catalyzed reaction and hence most frequently used commercially (Miao and Wu, 2006).

**Biochemical conversion**

**Biomethane production:** The production of biogas from biomass is gaining increasing importance worldwide. An anaerobic digester contains synergistic microbial populations to convert a variety of organic substrates to methane and carbon dioxide. Thus algal organic compounds (lipid, protein, or carbohydrate)
can be converted to methane. Methane is widely used as both a fuel and a chemical feedstock however under normal conditions it is a gas and therefore, bulky to handle, its use as a transportation fuel is limited. Chynoweth et al. (1993) compared the technical potential of different biomass sources (marine algae, wood and grass species, municipal solid waste) to be used in energy farms, and concluded that marine biomass offered the highest potential for biomethanation. The growth rates of marine macroalgae exceed those of land plants; however, growth is often limited by the availability of nutrients. Conversion of methane to methanol through photochemical conversion is possible.

Table 5. Carbohydrate and Lipid content of some commonly found algae

<table>
<thead>
<tr>
<th>Organism</th>
<th>Carbohydrate (% of DW)</th>
<th>Lipid (% of DW)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ±SD</td>
<td>Max</td>
</tr>
<tr>
<td>S. quadricauda</td>
<td>20.2</td>
<td>27.76±5.79</td>
</tr>
<tr>
<td>Pleurotonium sp.</td>
<td>25.1</td>
<td>28.02±2.09</td>
</tr>
<tr>
<td>Anabaena sp.</td>
<td>22.9</td>
<td>25.56±3.03</td>
</tr>
</tbody>
</table>

Ethanol production: Algae are the optimal source for bioethanol due to high content of carbohydrates/polysaccharides and thin cellulose walls. Generally two methods are employed for the production of bioethanol from microalgal biomass, namely fermentation (biochemical process) and gasification (thermo-chemical process) (Minowa and Sawayama, 1999). Fermentation is used commercially on a large scale in various countries to produce ethanol from sugar crops and starch crops. The biomass is ground and starch is converted to sugar by enzymes to sugar. The sugar is converted to ethanol by yeast. The purification process of ethanol by distillation is an energy intensive step (Minowa et al., 1995). The starch of microalgae is released from the cells with the aid of mechanical equipment or an enzyme and yeast, Saccharomyces cerevisiae is added when the biomass starts degrading to initiate fermentation. The product of fermentation i.e ethanol is drained from the tank and pumped to a holding tank to be fed to a distillation unit. Ethanol production by dark fermentation in the marine green alga Chlorococcum littorale was also investigated (Ueno et al., 1998). Under dark anaerobic conditions, 27% of the cellular starch was consumed within 24 h at 25°C, the cellular starch decomposition being accelerated at higher temperature. Ethanol, acetate, hydrogen and carbon dioxide were obtained as fermentation products. Some prominent strains of algae that have a high carbohydrate content and hence, promising candidates for ethanol production are Sargassum, Gracilaria, Prymnesium parvum, Euglena gracilis (Piorreck and Pohl, 1984).

Thermochemical conversion

Thermal decomposition of algal biomass can yield different types of energy fuels depending on temperature used for conversion. Pyrolysis is a phenomenon related to decomposition of biomass under the condition of oxygen deficiency and high temperature. Pyrolysis of biomass produces charcoal, condensable organic liquids, acetic acid, acetone, methanol and non-condensable gaseous products by a simple, effective, wasteless and pollution free process. This technology may be more suitable for microalgae because of the lower temperature required for pyrolysis and the higher-quality of oils obtained (Olson and Ingram, 1975). Compared to lignocellulose, microalgae contain high content of cellular lipids, resolvable polysaccharides and proteins, which are easier to be pyrolyzed to bio-oils and bio-gases.

Gasification is a term that describes a chemical process by which carbonaceous materials (hydrocarbon) are converted to a synthesis gas (syngas) by means of partial oxidation with air, oxygen and/or steam at high temperatures, typically in the range 800-900°C. Syngas can be burned directly or used as fuel for diesel or gas turbine engines. A novel energy production system using microalgae with nitrogen cycling combined with low temperature catalytic gasification of the microalgae has been proposed (Sebnem Aslan, 2006). Other conversions are also possible, most notably a thermochemical conversion to produce higher alcohols, which have octane-enhancing properties of
ethanol and methanol but pose fewer water solubility and phase separation problems.

**Thermochemical liquefaction**

High content of water often exists in micro algae after harvesting which requires a great deal of energy to remove moisture from algal cells during pretreatment. Liquefaction has been developed to produce bio-fuel directly without the need of drying micro algae (Singh and Gu, 2010). Moreover, wet microalgae can provide hydrogen for hydrogenolysis. It was reported that *Dunaliella tortiolecta* cells with 78.4% water content converts to oils directly. The yield of oils reached 37% of the total organic matters (Singh and Gu, 2010). Dote et al. (1994) reported that *B. braunii* produced liquid oils at 57-64% of dry weight under the conditions of a N₂ pressure of 10 MPa at 300°C in warm water and catalyzed by NaCO₃. Liquefaction of algae uses moderate temperature and pressure and, most interesting, wet material can be used in the process. Thermochemical liquefaction requires temperature around 350 and 395°C in order to have the optimal amount of extracted oil. Nevertheless, its composition depends on the working temperature. Among the technologies used, the thermochemical liquefaction seems to be more efficient than the extraction.

**Hydrogenation**

Hydrogenation is a reductive chemical reaction that results addition of hydrogen (H₂), usually to saturate organic compounds. The process consists of the addition of hydrogen atoms to the double bonds of a molecule through the use of a catalyst (Gaffron and Rubin, 1942). Algal hydrogenation is performed by using an autoclave under high temperature and pressure conditions in the presence of a catalyst and a solvent. Algal hydrogenation is a three-phase operation in which contact must be established between the gaseous phase (hydrogen and hydrocarbon phase), liquid phase (mixture of solvent and liquid product), and solid particle phase (algal and catalyst) in order to achieve algal conversion and to promote the transfer of momentum, heat and mass.

**Algal biohydrogen production**

Over the years microalgae for photo-biological hydrogen production from water are being developed into a promising and a potentially emission-free fuel stream for the future, which could also be coupled to atmospheric CO₂-sequestration. Bio-hydrogen production from micro algae has been known for more than 65 years and was first observed in the green alga *Scenedesmus obliquus* and in many other photosynthetic species (Boichenko and Hoffmann, 1994). Most studies on algal hydrogen production have been performed using the green alga *Chlamydomonas reinhardtii*, a model organism for photosynthesis research via an aerobic-anaerobic cycle developed by Melis and coworkers (2000). Earlier, algal biofuel projects were focused at obtaining biodiesel fuel, but at present, owing to innovative technologies, producers are becoming interested in the possibility of obtaining other kinds of fuel from algae that are close in composition to fuel products obtained by petroleum distillation e.g. aviation fuel, which is obtained by subjecting algae oil to hydroprocessing.

**Integrated biodiesel production from microalgae (IBPCS)**

IBPCS enables the overall system to be operated at a profit and the design requires the combination and optimization of several factors such as biomass culture, growth management, transport to conversion plants, drying, product separation, recycling, waste (liquid and solid) management, transport of saleable products and marketing. These factors can be simplified and reduced to three main groups; culturing of microalgae, harvesting and processing of biomass. In the idealized case, the conversion plants are located in or near the biomass growth areas to minimize the cost of transporting biomass to the plants, of which all the non-fuel effluents are recycled to the growth areas (Pushparaj et al., 1993). Integration approaches for sustainable micro algal biodiesel production use hydrothermal technology for direct liquefaction of algal biomass.

**Bio-refinery approach and other biofuels**

The economics of biodiesel production can be significantly improved by using the bio-refinery based production strategy where all the components of the biomass raw material are used to produce useful products (Antoni et al., 2007). Furthermore, it is recommended that a bio-refinery approach is the best solution to combine and integrate various processes to maximize economic and environmental benefits, while minimizing waste and pollution (Pushparaj et al., 1993).
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References


