GREEN RENEWABLE ENERGY FOR SUSTAINABLE SOCIO-ECONOMIC DEVELOPMENT

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ABSTRACT

Sustainability is a key principle in natural resource management, and it involves operational efficiency, minimization of environmental impact and socio-economic considerations; all of which are interdependent. As a result of the generalization of agricultural, industrial and domestic activities the demand for energy has increased remarkably. Recent studies indicate that continued reliance on fossil fuel energy resources is unsustainable, owing to both depleting world reserves and the green house gas emissions associated with their use. Therefore, renewable, carbon neutral, transport fuels are necessary for environmental and economic sustainability. Large-scale introduction of biomass energy could contribute to sustainable development on environmental, social, and economic fronts. Microalgae are considered as the most promising renewable feedstock for biofuel production and biore-fineries, due to their advantages of fast growth, efficient CO_2 fixation, not competing for arable lands and potable water, and potentially accumulating high amounts of lipids and carbohydrates. These products can be processed into both biofuels and valuable co-products. In this article we present an overview about microalgae use for biofuels production, including their cultivation, harvesting strategies, and processing. The economical challenges in the production of biofuels have been discussed in view of the future prospects in the commercialization of algal fuels.

Keywords: Algal biomass, Biofuel, Economy, Environment, Sustainable development

1. Introduction: Energy sources and environmental issues

Energy is a key factor in discussions of economic, social and environmental dimensions of sustainable development (Adnan *et al*., 2006). The fast growth of the global population and the rise of developing countries have led to a rapid increase in demand for energy (Harun *et al*., 2010). Energy is found in different forms, such as heat, light, motion, and sound. Energy sources can be classified into three groups; fossil, renewable, and fissile. Fossil fuels were formed many years ago and are not renewable. The fossil energy sources are petroleum, coal, bitumen, natural gas, oil shale, and tar sands. Fossil fuels accounted for 88% of the primary energy consumption, with oil (35% share), coal (29%) and natural gas (24%) as the major fuels, while nuclear energy and hydroelectricity account for 5% and 6% of the total primary energy consumption, respectively (BP, 2010). Currently, about 90% of energy needs come from coal, natural gas and petroleum, and sustainable energy supplies need to be developed due to the dwindling reserve of these fossil fuel resources (Chen *et al*., 2011). The global primary energy consumption, including oil, natural gas, nuclear and coal, has declined approximately 1.1% in 2009 (BP, 2010). However, the production of oil and natural gas also declined approximately 7.3 and 2.1%, respectively, showing that world energy source is reducing. With current consumption trends, world oil reserves may run out by 2050 (Harun *et al*., 2010). Moreover, the problems of environmental pollution and climate change are also mainly attributed to the over-consumption of fossil fuels (Sivakumar *et al*., 2010).

Fossil fuels are the largest contributor of greenhouse gases (GHGs) to the biosphere, and in 2006 associated CO_2 emissions were 29 G tons (EIA, 2006). Global climate change caused by the net increase in atmospheric CO_2 due to combustion of the fossil fuels. Combustion of fossil fuels is adding about 6 gigatons (Gton 10^9 tons) per year of C (in the form of CO_2) to the atmosphere each year (IPCC, 2007). Thus, the atmospheric CO_2 level has been increasing at an accelerating rate since the start of the industrial revolution (Table 1).

Table 1: Trends in atmospheric CO_2 and average air temperature

Year	Atmospheric CO_2 (ppmv)	Average temperature (°C)	Comment
1800	280	15.0	Pre-industrial revolution
1870	280	15.0	Early industrial revolution
1950	305	15.2	Target for 2006 CO_2 levels[a]
1970	325	15.2	Major increases observed
1988	350	15.5	Increases accelerate
2000	360	15.8	Increases accelerate
2006	375	16.0	Increases accelerate
2050 est	~550	Up to ~17.2	Hoped for stabilization[b]
2100 est	Up to ~800	Up to ~19.2	Stabilization does not occur

Source: IPCC (2007).

[a]The CO_2 emission rate of 1950 would hold the 2006 CO_2 concentration; [b]Stabilization requires that CO_2 emissions are lower in 2050 than today and that they continue to decline.

Renewable, carbon-neutral, economically viable alternatives to fossil fuels are urgently needed to avert the impending oil crisis and the dramatic consequences of climate change (Chisti, 2007). Therefore, a number of countries have expressed increased interest in developing alternative energy sources that are renewable, economically competitive and environmentally friendly (Mussgnug *et al*., 2010). Amongst the renewable energies, one of the most important energy sources in near future is biomass.

2. Development of biofuel resources

Biomass is one of the better sources of energy to mitigate GHG emissions and to function as a substitute for fossil fuels (Widjaja *et al*., 2009). Biomass energy potential is addressed to be the most promising among the renewable energy sources, due to its spread and its availability worldwide. Biofuel is a renewable energy source produced from biomass, which can be used as a substitute for petroleum fuels. Biofuels are referred to solid, liquid or gaseous fuels derived from organic matter. They are generally divided into primary and secondary biofuels (Fig. 1). While primary biofuels such as fuel wood are used in an unprocessed form primarily for heating, cooking or electricity production, secondary biofuels such as bioethanol and biodiesel are produced by processing biomass and are able to be used in vehicles and various industrial processes. The secondary biofuels can be categorized into three generations: first, second and third generation biofuels on the basis of different parameters, such as the type of processing technology, type of feedstock or their level of development (Nigam and Singh, 2011).

Although biofuel processes have a great potential to provide a carbon-neutral route to fuel production, first generation production systems have considerable economic and environmental limitations. First generation biofuels which have attained economic levels of production, have been mainly extracted from food and oil crops including rapeseed oil, sugarcane, sugar beet, and maize as well as vegetable oils and animal fats using conventional technology (FAO, 2008). The use of first generation biofuels has generated a lot of controversy, mainly due to their impact on global food markets and on food security, especially with regards to the most vulnerable regions of the world economy.

The advent of second generation biofuels is intended to produce fuels from lingo-cellulosic biomass, the woody part of plants that do not compete with food production. Sources include agricultural residues, forest harvesting residues or wood processing waste such as leaves, straw or wood chips as well as the non-edible components of corn or sugarcane. However, converting the woody biomass into fermentable sugars requires costly technologies involving pre-treatment with special enzymes, meaning that second generation biofuels cannot yet be produced economically on a large scale (Brennan and Owende, 2010). Therefore, third generation biofuels derived from microalgae are considered to be a viable alternative energy resource that is devoid of the major drawbacks associated with first and second generation biofuels (Chisti, 2007). Microalgae are able to produce 15-300 times more oil for biodiesel production than traditional crops on an area basis. Furthermore compared with conventional crop plants which are usually harvested once or twice a year, microalgae have a very short harvesting cycle (≈1-10 days depending on the process), allowing multiple or continuous harvests with significantly increased yields (Schenk *et al*., 2008).

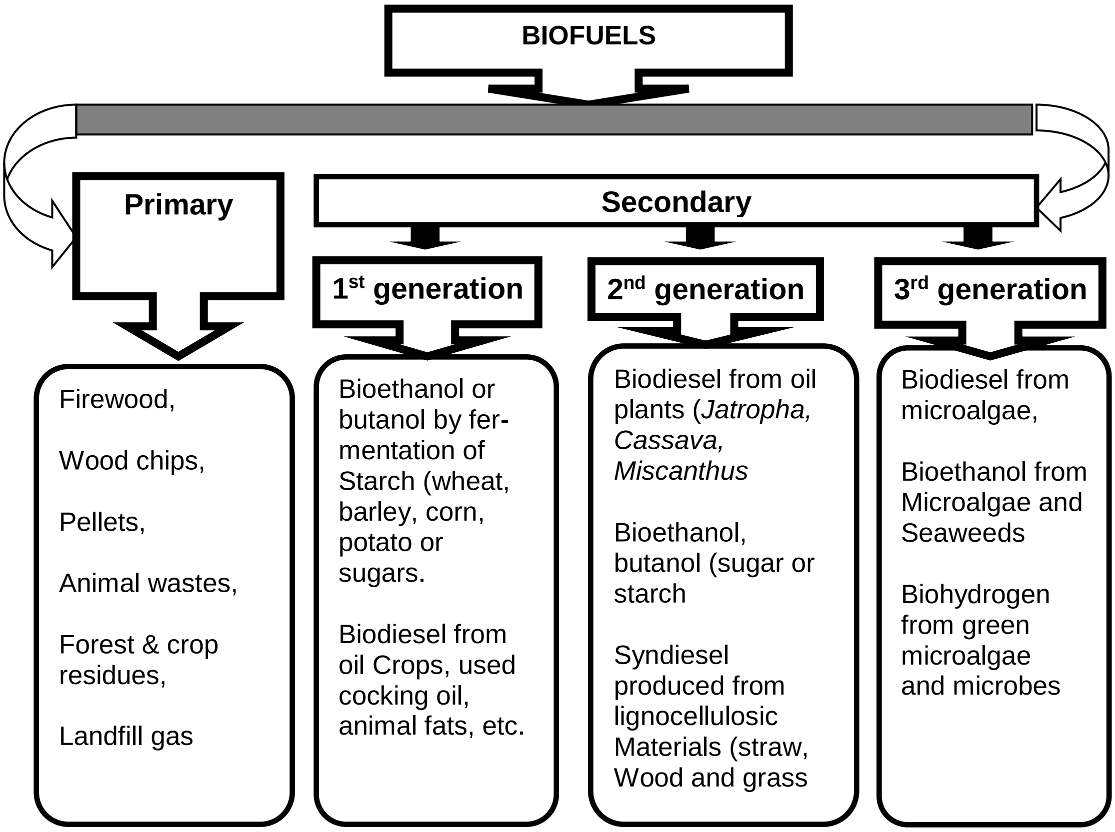

Figure 1: Classification of biofuels (modified from Dragone *et al*., 2011)

3. Characteristics of algae

Algae are recognized as one of the oldest life-forms (Falkowski and Raven, 1997). They are primitive plants (thallophytes), i.e. lacking roots, stems and leaves, have no sterile covering of cells around the reproductive cells and have chlorophyll a as their primary photosynthetic pigment (Lee, 2008). Algae structures are primarily for energy conversion without any development beyond cells, and their simple development allows them to adapt to prevailing environmental conditions and prosper in the long term (Falkowski and Raven, 1997). The algal organisms are photosynthetic macroalgae or microalgae growing in all existing earth ecosystems, both aquatic and terrestrial, and can flourish under a wide range of environmental conditions, including freshwater, brackish water, seawater, and even wastewater (Richmond, 2004; Abou-Shanab *et al*., 2014).

Figure 2: Some of macroalgae (A) and microalgae (B) species

Macroalgae are the large (measured in inches), multi-cellular algae often seen growing in ponds. The largest multi-cellular algae are called seaweed; an example is the giant kelp plant which can be more than 100 feet long. Microalgae, on the other hand, are tiny (measured in micrometers), unicellular algae that normally grow in suspension within a body of water (Fig. 2).

4. Microalgae mass-cultivation systems

Microalgae are adapted to scavenge their environments for resources, to storage them, or increase their efficiency in resource utilization. In general for biomass growth (consisting of 40-50% carbon) microalgae depend on a sufficient supply of a carbon source and light to carry out photosynthesis (Moheimani, 2005). Yet they can adjust or change their internal structure (e.g. biochemical and physiological acclimation), whilst externally they can excrete a variety of compounds to amongst others, render nutrients available or limit the growth of competitors (Richmond, 2004). Microalgae may assume many types of metabolisms (e.g. photoheterotrophic, heterotrophic, mixotrophic, autotrophic) and are capable of a metabolic shift as a response to changes in the environmental conditions.

- Photoautotrophically, i.e. using light as a sole energy source that is converted to chemical energy through photosynthetic reactions.
- Heterotrophically, i.e. utilizing only organic compounds as carbon and energy source.
- Mixotrophically, i.e. performing photosynthesis as the main energy source, though both organic compounds and CO_2 are essential. Amphitrophy, subtype of mixotrophy, means that organisms are able to live either autotrophically or heterotrophically, depending on the concentration of organic compounds and light intensity available.
- Photoheterotrophycally, also known as photoorganitrophy, photoassimilation, photometabolism, describes the metabolism in which light is required to use organic compounds as carbon source. The photoheterotrophic and mixotrophic metabolisms are not well distinguished, in particular they can be defined according to a difference of the energy source required to perform growth and specific metabolite production.

There are several factors influencing algal growth: abiotic factors such as light (quality, quantity), temperature, nutrient concentration, O_2, CO_2, pH, salinity, and toxic chemicals; biotic factors such as pathogens (bacteria, fungi, viruses) and competition by other algae; operational factors such as shear produced by mixing, dilution rate, depth, harvest frequency, and addition of bicarbonate. Commercial production of microalgal biomass at low cost through large-scale cultivation is a prerequisite for realizing these potentials of microalgae. Presently, most methods of producing bulk production of microalgal biomass are mainly based on suspension culture using open pond production and closed photobioreactor systems (Chisti, 2007; Mata *et al*., 2010). Table 2 makes a comparison between closed system (PBRs) and open system for several culture conditions and growth parameters (Del Campo *et al*., 2007). From a commercial point of view, a microalgae culture system must have as many of the following characteristics as possible: high area productivity; high volumetric productivity; inexpensiveness (both in terms of investment and maintenance costs); easiness of control of the culture parameters (temperature, pH, O_2, turbulence); and reliability (Olaizola, 2003). Cultivation systems of different designs attempt to achieve these characteristics differently.

5. Algae harvesting technologies

The recovery of microalgal biomass which generally requires one or more solid-liquid separation steps is a challenging phase of the algal biomass production process and accounts for 20-30% of the total costs of production (Wang *et al*., 2008). The selection of harvesting technique is dependent on the properties of microalgae, such as density, size, and the value of the desired products (Brennan and Owende, 2010). The major techniques presently applied in the harvesting of microalgae include centrifugation, flocculation, filtration and screening, gravity sedimentation, flotation, and electrophoresis techniques (Uduman *et al*., 2010).

Table 2: Advantages and limitations of open ponds and photobioreactors

Production system	Advantages	Limitations
Raceway pond 	Relatively cheap Easy to clean Utilises non-agricultural land Low energy inputs Easy maintenance	Poor biomass productivity Large area of land required Limited to a few strains of algae Poor mixing, light and CO2 utilisation Cultures are easily contaminated
Tubular photobioreactor 	Large illumination surface area Suitable for outdoor cultures Relatively cheap Good biomass productivities	Some degree of wall growth Fouling Requires large land space Gradients of pH, dissolved oxygen and CO2 along the tubes
Flat plate photobioreactor 	High biomass productivities Easy to sterilise Low oxygen build-up Readily tempered Good light path Large illumination surface area Suitable for outdoor cultures	Difficult scale-up Difficult temperature control Small degree of hydrodynamic stress Some degree of wall growth
Column photobioreactor 	Compact High mass transfer Low energy consumption Good mixing with low shear stress Easy to sterilize Reduced photoinhibition and photo-oxidation	Small illumination area Expensive compared to open ponds Shear stress Sophisticated construction

6. Algae as a biofuel feedstock

Algae are sunlight-driven miniature factories that convert atmospheric CO_2 to polar and neutral lipids (biomass) which after esterification can be utilized as an alternative source of petroleum. Further, other metabolic products such as bioethanol and biohydrogen produced by algal cells are also being considered for the same purpose. Algae biomass contains three main components: proteins, carbohydrates, and natural oil (Table 3). Microalgae have been suggested as good candidates for fuel production because of their higher photosynthetic efficiency, higher biomass production and faster growth compared to those of other energy crops (Becker, 1994). Microalgae systems also use far less water than do traditional oilseed crops. For these reasons, microalgae are capable of producing more oil per unit area of land compared to terrestrial oilseed crops (Chisti, 2007). According to some estimates, the yield (per acre) of oil from algae is over 200 times the yield from the best performing plant/vegetable oils (Sheehan *et al*., 1998). Although the microalgae oil yield is strain-dependent it is generally much greater than other vegetable oil crops in a dry weight basis and the oil yield per hectare, per year (Table 4).

Table 3: Biochemical composition of algae expressed on a dry matter basis

Strain	**Protein**	**Carbohydrates**	**Lipid**
		%	
Scenedesmus obliquus	50–56	10–17	12–14
Scenedesmus quadricauda	47	-	1.9
Scenedesmus dimorphus	8–18	21–52	16-40
Chlamydomonas rheinhardii	48	17	21
Chlorella vulgaris	51–58	12–17	14-22
Chlorella pyrenoidosa	57	26	2
Spirogyra sp.	6–20	33–64	11-21
Dunaliella bioculata	49	4	8
Dunaliella salina	57	32	6
Euglena gracilis	39–61	14-18	14-20
Prymnesium parvum	28–45	25-33	22-39
Tetraselmis maculata	52	15	3
Porphyridium cruentum	28–39	40-57	9-14
Spirulina platensis	46–63	8-14	4-9
Spirulina maxima	60–71	13-16	6-7
Synechoccus sp.	63	15	11
Anabaena cylindrica	43–56	25-30	4-7

Source: Becker, 1994

Table 4: Comparison of microalgae with other biodiesel feedstocks.

Plant source	Seed oil content (%)	Oil yield (L /ha/ year)	Land use (m^2 year/kg biodiesel)	Biodiesel productivity (kg biodiesel/ha year)
Zea mays L.	44	172	66	152
Cannabis sativa L	33	363	31	321
Glycine max L.	18	636	18	562
Jatropha curcas L	28	741	15	656
Camelina sativa L	42	915	12	809
Brassica napus L	41	974	12	862
Helianthus annuus L	40	1070	11	946
Ricinus communis	48	1307	9	1156
Elaeis guineensis	36	5366	2	4747
Microalgae[a]	30	58,700	0.2	51,927
Microalgae[b]	50	97,800	0.1	86,515
Microalgae[c]	70	136,900	0.1	121,104

[a]low oil content; [b]medium oil content; [c]high oil content

7. Algal biofuels conversion technologies

The conversion of algal biomass-to-energy encompasses the different processes ordinarily used for terrestrial biomass and which depend, to a large extent, on the types and sources of biomass, conservation options and endues (McKendry, 2002). There are several ways to convert microalgal biomass to energy sources, which can be classified into biochemical conversion, chemical reaction, direct combustion, and thermochemical conversion (Fig. 3). Thermochemical conversion covers the thermal decomposition of organic components in biomass to yield fuel products, and is achievable by different processes such as direct combustion, gasification, thermochemical liquefaction, and pyrolysis (Tsukahara and Sawayama, 2005). Biochemical conversion it is the biological process of energy conversion of biomass into other fuels includes anaerobic digestion, alcoholic fermentation and photobiological hydrogen production (USDOE, 2002). Photobiological production of hydrogen by photosynthetic microorganisms is of interest due to the promise of generating clean carbon-free renewable energy from abundant natural resources, such as sunlight and water. Cyanobacteria and green algae are, so far, the only known organisms with both an oxygenic photosynthesis and hydrogen production ability (Hemschemeier *et al*., 2009). Microalgae possess the necessary genetic, metabolic and enzymatic characteristics to photoproduce H_2 gas (Ghirardi *et al*., 2000). Under anaerobic conditions hydrogen is produced from eukaryotic microalgae either as an electron donor in the CO_2 fixation process or evolved in both light and dark (Greenbaum, 1988). During photosynthesis, microalgae convert water molecules into hydrogen ions (H^+) and oxygen; the hydrogen ions are then subsequently converted by hydrogenase enzymes into H_2 under anaerobic conditions (Cantrell *et al*., 2008).

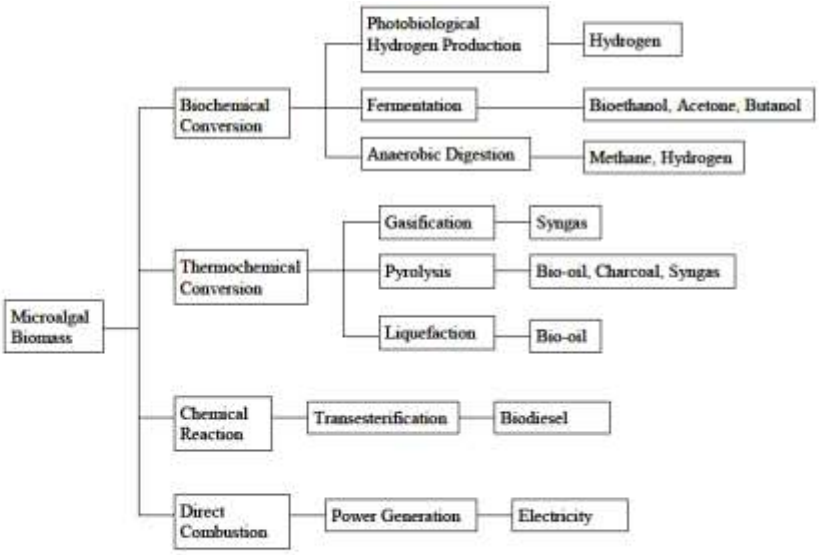

Figure 3: Conversion processes for biofuel production from microalgal biomass (modified from [Lee, 2008]).

Biodiesel is a derivative of oil crops and biomass which can be used directly in conventional diesel engines (Brennan and Owende, 2010). Biodiesel is defined as the mono-alkyl esters of fatty acids obtained by transesterification of vegetable oils, algal oil or animal fats. The overall transesterification reaction is described in Figure 4 where the radicals R1, R2, R3 represent long chain hydrocarbons, known as fatty acids. Algal biodiesel has several advantages over petroleum diesel in that: it is derived from biomass and therefore is renewable, biodegradable, and quasi-carbon neutral under sustainable production; it is non-toxic and contains reduced levels of particulates, carbon monoxide, soot, hydrocarbons and SOx. Compared with petroleum oil, algal biodiesel is more suitable for use in the aviation industry where low freezing points and high energy densities are key criteria. Biodiesel can be blended and used in many different concentrations, including B100 (pure biodiesel), B20 (20% biodiesel, 80% petroleum diesel), B5 (5% biodiesel, 95% petroleum diesel) and B2 (2% biodiesel, 98% petroleum diesel). B20 is popular because it represents a good balance of cost, emissions, cold-weather performance, materials compatibility, and ability to act as a solvent.

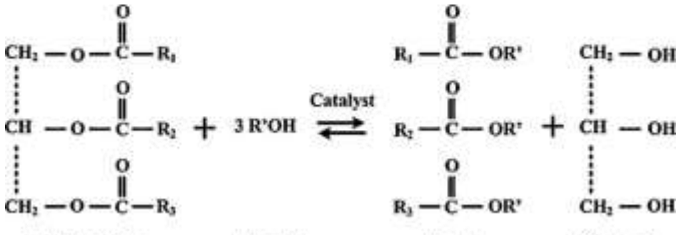

Figure 4: Transesterification of oil to biodiesel

8. Socio-economic issues of algal fuel production

The biofuel economy will grow rapidly during the 21st century. The biofuel economy, and its associated biorefineries, will be shaped by many of the same forces that shaped the development of the hydrocarbon economy and its refineries over the past century. The emergence of biofuel markets is expected to directly affect the livelihood and economy of rural, and bedouin communities, given that almost all feedstock are cultivated in rural and desert areas. Most economists support the notion that global biofuel programs will generally contribute to the sustainable livelihood of agricultural laborers by increasing employment rates in most rural communities since a large portion of feedstock cultivation and refinery processing involves manual labor. It was estimated that the Malaysian biodiesel industry is projected to employ ~1 million people, while the Indian sugarcane-based ethanol industry is expected to employ ~45.5 million people (Yan and Lin, 2009). Biofuel programs may also provide economic benefits for auxiliary service sectors, such as animal husbandry and milk production (Demirbas, 2009). In addition to that the usage of biodiesels in engines may decrease emissions of NOx by ~10%, CO and particulate matter by ~45%, hydrocarbons by ~65%, and sulfur oxides by ~100%.

9. Conclusions

In summary, green energy strategies can make an important contribution to the economies of countries where green energy is abundantly produced. Therefore, the investments in green energy supply should be, for the future of world nations, encouraged by governments and other authoritative bodies who, for strategic reasons, wish to have a green alternative to fossil fuels.

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