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Original Research

Algal biomass as a global source of transport fuels: Overview and development perspectives

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Abstract

As a result of the global fuel crisis of the early 1970s, coupled with concerns for the environment, the use of biofuel has been on the increase in many regions throughout the world. At present, a total of approximately 30 billion (30×10^9) liters of biofuel are utilized worldwide annually, although most countries rely hugely on the first generation biofuel. The limitations of the first and second generation biofuel gave rise to current interest in algae as a promising alternative to these conventional biofuel sources. Algal biomass could provide a lion's share of the global transport fuel requirements in future. The present review highlights some important developments in, and potentials of algaculture as a major biomass resource of the future. However, the major constraint to commercial-scale algae farming for energy production is the cost factor, which must be addressed adequately before its potentials can be harnessed.

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1. Introduction

With current global oil production approaching its peak, along with billions of tonnes of carbon emissions released into the atmosphere leading to global warming, threats of climatic change coupled with great obstacles to further development of conventional energy sources, it is very important that the great attention will be given to a range of environment-friendly renewable energy resources which are expected to play an important role in averting an impending future energy crisis.

Limiting global greenhouse gas concentrations to levels below the currently high 550 ppm carbon dioxide equivalent

would require drastic emissions reductions equivalent to a phase out of all fossil fuel emissions in developed countries by 2050, if developing country emissions continue to grow as expected [1,2]. The use of energy accounts for a major fraction of all anthropogenic emissions of greenhouse gases [3,4] and in most industrialized countries the use of transportation fuels and electricity accounts for a lion's share of all energy related emissions. It is a known fact that at the present moment renewable energy contributes only 11% to global primary energy, although it is expected that 60% of all our energy will come from renewable sources by the year 2070.

The transportation sector accounts for 21% of the current global fossil fuel CO₂ emissions to the atmosphere, second only to emissions from power production (Fig. 1). With global economic growth assumed to average 3.2% per year to 2030, growth in energy demand for transport is forecast to increase at

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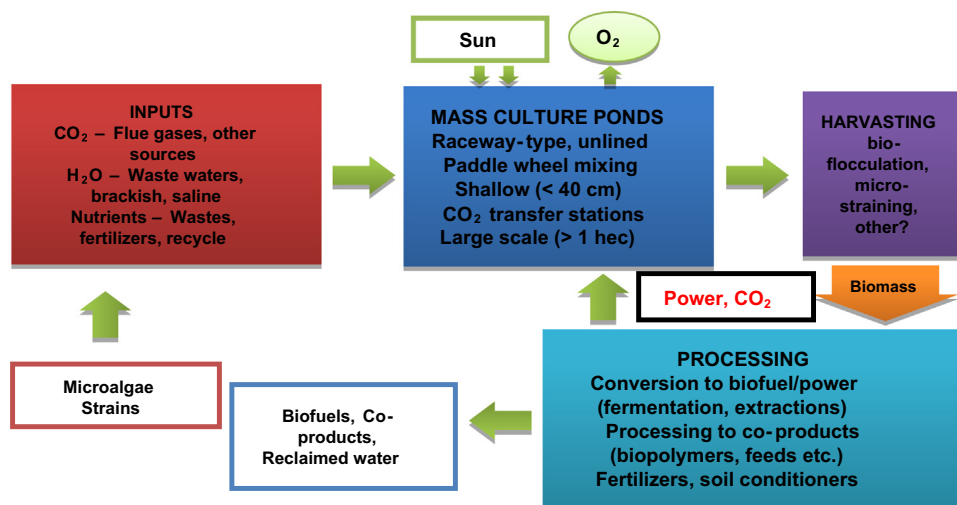


Fig. 1. CO₂ sequestration using algae. Source [17].

an average annual rate of 2.1% over the same period. Transport sector contribution to total anthropogenic greenhouse gases (GHG) emissions is projected to increase to 23% in 2030 [5]. Bioenergy has been recognized as a significant component in many future energy scenarios. Substitution of fossil fuels by biofuel appears to be an effective strategy to meet not only future world energy demands but also the requirement for reducing carbon emissions from fossil fuels. Although there is increasing demand for fossil energy due to rising economic activities in the emerging markets, especially China and India, soaring oil prices have encouraged major consumers worldwide to sharply increase their use of “green” biofuel.

The use of biofuel is, therefore, increasing in many regions throughout the world. At present, a total of approximately 30 billion (30×10^9) liters of biofuel are used annually in Europe, North America, and South America. This amount is expected to grow significantly as the demand for sustainable transportation fuels increases. According to recent IEA estimation bioethanol and biodiesel have the potential to reach 10% of world fuel use for transport by 2025 [6,7].

First generation biofuel sources have been exploited for nearly three decades but have proven grossly inadequate to augment rising global requirements. Instead, their continued use has contributed towards global food for fuel crisis, necessitating a gradual shift towards second generation biofuel sources, which offer greater potentials. However, the main argument against the second generation fuels is based on land availability and protection of global ecosystems. It is true that these fuel sources have immense potentials but there are indications that algal biomass (third generation biofuel sources) could well be the panacea to rising global demands for transport fuels. Various assessments advanced by different scholars indicate that algae offer great potentials as a biomass resource for the provision of future green transport fuels but also for direct use in carbon sequestration in many parts of the world.

Although the precise quantity of algae that can be grown, harvested and processed in a sustainable manner appears

unclear, much effort has been made in the application of algae as a biomass resource especially for the provision of food supplements and specialty products. The present communication highlights the evolution of transport biofuel while giving priority attention to algal biomass as a potential source of future biofuel. Areas requiring further R&D as well as some limitations of certain technological approaches will be discussed.

2. Land based biofuel sources

The oil crisis of the early 1970s triggered the interest in the adoption of land-based agriculture-derived fuels known as biofuel (bio-organic fuels) in a bid to augment the supply of fossils. Although, it was thought that mass cultivation of these first generation biofuel resources such as sugarcane, corn, soybean, rapeseed (canola), oil palm trees etc. could resolve both problems of edible oil and fuel at the same time, it became obvious with time that the increasing global demand for fuel could not be met sustainably by these fuel sources. Thus, emerged the adoption of non-edible (second generation) biofuel sources as supplementary and alternative to fossil-derived fuels, which are finite in nature and portend a great source of greenhouse gas pollutants to the environment.

Although established technological approaches for transport biofuel production—such as the American corn to ethanol and soybean to biodiesel programmes; the European Union rapeseed to biodiesel and sweet sorghum to ethanol programmes; the Brazilian sugarcane to ethanol process; the Malaysian palm oil to biodiesel experience etc.—are still heavily dependent on first generation sources, they only generate about 0.3% of all global transport fuels presently [8].

No doubt, bioenergy with the potential to meet 50% of world energy demands while reducing carbon emissions from fossil fuels appears to be a potential energy resource but increased biofuel production on arable land could have long term severe consequences for global food supply.

2.1. First generation biofuel

First-generation fuels refer to biofuel made from sugar, starch, vegetable oil, or animal fats using conventional technology [9]. These liquid biofuel comprise the already available fuels like pure plant oil (PPO) from oil crops, biodiesel from esterification of pure plant oil or waste vegetable oils, bio-ethanol from sugar or starch crops fermentation, and ethanol derivate ETBE (i.e. the t-butyl ether of ethanol). The most common first generation transport biofuel are listed below.

2.1.1. Vegetable oil

Vegetable oil can be used for either food or fuel. The potential to run engines on straight using vegetable oils (SVOs) dates back to the nineteenth century, notably to attempts by the famous German inventor, Rudolph Diesel leading to the successful development of his Diesel engine in 1895 [10]. In most cases, vegetable oil is used to manufacture biodiesel, which is compatible with most diesel engines when blended with conventional diesel fuel. First generation Straight Vegetable Oils (SVOs) include rapeseed, sunflower, soybean, palm and palm kernel oils.

2.1.2. Biodiesel

Biodiesel refers to a variety of ester-based fuels (fatty esters) generally defined as the monoalkylesters made from several different types of vegetable oils, such as soybean oil, canola or hemp oil, or sometimes from animal fats through a simple transesterification process. Oils are mixed with sodium hydroxide and methanol (or ethanol) and the chemical reaction produces biodiesel (FAME) and glycerol. One part glycerol is produced for every 10 parts biodiesel. Biodiesel can be used in any diesel engine when mixed with mineral diesel, but also in neat composition.

2.1.3. Bio-alcohol

Biologically produced alcohols, most commonly ethanol, but also propanol and butanol, are produced by the action of microorganisms and enzymes through fermentation of sugars or starches, or cellulose (which is more difficult). Biobutanol is often claimed to provide a direct replacement for gasoline because it can be used directly in a gasoline engine (in a similar way to biodiesel in diesel engines). Butanol is formed by ABE (acetone, butanol, ethanol) fermentation and experimental modifications of the process show potentially high net energy gains with butanol as the only liquid product. Butanol produces more energy and can probably be burned “straight” in existing gasoline engines (without modifications). It is less corrosive and less water soluble than ethanol, and could be distributed via existing infrastructures.

2.1.3.1. Ethanol fuel. Ethanol is the most common biofuel worldwide, particularly in Brazil and the USA, where it has been used in blends with ethanol (gasohol) for almost three decades. Ethanol fuels are produced by fermentation of sugars derived from wheat, corn, sugar beets, sugarcane, molasses

and any sugar or starch that alcoholic beverages can be made from (like cassava, potatoes and fruit waste, etc.).

The ethanol production methods used are enzyme digestion (to release sugars from stored starches, fermentation of the sugars, distillation and drying. These processes require significant energy input for heat (often provided by burning fossil fuels).

Ethanol has a higher octane rating than petrol and can be mixed with gasoline to any percentage and used in petrol engines as a replacement for gasoline [11]. However, this quality of the fuel can be exploited only if the compression ratio of engines is adjusted accordingly. Thus, most existing automobile internal combustion engines can run on blends of up to 15% bioethanol with petroleum gasoline. The oxygen content of ethanol also leads to higher efficiency, which results in a cleaner combustion process at relatively low temperatures. Compatibility problems between ethanol and some components of the engines such as some types of plastics or metals are well known and have been progressively solved. In high-compression engines, less ethanol, slower-burning premium fuel is required to avoid harmful pre-ignition (knocking).

Very-expensive aviation gasoline (Avgas) is 100 octane made from 100% petroleum. Again, ethanol cannot be transported in petroleum pipelines being corrosive. Therefore, more-expensive over-the-road stainless-steel tank trucks, which increase the cost and energy consumption required to deliver ethanol to the customer at the pump, have to be used. The life cycle assessment is not very bright when considering the total energy consumed in its production. Many car manufacturers are now producing flexible-fuel vehicles (FFVs), which can safely run on any combination of bioethanol and petrol, up to 100% bioethanol.

2.1.3.2. Methanol fuel. Methanol is currently produced from natural gas, a non-renewable fossil fuel but can also be produced from biomass as biomethanol. The methanol economy is an interesting alternative to the hydrogen economy, compared to today's hydrogen produced from natural gas, but not hydrogen production directly from water and state-of-the-art clean solar thermal energy processes.

2.2. Second generation biofuel

Second generation biofuel technologies have been developed to overcome some important limitations of first generation biofuel, notably their use as food. Moreover, the first generation energy crops also require high agricultural inputs in the form of fertilizers, which limit the greenhouse gas reductions that can be achieved. They are not cost competitive with existing fossil fuels such as oil, and some of them produce only limited greenhouse gas emissions savings.

There is a great deal of interest in using tree biomass for second generation biofuel. In addition to being an obvious source of sustainable supply when methods are developed for breaking down the plant matter cheaply and effectively, trees also contain more carbohydrates, the raw material for biofuel, than food crops. Genetic Modification (GM) technology is

being used to try to reduce the level of lignin in trees and change the structure of the hemicellulose.

The general aim is to reduce the cost of ethanol production and increase the volume so that it can compete with fossil fuels on price without needing subsidy. Willow, poplar and eucalyptus are major targets for research.

2.2.1. Cellulosic ethanol

This type of fuel is derived from non-food crops or inedible waste products, which have less of an impact on food, such as switch grass, sawdust, rice hulls, paper pulp, wood chips, etc. Lignocelluloses is the “woody” structural material of plants. This feedstock is abundant and diverse, and in some cases (like citrus peels or sawdust) it poses a significant industry-specific disposal problem.

Producing ethanol from cellulose is a more difficult and expensive additional step, technical problem to solve. Ruminant livestock (like cattle) eat grass and then use slow enzymatic digestive processes to break it into glucose (sugar). Lignocellulosic ethanol is made by freeing the sugar molecules from cellulose using enzymes (proteins that by lowering the activation energy accelerate chemical reactions). Cellulose and lignin are complex carbohydrate molecules based on sugar, which are found in all plants. These sugars can then be fermented to produce ethanol in a similar way to first generation bioethanol production. The by-product of this process is lignin, which can be burned as a carbon neutral fuel to produce heat and power for processing plants and possibly for surrounding homes and businesses.

The greenhouse gas emissions savings for lignocellulosic ethanol are greater than those obtained by first generation biofuels. Lignocellulosic ethanol can reduce greenhouse gas emissions by around 90% when compared with fossil petroleum [12]. A demonstration-scale lignocellulosic ethanol production plant in Canada produces around 700,000 l of bioethanol each year. Many other lignocellulosic ethanol plants have been proposed in North America and around the world. In the future, there might be bio-synthetic liquid fuel available. It can be produced by the Fischer-Tropsch process, also called Biomass-To-Liquids (BTL).

2.2.2. Impact of second generation biofuel on ecosystems, the carbon cycle and the global climate

Large-scale use of biomass for second generation biofuel means constant supply of large amounts of wood, grasses, and “plant waste”. The removal of organic residues from fields will require greater use of nitrate fertilizers, thus increasing nitrous oxide emissions, nitrate overloading and its devastating impacts on biodiversity, on land, freshwater and in the oceans. It is also likely to accelerate top soil losses. The removal of dead and dying trees from managed forests is already leading to large-scale biodiversity losses, and also to lower carbon sequestration in forests. On the other hand, growing millions of hectares of land under perennial crops for bioenergy will put intense pressure on land both for food production and for natural ecosystems.

There have been suggestions that bio-diverse prairie or meadow grasses could offer the most productive feedstock for second generation biofuel. There is no doubt that such healthy bio-diverse ecosystems contain more biomass than intensively farmed monocultures. However, the technical hurdles for using such multiple feedstocks are considerably greater than for using monoculture feedstock. A mix of different enzymes will be required to break down the different plant materials effectively, which will be far more complicated than breaking down one particular feedstock.

R&D investment is very clearly biased in favor of genetically modified monocultures, rather than native, bio-diverse grass mixes. Furthermore, most projections for land requirements together with falling per-hectare grain yields will result in more pressure on land to produce the same amount of agro fuels. In view of the foregoing, it can be stated that there is no evidence that large-scale second-generation biofuel would be either sustainable or climate-friendly.

3. Third generation biofuel sources

In order to ameliorate the problems often associated with land-based biofuel feedstock, there have been calls for the adoption of third generation biofuel sources, which require much less land and can be applied for reducing CO₂ emissions into the atmosphere. Particularly, biofuel derived from Aquatic Microbial Oxygenic Photoautotroph (AMOPS), more commonly referred to as cyanobacteria, algae and diatoms [13] have been advanced as a more sustainable resource that could address the global fuel demands without affecting food supply in the developing countries.

Of these, biofuel from algae appear to have greater prospects being the only renewable energy source that could meet global demand for transport fuels while addressing the carbon build-up and global warming issues at the same time. This has created unprecedented interest in algaculture (farming algae) for the production of transport biofuel.

3.1. Algae as a biomass resource

Recently, algae have become the latest feasible source being targeted for biofuel production since they exhibit several attractive features [14–16]. According to experts, algae grow 20–30 times faster than food crops, contain up to 30 times more fuel than equivalent amounts of other biofuel sources such as soybean, canola, jatropha or even palm oil, and can be grown almost anywhere. Studies show that they can also produce up to 60% of their biomass in the form of oil or carbohydrates, from which biofuel and many other industrially important products can be obtained. Most importantly, algae require CO₂ to grow, which implies they can be used for bio-fixation and bioremediation. As they grow, the oil is harvested for fuel while the remaining green mass by-product can be used in fish and oyster farms.

In fact, algae could yield up to 10,000 gal per acre (about 94,000 l per ha) of biofuel per year while corn would only yield

60 gal per acre (about 560 l per ha) annually. The potential use of algae for CO₂ sequestration is depicted in Fig. 1.

Research and scientific studies carried out at several universities and research institutes around the world regarding the benefits and potentials of algaculture have proven that algae can provide future global energy needs in a sustainable and cost-effective way.

In comparison with other renewable energy sources such as wind, solar, geothermal, tidal energy etc., algae derived energy is more controlled and stable compared to land based biomass, algaculture has the potential to produce larger amounts of biofuel with no fertile land or good water use. In spite of all these, the major obstacle militating against the widespread utilization of algae for biofuel production remains their high cost of cultivation.

Although there is extensive global experience in commercial scale growth of food-grade AMOPS in several countries worldwide [13,18], this experience is limited to open pond systems usually not bigger than 5 ha. Van Hamelen and Oonk [19], who carried out a techno-economic feasibility study of large-scale cultivation of microalgae concluded that the net revenues accruable from a 100 t/ha yr microalgae production system ranges from Euro –415 (worst case) to Euro 210 (best case). Such wide variations only suggest that there are still uncertainties regarding the large scale application of algae for energy production.

Although the process of growing, harvesting and converting algae into fuel and other important products in an economically competitive manner is still being perfected, the following advantages are often attributed to algae:

- They can be grown almost anywhere, even on sewage or salt water, and do not require fertile land or food crops.
- They are very efficient and can be made cost-effective with more effort.
- Algae are very energy and oil dense with a very high yield per acre and sequester CO₂ permanently while growing,
- They only require sunlight and water which is not suitable for drinking or farm use,
- They only take hours to reproduce, since they have a high photon conversion efficiency,
- Algae are very eco-friendly being non-toxic, do not contain sulfur, and are very biodegradable.

For more than three decades, researchers in the US Aquatic Species Program (ASP) investigated the use of algae for the production of energy. Initially, the group focused its attention on the production of hydrogen but later during the year 1982, their primary research objective shifted to study the oil production [20,21]. The ASP grew algae in open pond test sites in Hawaii, California and New Mexico and achieved maximum yields of more than one hundred times that of oil palm. From 1982 through their culmination, the majority of the program research was focused on the production of transport fuels, notably biodiesel, from algae. However, all research activities were stopped in 1996. The report entitled “A Look

Back at the U.S. Department of Energy’s Aquatic Species Program: Biodiesel from Algae” [22] indicates that algae-based biofuel hold great promise due to their enormous energy potential.

From 1990 to 2000 the Japanese RITE (Research Innovative Technologies of the Earth) program for microalgae biofixation of CO₂, supported by MITI (Ministry of International Trade and Industry) was executed [23]. This 10 year effort, involved over 20 private companies and several government research institutions, in parallel efforts to develop closed photobioreactor technologies for the production of high value products using power plant flue gas for CO₂.

The program focused on the development of so-called optical fiber photo-bioreactors, which use concentrating mirrors to collect light that is injected into a bioreactor by means of light guides of various designs, although other closed photobioreactors were also investigated.

However, although these R&D efforts were not continued, partly because of the very unfavorable economic projections for such approaches, research along similar lines continues presently elsewhere [24–26]. Recent commercial developments in microalgae biotechnology have been the mass cultivation of several novel algal species, in particular *Haematococcus pluvialis*, a source of the carotenoid astaxanthin, used in salmon aquaculture and also in food supplements. Although all large-scale algal production systems use open ponds, a number of small-scale commercial production systems using closed photo-bioreactors have been established. A conceptual integrated approach to algae cultivation and utilization highlighting coupling options for algaculture was described by Cristi (Fig. 2).

3.1.1. Types of algae

Research into algae for the mass-production of oil is mainly focused on microalgae—organisms capable of photosynthesis that are less than 0.4 mm in diameter, including the diatoms and cyanobacteria; as opposed to macroalgae, e.g. seaweed. However, some research is being done into using seaweeds for biofuel, probably due to the high availability of this resource [27].

This preference towards microalgae is due largely to its less complex structure, fast growth rate, and high oil content (for some species). There are more than 100,000 strains of algae, with differing ratios of three main types of molecule: oils, carbohydrates and protein. Strains of algae high in carbohydrates as well as oils produce starches that can be separated and fermented into ethanol; the remaining proteins can be turned into animal grains.

The following species are currently being studied for their suitability as a mass-oil producing source, across various locations worldwide [28–30]: i. *Botryococcus braunii*, ii. *Chlorella*, iii. *Dunaliella tertiolecta*, iv. *Gracilaria* and v. *Pleurochrysis carterae* (also called CCMP647).

3.1.2. Methods of cultivation and yield

Algae-growing facilities can be built on coastal land unsuitable for conventional agriculture. The hard part about

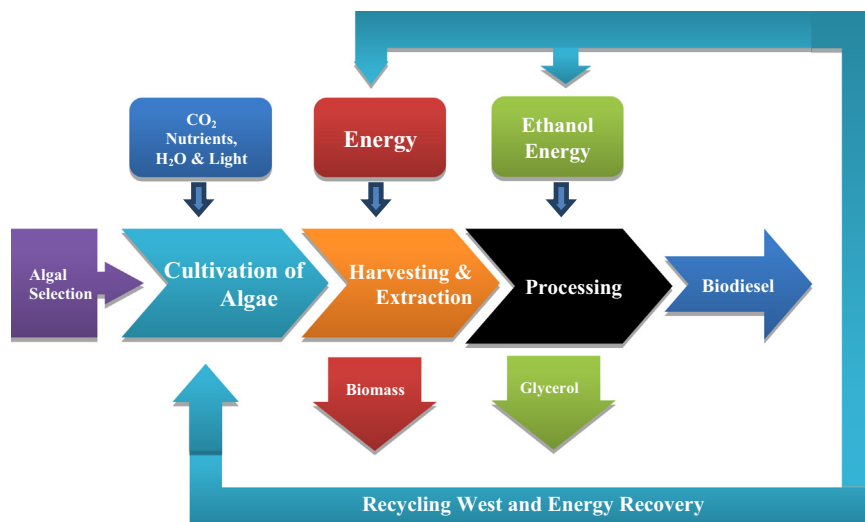


Fig. 2. Schematic presentation of various steps of algal biodiesel.

algae production is growing the algae in a controlled way and harvesting them efficiently. If all aspects of the cultivation are controlled—temperature, CO₂ levels, sunlight and nutrients (including carbohydrates as a food source), then extremely high yields can be obtained. Microalgae cultivation using sunlight energy can be carried out in open ponds, covered ponds or closed photobioreactors, based on tubular, flat plate or other designs [20].

Closed systems are much more expensive than ponds, and present significant operating challenges (overheating, fouling), and due to gas exchange limitations, among others, cannot be scaled-up much beyond about a hundred square meters for an individual growth unit. Large-scale biofuel production comprising systems of hundreds of hectares in scale would obviously require deploying tens of thousands such repeating units, at great capital and operating cost.

Open ponds, specifically mixed raceway ponds are much cheaper to build and operate, can be scaled up to several hectares for individual ponds and are the method of choice for commercial microalgae production. However, such open ponds also suffer from various limitations, including more rapid (than closed systems) biological invasions by other algae, algae grazers, fungi and amoeba, etc., and temperature limitations in colder or hot humid climates. The hydraulics (e.g. dispersion and mass transfer coefficients) of large ponds are also uncertain. Nevertheless, about 98% of commercial algae biomass production is currently with open ponds, even for high value nutritional products, which sell for prices over a hundred and even a thousand-fold higher than allowable for biofuel.

Algae can also grow on marginal lands, such as in desert areas where the groundwater is saline, rather than utilize fresh water. Given the right conditions, algae can double its volume overnight and are capable of yielding 15–25 t dry biomass per hectare per annum [31]. Unlike other biofuel feedstock, such as soya or corn, it can be harvested day after day. Up to 50% of an alga's body weight is comprised of oil, whereas oil

palm trees currently the largest producer of oil to make biofuel yield just about 20% of their weight in oil.

3.1.2.1. Nutrients. Nutrients like nitrogen (N), phosphorus (P) and potassium (K) are important for plant growth and are essential parts of fertilizer. Silica and iron, as well as several trace elements, may also be considered important marine nutrients as the lack of one can limit the growth or productivity [32]. A possible nutrient source for algae is waste water from the treatment of sewage, agricultural, or flood plain run-off, all currently major pollutants and health risks. However, this waste water cannot feed algae directly and must first be processed by bacteria, through anaerobic digestion. If waste water is not processed before it reaches the algae, it will contaminate and possibly kill much of the desired algae strain.

Anaerobic digestion of wastewater (similar to other organic waste) produces a mixture of carbon dioxide, methane, and organic fertilizer. Since the organic fertilizer that comes out of a digester is liquid, and nearly suitable for algae growth, it must first be cleaned and sterilized.

3.1.2.2. Photobioreactors. Apart from cleaning up algae from existing sewage plants and waterways before processing into fuel grade products, algae can be cultivated for energy. Indeed, most companies pursuing algae as a source of biofuel are pumping nutrient-laden water through plastic tubes (called “bioreactors”) that are exposed to sunlight (and so-called photobioreactor or PBR). Photobioreactors are of flat plate, tubular and vertical column types. Running a PBR is more difficult and also costlier than an open pond.

Recent researches aimed at improving the efficiency of photo-bioreactors [33,34] have shown that the key to greater yields of up to 100 gm dry mass m⁻² h⁻¹ is a pronounced heightening of algal flux tolerance, which is achievable by tailoring the photonic temporal, spectral and intensity characteristics with pulsed light emitting diodes.

Advances in ultra-efficient concentrator photovoltaic, as well as high performance light emitting diodes, create a practical reality for converting sunlight into pulsed red light and delivering it to indoor photobioreactors resulting in very high dark reactions of photosynthesis.

3.1.2.3. Closed loop system. In a closed system (not exposed to open air) there is not the problem of contamination by other organisms blown in by the air. The problem for a closed system is finding a cheap source of sterile carbon dioxide (CO₂). Some researchers have found the CO₂ from a smoke-stack works well for growing algae [35]. To be economical, some experts suggest that algae farming for biofuel will have to be sited next to power plants, where they can also help soak up the pollution. Although the closed loop systems are cheaper than PBRs, they are costlier than open ponds.

3.1.2.4. Open ponds. Open-pond systems for the most part have been given up for the cultivation of algae with high-oil content [36]. Open systems using a monoculture are vulnerable to viral infection. The energy that a high-oil strain invests into the production of oil is energy that is not invested into the production of proteins or carbohydrates, usually resulting in the species being less hardy, or having a slower growth rate. Algal species with lower oil content, not having to divert their energies away from growth have an easier time in the harsher conditions of an open system. In general, open ponds constitute the cheapest method of producing algae in large quantities.

3.2. Algae derived biofuel

Microalgae have much faster growth rates than terrestrial crops. The per unit area yield of oil from algae is estimated to be between 25,000 and 50,000 l per hectare per year, although there are claims of higher yields of up to 100,000 l per hectare per year. Studies show that algae can produce up to 60% of their biomass in the form of oil because the cells grow in aqueous suspension where they have more efficient access to water, CO₂ and dissolved nutrients. Many fuel grade products can be obtained from algae.

3.2.1. Hydrogen production

The potential of algae to be used as “microscopic power plants” was first discovered by Hans Gaffron, who observed in 1939 that the algae would for a then unknown reason sometimes switch from producing oxygen to instead creating hydrogen, but only for a short period of time [37]. It was only during the year 1999 when Professor Tasios Melis, along with researchers from the National Renewable Energy Laboratory (NREL), discovered that depriving the algae of sulfur and oxygen would enable it to produce hydrogen for sustained periods of time.

Generally, there are three methods by which hydrogen can be produced from algae, namely biochemical process, gasification and steam reforming.

- Biochemical processes—A microscopic green algae (known as *Chlamydomonas reinhardtii*, or pond scum) split water into hydrogen and oxygen under controlled conditions. Under these conditions, enzymes in the cell act as catalysts to split the water molecules. A recent breakthrough in controlling the algae's hydrogen yield has prompted interest in commercialize scale H₂ production from algae.
- Gasification of algal biomass—During gasification, biomass is converted into a gaseous mixture comprising primarily of hydrogen and carbon monoxide, by applying heat under pressure in the presence of steam and a controlled amount of oxygen. A number of methods are available for the separation of H₂ from syngas [38–40].

Steam reformation of methane—Fermentation of algal biomass produces methane. The traditional steam reformation (SMR) techniques can be used to derive hydrogen from methane. Steam reforming is the most common method of producing commercial bulk hydrogen as well as the hydrogen used in the industrial synthesis of ammonia. It is also the least expensive method. At high temperatures (700–1100 °C) and in the presence of a metal-based catalyst (nickel), steam reacts with methane to yield carbon monoxide and hydrogen [41,42].

Although algal hydrogen production has been extensively researched for decades, no mechanism that could plausibly be scaled up has yet been demonstrated, even in the laboratory, and is, thus, not further addressed at the moment.

3.2.2. Straight vegetable oil and biodiesel production

At an average annual growth rate of 42%, the global biodiesel market is estimated to reach about 168 billion liters by 2016 [43]. In order to meet the rapid expansion in biodiesel production capacity, observed not only in developed countries but also in developing countries such as China, Brazil, Argentina, Indonesia and Malaysia, other oil sources especially non-edible oils need to be explored [44]. A comparison of the oil yield of various crops with algae (Table 1) shows that

Table 1
Comparison of crop dependent biodiesel production efficiencies from plant oils. Source [45].

Plant source	Bio-diesel L/ha/yr	Area to produce global oil demand (10 ⁶ ha)	Area required as % of global land mass	Area as % of arable land mass
Cotton	325	15,002	100.7	756.9
Soybean	446	10,932	73.4	551.6
Mustard seed	572	8524	57.2	430.1
Sunflower	952	5121	34.4	258.4
Rapeseed	1190	4097	27.5	206.7
Jatropha	1892	2577	17.3	130
Oil palm	5950	819	5.5	41.3
Algae	12,000	406	2.7	20.5
(10 gm ⁻² day ⁻¹ at 30% TAG)				
Algae	98,500	49	0.3	2.5
(50 gm ⁻² day ⁻¹ at 50% TAG)				

microalgae seems to be the only source of renewable biodiesel that has the potential to completely displace petroleum-derived transport fuels without the controversial “food for fuel” conflicts [45].

The algal-oil feedstock that is used to produce biodiesel can also be used for fuel directly as “Straight Vegetable Oil” (SVO). The benefit of using the oil in this manner is that it requires no additional energy for transesterification, (processing the oil with an alcohol and a catalyst to produce biodiesel). The drawback is that it does require modifications to a normal diesel engine. Trans-esterified biodiesel can be run in an unmodified modern diesel engine, provided the engine is designed to use ultra-low sulfur diesel. The algal oil feedstock that is used to produce biodiesel can also be used for fuel directly as “Straight Vegetable Oil” (SVO). The benefit of using the oil in this manner is that it requires no additional energy for transesterification, (processing the oil with an alcohol and a catalyst to produce biodiesel). The drawback is that it does require modifications to a normal diesel engine. Trans-esterified biodiesel can be run in an unmodified modern diesel engine, provided the engine is designed to use ultra-low sulfur diesel.

The difficulties in efficient biodiesel production from algae lie in finding an algal strain with a high lipid content and fast growth rate that is not too difficult to harvest, and a cost-effective cultivation system (i.e. type of photobioreactor) that

is best suited to that strain. There is also a need to provide concentrated CO₂ to turbocharge the production.

3.2.3. Biobutanol

The green waste left over from the algae oil extraction can be used to produce butanol. This fuel has an energy density similar to gasoline and greater than that of either ethanol or methanol. It can be used in most gasoline engines in place of gasoline with no modifications. In several tests, butanol consumption is similar to that of gasoline and when blended with gasoline, provides better performance and corrosion resistance than that of ethanol or E85 [46].

3.2.4. Biogas (methane) and bioethanol

Methane was the focus of most of the early work in microalgae biofuel production when microalgae were considered mainly for their applications in wastewater treatment. Anaerobic digestion of algal biomass remains an option, but the higher value of liquid transportation fuels from microalgae has been the focus of most attention on algae oil, specifically biodiesel production since the 1980s, after the first oil shocks. Corn and sugarcane are currently the most common commercially viable sources of ethanol fuel production but growing demand for corn and sugarcane due to the expansion of ethanol has increased concerns that environmentally sensitive lands will return to production. In addition, the use of corn for ethanol greatly reduces its availability for food products, thus generating higher food prices for consumers.

Some researchers who have studied the concept of ethanol production with algae assert that ethanol production from microalgae has many inherent limitations [46,47]. The possibilities are to either have the algae themselves directly produce ethanol by photosynthesis or alternatively to accumulate large amounts of starch and then metabolize this to ethanol. In either case, the ethanol would need to be excreted into the growth medium at very high levels to allow its recovery. These would be daunting challenges for even advanced genetic engineering techniques.

More simply would be the production of starch by microalgae and its subsequent fermentation by yeasts as practiced with cane sugar and corn starch in fuel ethanol production.

Table 2
Break-even crude oil prices of established biofuel technologies. Source [8,50,51].

Biofuel technologies (Feedstock)	Break even crude oil price (US \$)
Brazilian bioethanol (SugarCane)	40.00
American bioethanol (Corn)	60.00
EU bioethanol (sugar beet and wheat)	SE Asian biodiesel (palm oil) 100.00–120.00
US biodiesel (soybean oil)	Biofuels from algae 52.00–91.00
EU biodiesel (canola oil)	71.60

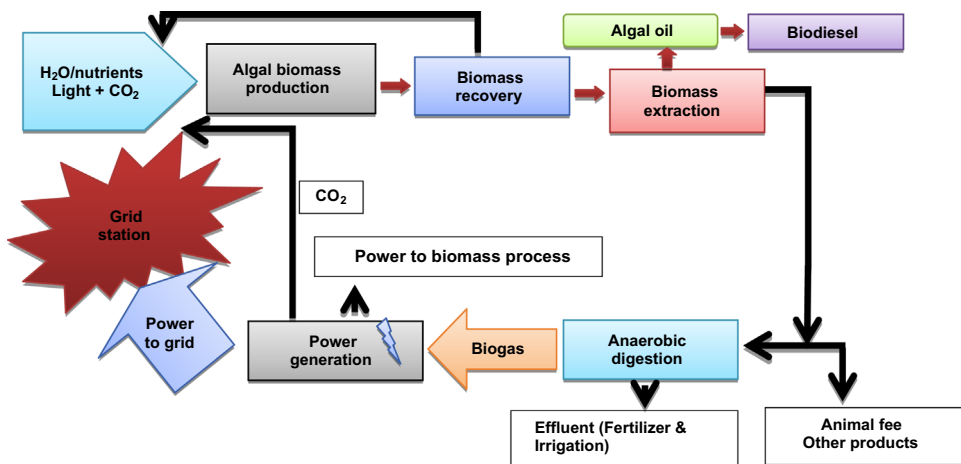


Fig. 3. Possible coupling options for algalculture.

Such an approach, however, would compete with very low cost sugar and starch produced by higher plants.

3.2.5. Jet fuel

Commercial application of algae derived jet fuel was further buttressed when on January 8, 2009; Continental Airlines ran the first test for the first flight of an algae-fueled jet. The test

was done using a twin-engine commercial jet consuming a 50/50 blend of biofuel and normal aircraft fuel. A series of tests executed at 38,000 ft (11.6 km), including a mid-flight engine shutdown, showed that no modification to the engine was required. The fuel was praised for having a low flash point and sufficiently low freezing point issues that have been problematic for other biofuel [48].

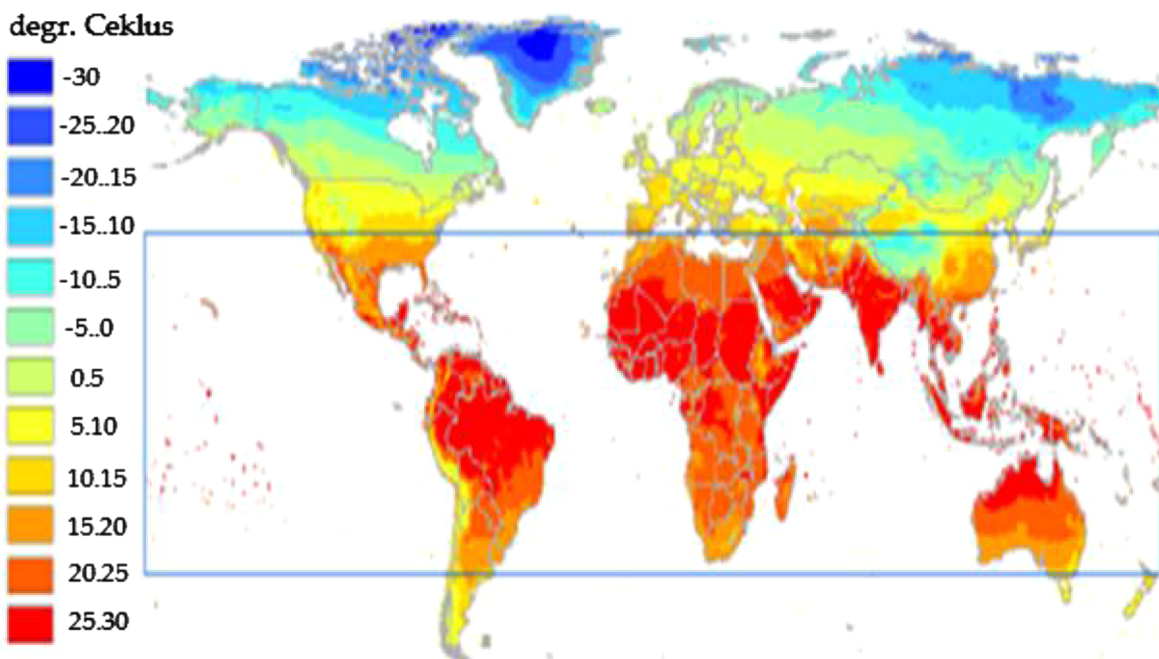
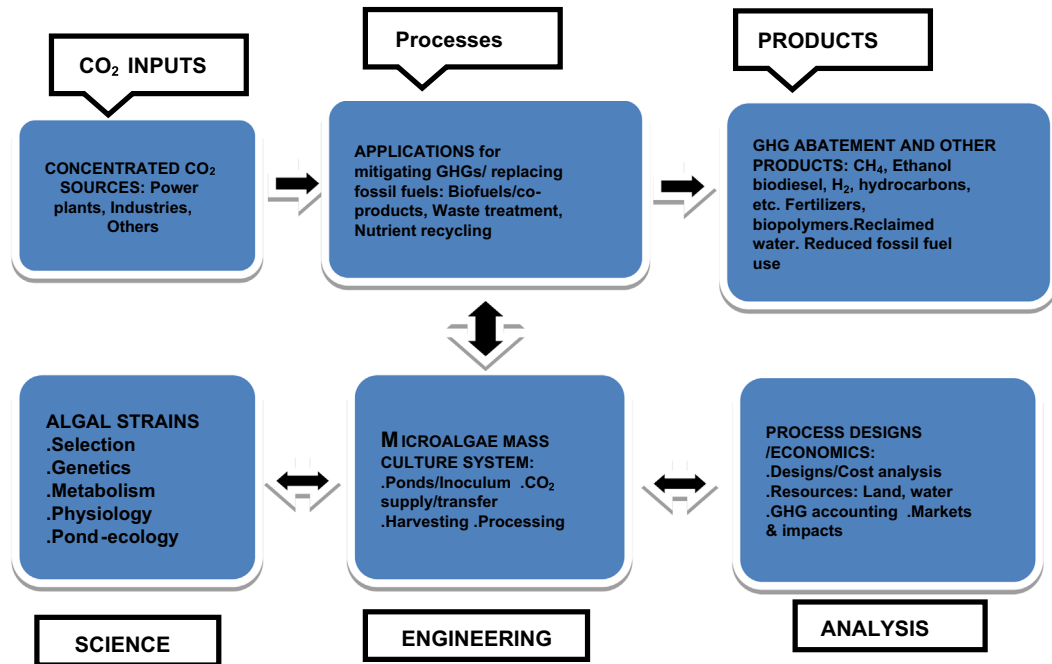


Fig. 4. (a) Various inputs for economically viable algaculture. Source [17]. (b) Worldwide potential of microalgae production. Source [19].

3.3. Problems and prospects of algaculture

The major constraint to commercial-scale algae farming for energy production is the cost factor. An economic environment that can support low production costs, research expertise in marine algae and in the conversion to a useful energy product, may all be key to the development of a commercially-viable algae-to-energy enterprise, which would produce an abundance of low cost fuel. However, there have been reports recently of breakthroughs in this direction. For instance, under an exclusive worldwide license, Diversified Energy will provide systems engineering and project management to commercialize the technology which could achieve profitable oil production costs of only \$0.08–0.12/pound (about \$0.18–0.26 per kg) [49–51].

Break even prices of crude oil needed to support existing biofuel technologies are shown in Table 2, whereas various inputs required for an economically feasible algae production are presented in Fig. 3.

3.3.1. Economics of algae cultivation

Overall capital and operating cost of algae cultivation systems is another critical issue. Prior economic engineering feasibility analyses have concluded that even the simplest open pond systems, including harvesting and algal biomass processing equipment, would cost at least \$100,000 per hectare, and possibly significantly more [20]. To this would need to be added operating costs. As of today, it can be rightly argued that current commercial algae production is very small scale and inefficient, and that the economies of scale possible for biofuel production as well as foreseeable advances in technology, could reasonably overcome this gap. R&D activities will be required to demonstrate that it is actually possible to mass culture algae for maximal oil productivity and harvest them cheaply, which would reduce the cost of such algal biomass production to an acceptable level.

3.3.2. Algae for biofixation and waste water treatment

Bio-fixation, especially waste water treatment appears to be the most feasible near-term application of algae cultivation. Climatic conditions, temperature, sunlight availability etc. will play an important role in alga culture development, based upon the report on global assessment of the regional potentials for microalgae production on wastes, locations with suitable climatic conditions and annual average temperature of 15 °C or higher, are shown in Fig. 4a and b.

Large scale algae cultivation for biofuel production in the medium term (next 10 years) appears more feasible when considered along with derived higher value co-products such as bio-fertilizers, biopolymers, nutritional supplements etc. However, with more R&D into the adaptation of more resistant algae strains and other cost saving measures, dedicated biofuel systems could become economically justifiable in the long term (15–20 years or more from now) [19].

4. Conclusion

The limitations of first and second generation biofuel resources show clearly that they are grossly inadequate to meet global demands for transport fuels in a sustainable way. Although, the use of microalgae for production of third generation biofuel has been studied for many years now, the fact remains that R&D activities still need to be undertaken to reduce the production cost of algal biomass to an acceptable level that could compete favorably with biomass from higher plants before commercial algae-for-energy cultivation can commence. Algae production technologies are quite mature but presently only its application for bio-fixation, especially wastewater treatment is economically feasible. Open pond cultivation method, specifically mixed raceway ponds, being much cheaper to build and operate, can be scaled up to several hectares for individual ponds and thus appear to be the method of choice for commercial microalgae production. Biofuel production from algae will become competitive in the medium term if considered along with production of higher value co-products such as bio-fertilizers, biopolymers etc.

Dedicated biofuel production from large scale algae cultivation appears to be more feasible in the long term when results of R&D efforts currently being made will have reduced the overall production cost.

Although the break even oil price for biofuel production from algae (\$52–91) is higher than most established bioethanol and biodiesel production from higher plant sources, it appears more feasible than the current European Union bioethanol production based on wheat and sugar beet.

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