Techno-Economic Analysis of Autotrophic Microalgae for Biofuel Production in India

تحليل تقني واقتصادي لفعالية استخدام الطحالب ذاتية التغذية لإنتاج الوقود الحيوي في الهند

By

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ABSTRACT

Modern society relies on non-renewable sources of energy which is the dominant source of energy, which accounts for nearly 84% of the overall increase in demand between 2005 and 2030 (Khan et al., 2009). The energy requirements are estimated to grow by 55% between 2005 and 2030, according to The International Energy Agency (2011). There is an increased demand for transportation of industrial and agricultural goods in India and more than three-quarters of the petroleum demands are met through imports (Khan et al., 2009). Exhaustion of the global petroleum reserve combined with the growing concern about environmental quality, particularly climate change has increased the search for alternate sources of energy.

With the rapid increases in fossil fuel prices combined with the need for sustainable alternatives has brought microalgae as a source of biofuel back into the research and development (R&D) limelight. Microalgae as a feedstock for biofuel production are attractive as it is a source of clean and renewable energy. Unlike first generation crops, algae do not come into conflict with the food supply. The process of producing biodiesel from carbon neutral biomass can contribute significantly to the development of the rural economy by providing a non-polluting, biodegradable and safe environment (Khan et al., 2009).

However, there are certain technical and economic challenges associated with the microalgae biofuel industry that limits the widespread use of this technology despite several efforts that have been made to solve these problems over the past several decades. For algae biofuels to substitute the fossil fuel industry and ensure sustainable and efficient energy production, distribution and use, a whole new set of technology-related materials and infrastructure needs to be set up to ensure that post-harvest losses are minimized with increased sustainability. The combination of generating energy from wastewater treatment along with a sustainable nutrient cycling addresses the reduction in greenhouse gas emission and the production of biofuels with long term sustainability. Providing long-term targets and supporting policies that stimulate investment in the production of algae biofuels can improve the economic situation. The main focus of this paper is to identify the challenges related to the sustainable production and commercialization of microalgae biofuel.

المجتمع الحديث يعتمد على المصادر الغير متجدده للطاقه والتي هي المصدر الرئيسي للطاقة و التي تمثل تقريبا 84 % من الزيادة الإجمالية في الطلب بين عامين 2005 و 2030 (Khan et al., 2009) . وتقدر ان تنمو الاحتياجات من الطاقه بنسبة 55 % بين عامين 2005 و 2030, طبقا لوكالة الطاقة الدولية (2011). هناك زيادة في الطلب على نقل البضائع الصناعية والزراعية في الهند وأكثر من ثلاثة أرباع مطالب المواد البترولية يتم تلبيتها من خلال الواردات (Khan et al., 200) . ان استنزاف احتياطي البترول العالمي بجانب القلق المتزايد حول جودة البيئة و خصوصا تغير المناخ زاد من البحث عن مصادر بديلة للطاقة.

مع الزيادة السريعة في أسعار الوقود الحفري بجانب الحاجة إلى بدائل مستدامة؛ جلبت الطحالب تحت الأضواء كمصدر للوقود الحيوي مرة أخرى في البحث والتطوير حيث ان الطحالب كمادة وسيطة لإنتاج الوقود الحيوي تعتبر جذابة لأنها مصدر للطاقة النظيفة والمتجددة على عكس محاصيل الجيل الأول ,الطحالب لا تتعارض مع الإمدادات الغذائية.
إن عملية إنتاج وقود الديزل الحيوي من الكتلة الحيوية محايد الكربون يمكن أن تسهم بشكل كبير في تنمية الاقتصاد الريفي من خلال توفير بيئة غيرملوثة وقابلة للتحلل وآمنة (Khan et al., 2009).

ومع ذلك، هناك تحديات تقنية واقتصادية معينة مرتبطه بصناعة الوقود الحيوي من الطحالب والتي تحد من انتشار استخدام هذه التكنولوجيا على الرغم من العديد من الجهود التي بذلت من أجل حل هذه المشاكل على مدى العقود العديدة الماضية.
اما بالنسبه للوقود الحيوي من الطحالب لكي يستبدل صناعة الوقود الحفري ويضمن إنتاج مستدام وفعال للطاقة وايضا لكي يتم ضمان توزيعه واستخدامه يجب تأسيس و إنشاء مجموعة جديدة كاملة من المواد المتعلقة بالتكنولوجيا والبنية الأساسية لضمان أن يتم الحد من خسائر ما بعد الحصاد مع زيادة الاستدامة.

ان المزيج من توليد الطاقة من معالجة مياه الصرف الصحي بجانب تدوير المغذيات المستدامة تعالج الانخفاض في انبعاثات غازات الاحتباس الحراري و ايضا إنتاج الوقود الحيوي مع الاستدامة على المدى الطويل. ان توفير الأهداف طويلة الأجل والسياسات الداعمة التي تحفز الاستثمار في إنتاج الوقود الحيوي من الطحالب يمكن أن تحسن الوضع الاقتصادي .

التركيز الرئيسي لهذا البحث هو تحديد التحديات المتعلقة بالإنتاج المستدام والتسويق للوقود الحيوي من الطحالب.

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1. INTRODUCTION

1.1 Background and Context

For many hundreds of years, biomass was the predominant fuel available to the human civilization to provide for food, shelter and energy. The birth of Industrial revolution in the 18^{th} century significantly changed the fate of biomass, as mankind could gain easy access to fuels that were buried in the earth for centuries. Coal and steam replaced wind, water and wood as primary sources of energy which improved productivity and technology. A massive increase in the use of fossil fuels made possible the development of new industries and transport causing a rapid growth in population and economy. Large numbers of people migrated from countryside to cities to seek economic opportunities. As Industrialization progressed, the relationship between humans and nature began to change dramatically, creating an environmental crisis which is now being recognized as a threat to humans and the global environment.

The Industrial revolution marks a turning point in human history. The most notable impact it had on the modern world is the increased growth in population. According to UNESCO (1999) the population has risen from roughly 3 billion to 6 billion from 1960- 1999, which means that the population has nearly doubled in less than 50 years and is expected to grow further. World population is projected to rise from 7 billion at the beginning of 2010 to 9.3 billion in 2050 (UNESCO, 1999). This unsustainable growth can have an enormous impact on human life as more the number of people, the more natural resources that will be needed for the existence. All of these concerns support the need for the development of alternative renewable and sustainable energy source.

As estimated by the World Energy Council, more than three-quarters (82%) of the world's energy demands are currently met by fossil fuels (Xueying, 2011). The fossil fuel is being depleted either by overuse or over exploitation and its continued consumption will make them unavailable for use by the future generation (Amin, 2009; Chisti, 2007). About 98% of CO_2 emissions results from burning of fossil fuels, mainly natural gas, oil and coal (Najafi et al., 2011). Despite countries agreeing to the Kyoto Protocol, there has been a rise in the consumption of fossil fuel which has led to a tremendous increase in the concentration of CO_2 in the atmosphere. The build-up of CO_2 and other greenhouse gases in the Earth's atmosphere induces a phenomenon called global warming, that affects the global environment (Mata et al., 2010). CO_2 is the primary greenhouse gas that is estimated to contribute to over one-third of any climate change. The greenhouse gases in the atmosphere continue to climb causing a substantial increase in temperature threating the existence of life on this planet.

Significant efforts are being made to reduce the dependence on fossil fuel resources through the introduction of energy efficient and renewable energy sources such as wind, solar and nuclear. Sustainable renewable energy sources are expected to play a crucial role in the world's future energy supply. (Demirbas et al.,2010). However, these technologies can only slow the build-up of CO_2 in the atmosphere and not reduce the emission to the required levels of almost 350ppm. Evidences show that, current CO_2 levels (about 385ppm) are too high and their side effects such as ocean acidification, loss of fresh water supplies and change in the climatic zone are beginning to seem inevitable (Hansen et al., 2008). According to Benemann (1997), the reduction of build-up of atmospheric CO_2 can be achieved by phasing out coal use except for cases where CO_2 can be captured and sequestered.

1.2 Indian Scenario

Like many developing countries, India has initiated programs to boost microalgae biofuel production, primarily with an aim to switch to cleaner source of energy and to offset the impact of high oil prices on the economy. The country has been relying on energy from fossil fuels, with most of its import from Middle East. According to a report by Ministry of Petroleum and Natural Gas (2007), India consumes more diesel fuel than gasoline as opposed to other countries. However, the demand for non-renewable sources of energy has shot up, due to the concern over global warming issues of climate change, leading to abnormal increase in crude oil prices. Figure 1.1 shows that the crude oil prices have risen by over 50% from 1990 to 2008, at an average growth rate of above 5% (Sudhakar et al., 2012). The government policy has been the major driving factor for the expansion of biofuels. All over the world, governments have implemented mandatory targets for use of biofuels in transportation fuels, creating guaranteed markets for biofuels for decades to come. In order to meet the growing demands, the government of India has initiated a programme called the National Biofuel Mission (NBM) in 2003 with an aim to ensure energy security with minimum damage to the environment, creating new employment opportunities, enhancing economic growth as well as greening of wastelands through cultivation of biofuel crops (GOI, 2009). In 2009, the National Policy on Biofuels was also released with an aim to mainstream biofuels by setting up targets for blending up to 20% of biofuel with petrol and diesel in the transport sector by the year 2017 (GOI, 2009). The main thrust is on the R&D with a focused attention on the plantation and production technologies of cellulosic biofuels. The program is to be carried out on non-edible feedstock that are cultivated exclusively on marginal or degraded wastelands unsuitable for agriculture, in order to avoid possible conflicts between the food versus fuel debate.

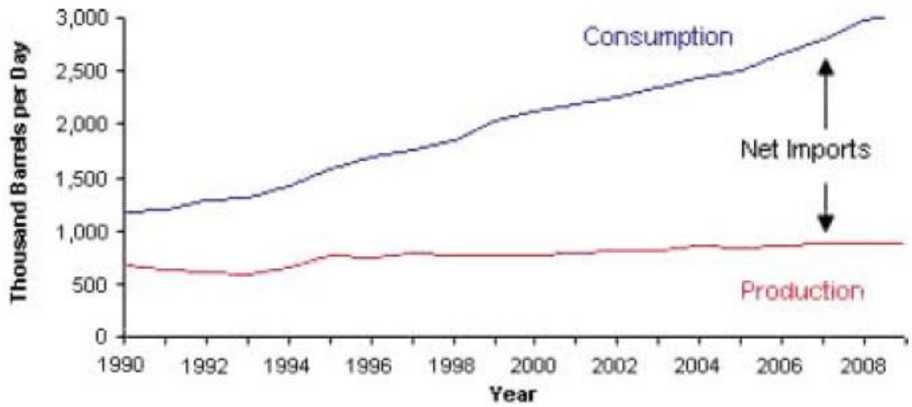

Figure 1.1: Crude oil consumption in India. Source: (Ministry of Petroleum and Natural Gas, Government of India, 2010)

With the rapid urbanization and industrialization of the modern industry, coupled with increasing import of fuel, there is a continued need for alternative source of energy. India is currently importing nearly 80 million tonnes of coal annually which is expected to increase to 150 million tonnes annually by 2017 (Venkatraman, 2012). Automobiles are the major consumers of petroleum (Khan et al., 2009). This constant world-wide demand for fossil fuels combined with concerns over the environment, has motivated researchers and developers to focus on renewable energy sources.

According to current research, biodiesel from microalgae seems to be a promising source of renewable energy. Microalgae biodiesel as a transportation fuel has grown in popularity over the past decade. The production of microalgae biodiesel in India is attractive for many reasons. The Indian government has been subsidizing the diesel prices rate in order to keep transport cost low and increase GDP. Additionally, vehicle manufacturing companies in India are investing heavily on the production of diesel cars (Bajhaiya et al., 2010).

India's tropical climate with the potential to create cheap feedstock serves as a natural benefit over other countries for the production of microalgae biodiesel (Figure 1.2). Algae can be grown in large-scale on the wastelands of India and has the potential to displace a portion of petro-fuels (Sudhakar et al., 2012). Algae can yield nearly 19000-57000 litres per acre as compared to first generation crops like palm that can produce nearly 2000-2500 litres per acre (Banerjee et al., 2002). The large scale production and consumption of microalgae biodiesel can significantly reduce the dependence on foreign countries for oil. Additionally, switching to renewable energy will also help improve the air quality, provide employment opportunities, reclaim unusable wastelands and in turn improve the economic growth on the country.

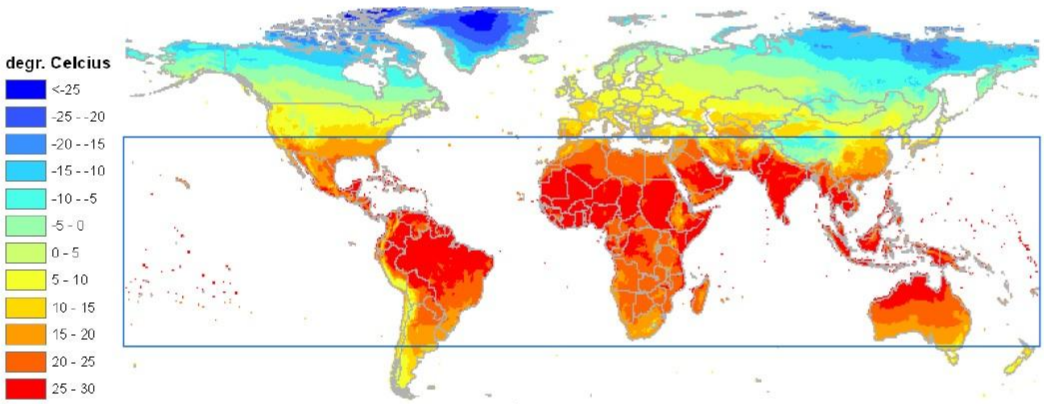

Figure 1.2: Areas suitable for microalgae cultivation corresponding to annual average temperature of more than 15ºC. Source: (Harmelen and Oonk, 2006)

The International Bioenergy Summit in 2012 sponsored by the Government of India united scientist and researchers for exploring new concepts, exchange of knowledge and innovation in technologies and government policies in an effort to promote the field of algae biofuels. The conference provided for a platform for communication and collaboration between academia researchers, professionals from industries and non-profit organizations, planners and policy makers. The vision was to create a guide to development and implementation of technologies and policies for biofuel production in India in the next five years. The aim of the guide was to accelerate sustainable deployment of biofuels by enabling policy makers, industry professionals and financial partners to identify and implement the necessary steps required in the development of the technology (TERI, 2012).

1.3 Algae biofuel producers in India

Algae-based biofuels could be the answer to India's energy crisis and heavy dependence on coal import. Several companies and research institutes in India are focusing on the large scale commercial production of biodiesel from algae. A national bio-diesel board has been created with an aim to support and promote organizations active in the field of oil-seed cultivation and production by providing them incentives and other financial support.

EWBioFuel & ReEnergy (I) Pvt. Ltd. headquartered in Gujarat is the first company to commercially produce biodiesel from algae in India and Asia-pacific region. The company specializes in advanced gasification techniques with expertise in designing and delivering innovative technology solutions for government and commercial users. Production of 50,000 gallons per acre is being achieved currently. Current research on genetically modified algae strains cultivated in closed photobioreactors is expected to increase production by two-fold. Also headquartered in Gujarat is *Altret Greenfuels Ltd*. This is the only company to produce large quantities of different algae and markets it to national and international clients.

Radhe Renewable Energy Development Pvt. Ltd. founded in 1998 and headquartered in Gujarat, focuses on R&D, manufacturing and marketing of non-conventional & renewable energy equipment, i.e. Biomass, Coal Gasifier and Fluidized Hot Air Generator (Direct and Indirect). The company has a R&D center approved by the government focusing on developing new applications. The center is equipped with modern facilities to carry out research on algae to liquid fuels, fluidized bed gasifier and efficient dryers.

National Institute of Ocean technology (NIOT), Chennai was established in 1993 with an aim to provide world class technologies for utilizing ocean water for algae cultivation. Also headquartered at Chennai is the *Krishnamurthy Institute of Algology* which focuses on providing infrastructural facilities for students researching on microalgae biofuels. The institute specializes in collecting and analyzing marine and freshwater algae vegetation for maintenance at their research facility. The institute is in collaboration with *Vivekananda Institute of Algology* (VIAT) and *Phycospectrum Consultants Pvt Ltd*. both headquartered at Chennai. VIAT and *Phyco Spectrum Consultants Private Ltd*. are dedicated to the research and development in algae based activities with an aim to mitigate pollution using phycoremediation techniques. Phycoremediation technology helps in pH correction of the acidic effluents and reduces sludge formation making the process safe, economical and eco-friendly. The main area of expertise is in industrial effluent, sewage and wastewater treatment using microalgae without the use of chemicals. The centre uses low cost harvesting techniques by combining auto flocculation and chemical flocculation. The world's first phycoremediation plant was set up in *SNAP Natural & Alginate Products Pvt. Limited*, Tamil Nadu. The plant has been in operation from 2006. High levels of productivity have been achieved by combining phototrophic and heterotrophic modes of cultivation.

Enhanced Biofuels & Technologies (I) Pvt. Ltd. in Coimbatore, Tamil Nadu is focused on the production of pesticides, fertilizers, lubricant, biodiesel, bioethanol and other value added products from algae and other biomass resources. For economic reasons, they are also focusing on high valued products such as Omega 3 fatty acids while producing biodiesel from microalgae.

Energy Microalgae in Kerala has a specialized team of professionals working on cultivating seawater algae in an open trough bioreactor system which has benefits over open pond and photobioreactor systems. They also employ fully automated built in harvesting mechanism called the Hydrophobia Cell Escalation which provides multiple harvests a day depending on the cell density of the algae strain.

Centre for Conservation & Utilization of Blue Green Algae is a research centre under Indian institute of Agricultural Research (IARI) in Delhi. Their main activities are to provide services for uni-algal culture isolation and provide expertise in research on blue-green algae. Established in 2009 is the *TRA International* engaged in the development of a scalable bioreactor suitable for cultivation under varied climatic conditions. They also concentrate on developing genetically modified algae strains suitable for cultivation under various climates. The company is supported by a team of scientists and entrepreneurs interested in providing green solutions using advanced technology. Also focusing on microalgae cultivation is the Delhi based non-profit organization, *TERI (The Energy and Resource Institute)* established in 1974.

Shirke Biohealthcare Pvt. Ltd. Pune, established in 1997 is one of the leading companies in biotechnology. Their area of expertise lies in the field of pharmaceuticals, agriculture and environmental science. Also focused on producing pharmaceuticals is the Punjab- based *Hash BioTech Labs Pvt. Ltd.* established in 2007. They specialize in the research and development of cosmetics and pharmaceuticals using genetically modified algae apart from producing biodiesel and bioethanol.

Beckons Industries Ltd. in Chandigarh and *Birla Institute of Scientific Research (BISR)* in Jaipur are dedicated in microalgae cultivation while mitigating CO_2. In order to increase the productivity, Beckons developed a low cost photobioreactor technology that uses light energy instead of carbohydrates in the medium. While producing biofuels and animal feed, the company's main focus is to recycle the CO_2 from flue gases reducing the net CO_2 as waste. BISR on the other hand focuses on producing biodiesel and biobutanol from marine algae while sequestering CO_2.

Additionally, a US- Israeli algae biodiesel company World Health Energy Holdings Inc. (WHEN) has signed up a deal for US $100 million with Prime Inc., an industrial and Transport Company to develop a biodiesel production facility in 250acres of land in India. The main focus will be on producing fish feed, proteins and algae oil.

1.4 Usage history of Biofuels

Biofuels are non-fossil fuels derived from recently living organic matter such as plant matter, animal waste and municipal waste. Biofuels are intended as an alternative to fossil fuels and have been in use for a very long time. Wood was the earliest form of biofuel that was used by mankind and they continue to make an important contribution even in the present day.

The need for energy security and high oil prices were the contributing factors in the development of biofuel technology. The early usage of biofuels was discovered by Nikolaus August Otto and was first used by Rudolf Diesel to build his first diesel engine in 1885. In 1900, a version of Diesel's engine that runs on peanut oil was demonstrated at the Paris Exposition, where it received the Grand Prix. Rudolf Diesel continued his work on vegetable oil fuels as he believed it would help improve the economic growth of countries. In his speech in 1912, Diesel envisioned that vegetable oil as a fuel source would be a viable alternative in the future compared to petroleum and coal-tar products.

In 1908, Henry Ford, the founder of the Ford Motor Company, used bioethanol to run his Model T, calling it the oil of the future. People believed that biofuels would be primary fuel for diesel engines until the 1920's, when alterations were made to the diesel engine, which enabled the use of a residue of the fossil fuel petroleum, known as Diesel #2.

Although the engine gained popularity with petroleum emerging as the dominant energy source, the idea of biofuel as an alternative source was never completely forgotten. Experiments on biofuels continued during the 1920's and 1930's in several countries. With the shortage of petroleum based fuels during the Second World War, interest in biofuels was renewed. It has been reported that Brazil, India, China, Japan and Argentina used vegetable oil as a fuel source during the time of war.

The energy and oil crisis of the 1970's and 1980's coupled with the widespread concerns about the depletion of natural resources, again sparkled growing interest in biofuels, especially in United States and Europe where the economy was most affected. Following the oil crisis, a number of researches on biodiesel were initiated in South Africa in 1981 and also in Germany, New Zealand and Austria in 1982 (Korbitz, 1999). It appears that, the first patent was granted to G. Chavanne in 1937, for the trans-esterification of vegetable oil, a process of separating fatty acid ethyl esters from glycerol (known as biodiesel today) and it was applied to power urban buses in Belgium in 1938 (Knothe, 2005). Trans-esterification with ethanol to produce biodiesel was again patented in 1977 by a Brazilian scientist and this was the first industrial process for the production of biodiesel. Biodiesel received international recognition by 1983 and the first biodiesel plant was erected in 1987(Pahl Greg, 2008). Biodiesel has been extensively used and by mid-1990's, biodiesel plants were set up throughout Europe and other parts of the world. France launched the 'Diester', which is obtained by the trans-esterification of rapeseed oil.

Global biofuels production has grown exponentially since 2000. The biofuel production in 2007 has been estimated to be 16 billion gallons as compared to 4.8 billion gallons in 2000, but this provides only 3%of the world's fuel for road transport (Coyle, 2007). With the current depletion of worldwide fossil fuels, biofuel has become the necessary source of fuel and in the long term, biofuel is expected to grow globally. Availability of land is not the restricting factor for the supply of biofuels, although economic issues of each individual country are always an unstable issue.

1.5 Why Algae?

In order to achieve environmental and economic sustainability, it is essential to choose an energy source that is renewable and have the ability to sequester CO_2. “Third generation” algae biofuel technologies could be the key energy source that will help reduce CO_2 emissions from coal-fired power plants and other carbon intensive industrial plants (Tian et al., 2010; Demirbas, 2009). Biodiesel from microalgae is a sustainable and renewable energy source that has the potential to replace fossil fuels in the near future. Researchers and scientist are investing the potential of microalgae biofuel technology because of the growing concerns of increased fossil fuel prices and the issues of global warming which comes as a result of fossil fuel combustion (Gavrilescu and Chisti, 2005).

Microalgae are unicellular microorganisms that grow in either freshwater or marine systems. They are capable of carrying out photosynthesis to produce lipids, proteins and carbohydrates that can be processed into biofuels and other useful chemicals (Guschina and Harwood, 2006). Algae are responsible for more than 90% of all photosynthetic activity on earth (Meyer, 1971). Photo-synthetically produced algae biomass can be used in the solid form to generate heat and electricity or converted to gaseous or liquid state by various microbial processes (Sialve et al., 2009). The fermentation of algae biomass rich in starch can produce liquid biofuels such as bio-ethanol and bio-butanol (Mutsumoto et al., 2003). Microalgae can be converted to biodiesel bio-ethanol, bio-butanol, biogas and bio-hydrogen through biochemical processes.

There are several thousand species of algae in the world available in different colors and forms, but not all of them are suitable for making biodiesel. Some of the most commonly produced species of microalgae include *Spirulina, Chlorella, Dunaliella* and *Haematococcus.* The selection of algae will depend on factors such as growth rate, basic genetic characteristics and the desired products. The lipid content and biomass productivity of various microalgae species is provided in Table 1.1. There are certain species of algae that have a significantly high lipid or oil content, reaching nearly 50% of their overall mass and these species are ideally suited for biodiesel production (Wagner, 2007). Species of algae with high starch content are fermented to produce bioethanol (Kyndt and D’Silva, 2013). Unlike traditional crops, they have a fast growth rate and are capable of growing on non-arable land and saline waters. Studies have concluded microalgae as a viable alternative to carbon sequestration and the fuel produced can be incorporated into the existing fuel infrastructure with minimal changes. Major companies around the world are investigating the production of algae based biofuels as a potential replacement for petroleum. Advanced technologies and innovative techniques can be applied to enhance efficiency and increase productivity.

Table 1.1: Lipid content of various microalgae species. Source: (Chisti, 2007)

Microalgae	**Oil content (% dwt)**
Botryococcus braunii	25–75
Chlorella sp.	28–32
Crypthecodinium cohnii	20
Cylindrotheca sp.	1 6–37
Dunaliella primolecta	23
Isochrysis sp.	25–33
Monallanthus salina	>20
Nannochloris sp.	20–35
Nannochloropsis sp.	31–68
Neochloris oleoabundans	35–54
Nitzschia sp.	45–47
Phaeodactylum tricornutum	20–30
Schizochytrium sp.	50–77
Tetraselmis suecica	15–23
B. braunii	25–75

Algae can produce more oil per acre than the first and second generation vegetable crops. Table 1.2 shows the amount of biofuel that can be produced annually by different crops. Although incentives and subsidies from the government can accelerate the commercialization of algae biofuel technology, algae-to-oil is projected to be competitive with petroleum-based crude oil at a cost far below any other biofuel feedstock crop. The most appealing feature of using algae for biofuels is that, it does not entail a decrease in food production as opposed to crop-based biofuels, since algae does not require farmland or fresh water for its cultivation (Ryan, 2009). Algae can offer a significant yield, ranging from 5000-20,000 gallons per acre per year as compared to second generation crops like corn which can yield roughly 500 gallons of ethanol per acre per year (Tabak, 2009). Certain species of algae can be harvested everyday throughout the year, unlike land-based crops which have a longer growing period. (McGill, 2008).

Table 1.2: Comparison of microalgae with other biofuel feedstock. Source: (Mata et al., 2010)

Plant source	Seed oil content (% oil by wt in biomass)	Oil yield (L oil/ha yr)	Land use (m^2 yr/kg biodiesel)	Biodiesel productivity (kg biodiesel/ha yr)
Corn/Maize	44	172	66	152
Hemp	33	363	31	321
Soybean	18	636	18	562
Jatropha	28	741	15	656
Camelina	42	915	12	809
Canola/Rapeseed	41	974	12	862
Sunflower	40	1070	11	946
Castor	48	1307	9	1156
Palm oil	36	5366	2	4747
Microalgae (low oil content)	30	58,700	0.2	51,927
Microalgae (med. oil content)	50	97,800	0.1	86,515
Microalgae (high oil content)	70	1,36,900	0.1	1,21,104

Algae, like terrestrial crops, obtain most of their energy from the sun and convert it into chemical energy by photosynthesis. The energy is stored in the form of lipids, proteins, carbohydrates and nucleic acid in varying proportions. Microalgae are small in size and tend to grow very quickly in nutrient-rich water. It has been reported that, under favorable conditions, algae can double their size in less than 3.5 hours (Chisti, 2007). Algae grow in abundance in all conditions that are favorable to its synthesis and propagation. It can be produced year round, can be grown in any soil and is not restricted by the climatic conditions.

Biofuels produced from second generation vegetable crops suffer from higher conversion costs, low energy gains and leads to increased food prices as it is grown on arable land (Sanhueza, 2008). Algae, unlike first and generation crops, offer incredible space-efficiency. The U.S. Department of Energy (2010) has reported that, production from algae can yield roughly 30-100 times more oil per acre than land-based food crops such as corn and soybeans. It has been estimated by the U. S. DOE (2010) that if all the petroleum fuel in the United States was replaced by algae, it would require only 1/7th the area used to grow corn in the United States in 2000. Additionally, the cultivation of algae does not require application of herbicides and pesticides unlike other food crops (Rodolfi et al., 2008).

The Carbon Cycle shows that algae are a viable alternative to carbon sequestration (Figure 1.3). CO_2 in the atmosphere is used by algae through the process of photosynthesis and once converted to fuel, releases CO_2 back into the atmosphere. Varying the biological composition of algae biomass can enhance the growth conditions, thereby resulting in an increased lipid yeild (Qin, 2005). In addition to biofuel, several other by-products can be generated from algae feedstock, which is high in nutrition. The protein and carbohydrates from algae can either be used in the medical/cosmetic industry or as animal feed or fertilizers (Spolaore et al., 2006).

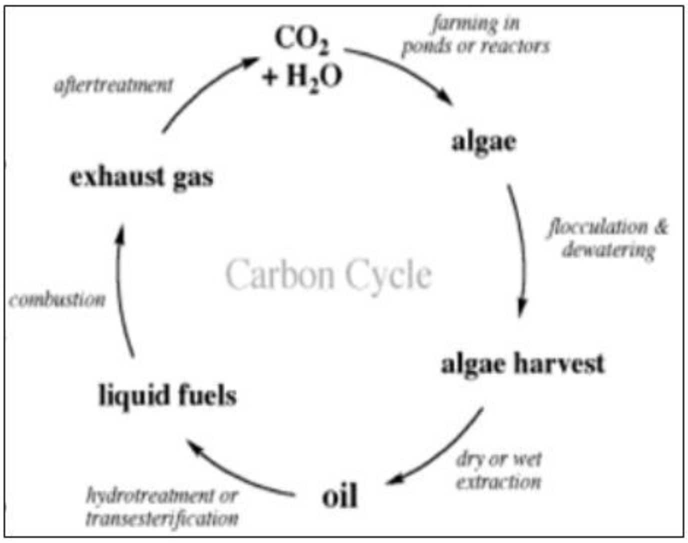

Figure 1.3: Carbon cycle of biodiesel production from algae biomass. Source: (Shirvani et al., 2011)

1.6 Purpose of research

Current pattern of producing, converting and consuming energy throughout the world are not sustainable. Innovation in technology and increased efficiency alone is not sufficient to advance towards a sustainable consumption pattern; it requires a change in the human behavior, lifestyle and consumption pattern. Growing concern of global warming coupled with limited amount of fossil fuels and high oil prices are the main drivers for the strong interest in developing renewable energy sources. The contribution of different biofuels in lowering the GHG emissions has been confirmed by several studies. Significant research is being done on solar energy, wind energy, biomass plants and other clean technologies to combat the problem of climate change and a number of policy makers around the world are promoting private investment in renewable technologies to boost the economy.

Recently, there has been renewed interest in the development of algae-based oil which was once considered infeasible and unviable. But the hypothesis is that, it is not known if commercially produced biodiesel from algae is economically viable. The purpose of this research is to evaluate the technical and economic feasibility of an algae-to-fuel venture incorporating the state-of-the-art technologies, for the successful commercialization of biofuel production from microalgae in India.

The research objectives are as follows:

1. Through research, identify and asses the theories, approaches and trends available from an agricultural, technical, financial and environmental perspective that drive the interest in biodiesel production.
2. To identify the new technologies, current practices, developments and limitations in the production of biodiesel from microalgae around the world with particular emphasis on India.
3. To analyze the economic aspects associated with algae biomass cultivation, harvesting i.e. isolation of the biomass from the culture, dewatering or concentration of algae to a suitable level for further processing, and algal oil extraction systems. Additional costs such as infrastructure installment and preparation, contractor fee and other O&M cost which include expenses for nutrients, water replenishment due to evaporative losses, component replacement, and cost of land and labor in India.
4. To develop an overview from a number of perspectives including resources, political and socio-economic issues, policies, strategies and the environment.
5. To state a conclusion on the technical and economic feasibility of commercial biodiesel production from algae.

1.7 Scope of paper

This paper focuses on the rapidly developing biofuel sector in India, with a critical review of the practical challenges faced by the industry in the commercialization of the microalgae oil. A wide range of issues are studied by putting the development of this sector within the context of the complex policy environment that confronts the future development of this sector in India. Furthermore, the paper assesses the complex range of issues associated with the large-scale development of microalgae biofuels in India, focusing mainly on identifying the major bottlenecks in the production potential of biofuels in India. The paper reviews a range of production technologies currently practiced in India and worldwide, the limitations and barriers of these production technologies, along with an insight into the socio-economic and technical factors that can enhance or limit their future growth. Besides discussing the problems related in the competitiveness of the microalgae biofuel industry, it also highlights some policy reforms and interventions that are necessary to the future efficiency and continued growth of this sector.

2. LITERATURE REVIEW

2.1 Introduction

According to a recent study from the International Energy Agency (2011), predicted that biofuels from microalgae have the potential to produce more energy as compared to other renewable sources of energy (IEA 2010). Biodiesel has currently attracted a lot of interest from technologists, scientists, governments and traders. The feedstock for biofuel can be produced from first generation oil- producing crops such as soybean, rapeseed, sunflower and palm oil. However, the use of oil from food crops for liquid transportation has been objected by many critics due to the food-vs-fuel debate. Biodiesel from second generation crops such as Jatropha are an attractive alternative to first generation crops but they require fertilization, regular irrigation and constant management and maintenance to ensure high lipid productivity (Lam et al., 2009). This calls for a more sustainable biodiesel feedstock that can meet the existing demands for fuel.

Reports suggest that microalgae are a promising biofuel feedstock (Chisti, 2007; Chisti, 2008). Some of the advantages of biofuel production from microalgae are the high oil content, fast growth rate, less use of resources such as water and land, CO_2 sequestration and cost-effective use of land (Li et al., 2008; Wijffels and Barbosa, 2010). They can grow at an exponential rate and can double in size in less than 24 hours (Tredici, 2010). Some strains of algae are capable of accumulating high lipid content, sometimes reaching as much as 50% of their overall weight that can be processed to produce biodiesel (Chisti, 2007). Biomass produced from algae can also be used to produce methane (Golueke et al., 1957; Gunaseelan, 1997; Yen and Brune, 2007), or used to produce bio-plastic materials (Chiellini et al., 2008). Apart from their high lipid content, there are certain species of algae that contain high carbohydrates content, which can be fermented to produce bio-ethanol or bio-butanol (Harun et al., 2010). The biomass residue obtained from these processes can be used as fertilizers or fish feed (Roeselers et al., 2008). In addition, microalgae are capable of capturing the energy of the sun 10-15 times greater than terrestrial crops and at the same time also sequester carbon and other flue gases from the atmosphere and use it for their growth (Khan et al., 2009; Li et al., 2008). Their capability to grow in wastewater and marine waters reduces the water demand for cultivation as compared to terrestrial crops which requires arable land (Hu et al., 2008).

Algae strain selection is an important criterion in the production of microalgae biofuels. The strains are selected based on their ability to adapt to local conditions, be tolerant to salinity, pH and temperature variations, have a fast productivity cycle, be able to resist contamination, have high lipid content and be able to survive under sheer stresses (Brennan and Owende, 2010). However, there are no algae strains that are capable of meeting all of the above mentioned criteria. But it can be argued that, the most basic criteria in the commercial production of microalgae biofuels is the ability to adapt to local conditions (Sheehan et al., 1998).

The potential and benefits of microalgae as a sustainable and renewable source of energy has been studied extensively and microalgae is expected to be the fuel of the future. However, the inability in finding a reliable, sustainable and cost-competitive method for cultivation, harvesting and extraction of algae to produce biodiesel has resulted in an unclear focus on the development of this technology. There are certain technical and economic barriers that must be overcome for the successful commercialization of algae biofuels (Pienkos and Darzins,2009). There is a requirement for further research and innovation in technology, to device a cost-effective solution for algae biofuel production (Lundquist et al., 2010).

2.2 Algae cultivation methods

Unlike terrestrial crops, microalgae are capable of producing more oil per acre compared and can be cultivated on land unsuitable for other food crops (Demirbas, 2009). Depending on the species, microalgae can be grown on freshwater or saline water (Carlsson et al., 2007). Algae, like other plants use photosynthesis to convert the energy of the sun to store it in the form of lipids, proteins and carbohydrates. Like plants, microalgae primarily require water, light, CO_2 and other basic nutrients to grow. This culture mode requiring the presence of light for cultivation of algae is called photoautotrophic. However, there are some species of algae that are can grow in the dark by using organic carbons such as sugar or acetate. This culture mode is called heterotrophic (Barsanti and Gualtieri, 2006).

Currently, the photoautotrophic system is the preferred method for the production of microalgae as it has proven to be technically more feasible and also economical (Brennan and Owende, 2010). Large scale cultivation of photoautotrophic microalgae can be carried out in an open-pond system or in closed photobioreactors (PBRs) (Grima et al. 1999) as discussed next. The growth medium should contain inorganic elements such as nitrogen, phosphorous, iron and sometimes silicon, essential for the growth of the algae cell (Grobbelaar, 2004). There are many advantages as well as concerns of harvesting microalgae in open ponds- the advantage being, it is cheaper to cultivate algae in open ponds as compared to PBRs but open ponds, however, are subject to daily and seasonal change in temperature and humidity. These systems and variations are discussed below.

2.2.1 Open- pond systems

Open-pond systems are one of the oldest and simplest methods for mass cultivation of microalgae. Most of the commercially grown algae are produced in open-pond system. They are relatively simple in construction and operation. Open-ponds include natural water bodies (lakes, lagoons, ponds) and artificial ponds. There are four major types of open-ponds currently in use: circular ponds, shallow big ponds, raceway ponds and tanks (Figure 2.1). Raceway ponds, however, are the preferred method for large-scale cultivation of microalgae as they are relative easy to control. The raceway pond design was first introduced in the 1950s by Professor W.J Oswald at the US Berkeley Sanitary Engineering Research Laboratory (SERL), California, as a solution to municipal wastewater treatment (Oswald et al., 1957; Golueke and Oswald, 1963).

Raceway ponds are oval shaped shallow channels typically 10cm- 30cm deep, in which a paddlewheel is generally used to circulate and mix the algae cells and nutrients. They help keep the algae suspended in water by circulating it back to the surface on a regular frequency. Baffles are placed around the bends to guide the flow. The depth and flow rate of water are two important criteria in raceway ponds and they need to be regulated in order to maintain algal suspension (James and Boriah, 2010). According to Lundquist et al., the frequency or the optimal mixing rate should be ranging between 20 and 30cm per second of channel velocity as the higher mixing rates would not only increase the energy requirements but can also result in algae settling down. Apart from mixing and circulation, paddlewheels also help prevent sedimentation, thus stabilizing the growth of microalgae.

Figure 2.1: Commercial production of microalgae in open raceway ponds. Source: Earthrise Nutritionals LLC, California, Spirulina production (left). Cyanotech Co., Hawaii, Haematococcus pluvialis and Spirulina production (right)

The raceways are typically made from concrete or sometimes out of compacted earth with a plastic liner to prevent seepage losses (James and Boriah, 2010). The ponds are usually kept shallow in order to allow for sunlight penetration. The system operates continuously, with the feed (CO_2 and nutrients) being constantly fed in front of the paddlewheel and the algae broth harvested from the other end. CO_2 is bubbled in to improve the aeration process and enhance the growth of algae biomass. A pH controller maintains the pH and CO_2 within an optimal range. According to Sander and Murthy, the typical harvest-growth-harvest cycle is around 4 days (Sander and Murthy, 2010).

Although raceway ponds offer lower capital cost per unit area of cultivation than closed PBRs, this system has its intrinsic disadvantages. Open ponds are susceptible to evaporative losses and contamination by other algae species and microorganisms (Chisti, 2007; Mata et al., 2010). Biomass production is limited as open-ponds do not effectively utilize the CO_2, due to the diffusion into the atmosphere (Chisti, 2007). Also, poor mixing of the broth can result in poor mass CO_2 transfer rates resulting in poor biomass productivity (Ugwa et al., 2008). Algae growth can also be hindered due to fluctuations in temperature caused due to diurnal cycle and seasonal variations (Chisti, 2007).

The low biomass productivity rate makes PBR an attractive alternative to raceway ponds. However, the cost analysis studies conducted by U.S Department of Energy's Aquatic

Species Program concluded that although open systems are less productive than PBRs, the cost benefits or low cost of fuel make them a good prospect for use in wastewater treatment (Sheehan et al., 1998).

2.2.2 Closed-systems

Photo-bioreactors (PBRs) are typically closed systems that have been employed to prevent evaporative losses and potential problems of contamination (Grima et al. 1999). They provide for a more structured and controlled process of cultivating algae. Apart from lower risk of contamination and evaporative losses, PBRs offer greater control over environmental factors such as light intensity, temperature and exposure, pH, CO_2, O_2 and nutrient levels (Mata et al., 2010; Shen, 2009; Chisti, 2007). PBRs are made of transparent tubes constructed from glass or plastic (Chisti, 2007) and are available in three different designs namely the- Flat Plate reactor, Column or Vertical reactor and Tubular or Horizontal reactor as shown in Figure 2.2 (Kunjapur and Eldrige, 2010). The tubes are generally less than 10cms in diameter in order to allow sunlight to penetrate through the dense medium to maximize biomass production. The tubes are always oriented North-South and the ground below is usually painted white in order to increase reflectance.

The reactors can either be placed under natural or artificial light (Figure 2.2). Closed systems placed under artificial light offer greater control over environmental factors as compared to closed outdoor systems (Suh and Lee, 2003). For example, closed outdoor systems are still reliant on “seasonal, latitudinal, and diurnal variations in light conditions” which closed indoor systems accommodate with “florescent lights, optical fibers or light emitting diodes or plates” (Suh and Lee, 2003). Artificial illumination of tubular photo-bioreactors is expensive and hence is used in biomass production for high-value products (Pulz, 2001).

Flat panels are the earlier forms of closed systems and are known for its large surface area exposed to illumination (Ugwa et al., 2008) and low energy consumption. They are basically rectangular containers aligned vertically or inclined holding the advantage of a shorter oxygen path i.e. less dissolved oxygen build-up (Ugwa et al., 2008) and high photosynthetic efficiency (Richmond, 2000). A biomass productivity of 70-100 dry Mg/ha/yr can be achieved using the flat panel reactor (Shen, 2009; Eriksen, 2008). The only drawback of the flat panel design is that they have a low photosynthetic efficiency (Kunjapur and Eldrige, 2010).

Figure 2.2: Microalgae cultivation in photobioreactors. Source: (CBDMT- Market and Business Intelligence, 2011)

Column or vertical reactors are known for its high photo-efficiency using the least amount of space. The reactor is comprised of a large hollow cylinder designed with an additional internal surface in order to avoid dark zones. They offer great control over algal growth, offer high mixing efficiency (Eriksen, 2008) and work extremely well in small scale or in laboratories, but face challenges for scalability (Hankamer et al., 2001). They are aerated from the bottom and are illuminated through transparent walls (Eriksen, 2008), or internally (Suh and Lee, 2003). A biomass productivity of 138 dry Mg/ha/yr can be achieved using the column design (Shen, 2009).

Tubular reactors are the most the widely used photo-bioreactors for large scale production (Chisti, 2007). They are known to have the highest biomass concentration and the highest volumetric biomass density. A biomass productivity of 70-150 dry Mg/ha/yr can be achieved using the tubular photo-bioreactors (Shen, 2009; Eriksen, 2008). They consist of an array of clean transparent tubes constructed from either glass or plastic, usually aligned with the sun's rays. The broth is circulated through the tubes using a pump, where it undergoes photosynthesis. Fresh culture is fed in continuously while an equal portion of microalgae broth is harvested at the same time (Chisti, 2007; Grima et al. 1999). Feeding is ceased at night but the culture is continuously mixed to prevent biomass from settling (Grima et al. 1999; Chisti, 2007; Brennan and Owende, 2010). A mechanical pump or an airlift pump is used to produce the flow, the latter also allowing CO_2 and O_2 to be exchanged between the liquid medium and aeration gas (Eriksen, 2008). The photosynthesis process generates oxygen, which in excess can damage algal cells. To prevent this damage, the culture is aerated continuously in order to remove the accumulated oxygen through a degassing column. This process is one of the major cost factors and limitations in PBRs (Weissman et al., 1988).

As the broth moves through tube, CO_2 is consumed increasing the pH levels (Rubio et al., 1999). CO_2 must therefore be fed into the system at regular interval. It is also important to cool the PBRs during daytime as they tend to retain more heat. Outdoor tubular PBRs can be cooled using heat exchangers that are located in the degassing column. Other methods of cooling the PBRs is by spraying water on tubes (Tredici, 1999), or by placing them in temperature controlled greenhouses (Pulz, 2001).

The advantages of PBRs are that the cost of harvesting in PBRs is less as the biomass produced is 30 times more as compared to the biomass produced using raceway ponds (Chisti, 2007). Table 2.1 provides a comparison between open ponds and closed PBRs. As compared to open pond systems, the PBRs can overcome evaporative losses and the problems of contamination by other species as the system is a closed one (Grima et al. 1999).

Table 2.1: Comparison of open and closed systems (Davis et al., 2011)

Metric	Pond	PBR
Capital Investment	Low	High
Ease of scale-up	Good	Variable(depend on PBR type)
Availability of technology	Readily available	Not demonstrated on large scale
Downstream processing cost	High (dilute culture)	Low (high density culture)
Flexibility of strain selection	Low(open to invasive species)	High (closed system)
Water use	High (evaporative)	Lower

However, these reactors are difficult to scale up as there are limitations on the length of the tubes (Eriksen, 2008). These tubular photo-bioreactors also require periodic cleaning increasing operational cost and water demand. Algae growth on the tube walls can limit sunlight penetration affecting the overall output. Temperature, intensity of light, toxic accumulation of oxygen and pH could be other limiting factor in the cultivation of algae (Mata et al., 2010; Grimaet al. 1999). This design can arguably represent the central problem with all PBR designs – though so effective that the tubular type is the choice for the world's largest PBR, it is extremely expensive and requires a large amount of auxiliary energy (Hankamer et al., 2001).

2.2.3 Hybrid system

This method works on the principle of leveraging the benefits of the PBR and open pond system for cost-effective cultivation. The cultivation initially takes place in a PBR where the growth conditions can be controlled, minimizing the risk of contamination by other organisms or microalgae species. The high construction and operational costs of closed PBRs can be minimized by such a design (Schenk et al., 2008). In the second stage, the culture is transferred from the PBR to the open pond, in order to expose the cells to nutrient stresses to favour continuous cell division and stimulate production (Rodolfi et al., 2008). This system balances the benefits of low cost of operation in open ponds along with the PBRs ability to offer greater control over culture parameters.

2.3 Inputs: Nutrients, Carbon and Water

Microalgae have received much attention for their ability to convert CO_2 into biomass at a much higher rate as compared to conventional biofuel crops (Kumar et al., 2010). In order to enhance the growth rate, it is essential to supply the culture with extra carbon dioxide. Typically, such high concentrations of CO_2 are found in fossil fuels power plants and other industries. However, algae does not sequester carbon in the production process, instead it captures and utilizes it for the cultivation process. Flue gases that contain CO2 concentrations ranging from 5-15% (v/v) (volume percent concentration) are introduced into the culture for optimal growth (Kumar et al., 2010).

Cultivating microalgae at an industrial scale requires a substantial amount of nutrients (especially nitrogen and phosphorous), carbon (from flue gases) and large quantities of water (wastewater or seawater) as shown in Figure 2.3 (Lam and Lee, 2012). Nutrients are essential components of protein and nucleic acid that make up a considerable percentage of the total dry weight cell mass. The nutrients are normally obtained from chemicals or inorganic fertilizers. Although fertilizers have found to reduce the contamination in the culture, a study by Clarens et al. (2010), has shown that nearly 50% of the GHG emissions are associated with the utilization of chemical fertilizers. Nevertheless, alternatives for fertilizers are found in nutrient rich wastewater from agricultural or industrial origin.

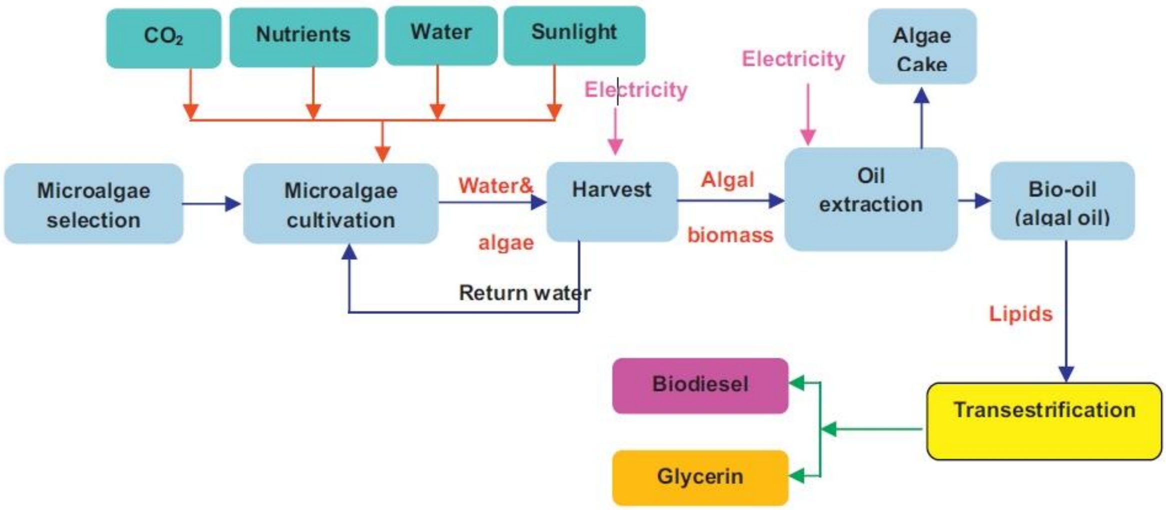

Figure 2.3: Microalgae biodiesel production. Source: (Najafi et al., 2011)

Large quantities of water are required for algae cultivation as the photosynthesis process requires water for carbon fixation. In addition to that, water losses due to evaporation in open ponds and cooling in photobioreactors needs to be taken into consideration. However, the cultivation process does not demand the use of fresh water. Seawater and wastewater from agricultural and industrial origin are interesting options. According to a study by Lundquist et al. (2010), an overall increase of 10% in operational costs was observed in case of cultivation in non-wastewater sources. Besides providing for free supply of nutrients and water, the cultivation of algae in wastewater has significant advantages of a potential saving in cost which would certainly be interesting from an economic point of view (Pittman et al., 2011).

2.4 Algae harvesting and dewatering methods

Efficient harvesting of biomass from the culture is essential for them to be used as a fuel source. After cultivation algae exist in a dilute solution, typically less than 500 mg L-1 on a dry weight organic basis (Benemann and Oswald, 1996), and the recovery of algae biomass from open ponds or PBRs can be highly energy intensive and complex (Wang et al., 2008). Since the biomass concentration is higher in PBRs, the cost of recovering algae biomass may be relatively smaller as compared to open ponds (Brennan and Owende, 2010; Chisti, 2007 Grima et al. 2003). According to Gudin and Therpenier, (1986), the harvesting of microalgae biomass accounts for nearly 20-30%of the overall cost of production.

The method chosen for harvesting will be based on the characteristics of the microalgae species, such as cell size, density, the quantity that needs to be processed and value of the end product (Brennan and Owende, 2010; Olaizola, 2003). Strain selection is an important process as certain species of algae (for example, *Spirulina*) are easier to harvest. Two processes are involved in the harvesting of microalgae, namely:

Bulk Harvesting- It is a large scale process involving the separation of micro algal biomass from the broth. Bulk harvesting methods include floatation, flocculation and gravity sedimentation (Brennan and Owende, 2010). Depending on the harvesting techniques, the slurry can reach a solid content of 2-7% with a concentration factor of 100-800 (Demirbas and Demirbas, 2010).

Thickening- It is a process of concentrating the slurry using technologies such as centrifugation, filtration and ultrasonic aggregation. The harvesting process is generally more energy intensive than bulk harvesting (Brennan and Owende, 2010).

2.4.1 Flocculation

Flocculation is a process of removing algae from the culture by the addition of chemicals known as flocculants that will increase the particle size; making it easier to harvest. It is important to choose a chemical that can coagulate the algae without affecting the composition or toxicity of the product (Grima et al, 2003). Flocculation is often done as a pre-treatment to other harvesting methods such as gravity sedimentation, floatation or filtration (Grima et al., 2003). Flocculants can be classified into organic and inorganic coagulants based on their chemical composition.

Inorganic metal salts such as Alum, Aluminum Sulphate, Ferric Sulphate and Ferric Chloride are effective flocculants that are added in order to neutralize or reduce the negative charge in microalgae that usually prevent the natural aggregation of cells in suspension (Grima et al., 2003). *Inorganic flocculants* can also be used to separate microalgae from the broth that has a low pH (Uduman et al., 2010). However, there are a few disadvantages of using inorganic flocculants such as:

- The separation process requires the use of a large concentration of inorganic flocculants that produces large quantities of sludge.
- There is also a rick of contamination by metal salts such as aluminum and sulphate.
- The use of inorganic flocculants is limited to certain species of microalgae.

Several other flocculants have been tested for harvesting microalgae. Divakaran and Pillai (2002) developed a biodegradable *organic flocculants* called 'Chitosan', which can separate microalgae from the broth without contaminating it. Chitosan is produced from natural sources and are commonly used for water purification but has proved to be very expensive. Cationic flocculants have been identified as the most effective flocculants for the recovery of biomass (Pal et al., 2005; Bilanovic and Shelef, 1988) Cationic starch has been found to be feasible for flocculation of microalgae in freshwater as well as marine waters (Muylaert et al., 2009). However, it has been reported that the high salinity of the marine waters can inhibit the flocculation process (Bilanovic and Shelef, 1988). In such cases, one or more flocculants can also be used for a combined flocculation process and this has been studied by Sukenik et al., (1988) with marine microalgae.

Factors such as concentration of microalgae biomass, molecular weight of the polymer, charge density of the molecules, ionic strength and pH of the culture are found to affect the efficiency of the flocculation process (Grima et al., 2003). High concentration of microalgae biomass in the culture accelerates the flocculation due to frequent cell-cell encounters.

Harvesting microalgae using chemical coagulants on a large scale can be often too expensive. Prolonged cultivation under sunlight with limited CO_2 supply can result in an elevated pH causing microalgae to flocculate on its own. This process is known as Autoflocculation (Sukenik and Shelef, 1984).

2.4.2 Gravity Sedimentation

Sedimentation is a low cost harvesting method of recovering algae biomass (Uduman et al., 2010). This technique separates the feed suspension into a concentrated slurry and clear liquid (Svarovsky, 1979). The settling of solids is determined by the density and radius of algal cells and sedimentation velocity, based on Stoke's law (Schenk et al., 2008). Harvesting using gravity sedimentation can be accomplished using lamella separators and sedimentation tanks (Uduman et al., 2010). Sedimentation is effective for large microalgae particles, such as Spirulina (Munoz et al., 2006), that have a reasonable settling velocity. However, if the density of the particle is very low, flocculants are added to increase the sedimentation rate (Shelf et al., 1984). This method of harvesting is inexpensive (Uduman et al., 2010), but the removal efficiency is generally considered poor without the use of flocculants (Shen et al., 2009).

2.4.3 Floatation

It is a process of separating microalgae from the broth by bubbling air through the medium. The air or gas molecules attach themselves to the solid particles, creating a froth that will float at the surface of the liquid, which can be removed by suction. Floatation is dependent on the instability of the suspended particle. A lower instability will correspond to a higher air-solid particle contact (Shelf et al., 1984). Floatation is most effective when the diameter of the particles is less than 500µm (Matis et al., 1993); as the smaller the particle size, the easier it is to float. Research shows that floatation is more effective than gravity sedimentation with regard to recovering microalgae from the broth (Chen et al., 1998). Based on the bubble size, the floatation process can be classified into dissolved air floatation, electrolytic floatation and dispersed air floatation (Svarovsky, 1979).

Dissolved air floatation

Dissolved air floatation is used to separate microalgae from the broth using features of froth floatation in conjunction with flocculation (Bare et al., 1975). It is the most widely used floatation process in industrial effluent treatment (Matis et al., 1993; Rubio et al., 2002). Dissolved air floatation involves the reduction in pressure of water that is pre-saturated with air (at pressures higher than atmospheric pressure). This liquid is then injected into the floatation tank through nozzles, which generates bubbles. These bubbles attach themselves to the solid particles carrying them to the surface, where they can be skimmed off. Portion of the liquid is recycled to be reused again (Rubio et al., 2002). Factors such as diameter of bubbles and air concentration are important parameters in the dissolved air floatation process. The harvesting of microalgae using dissolved air floatation depends on operational parameters such as: tank pressure, recycling rate, hydraulic retention time and particle floating rate (Bare et al., 1975).

It has been observed by Moraine et al (ed. 1980) and Bare et al (1975) that slurry up to 6% can be obtained when recovery of biomass from microalgae by dissolved air floatation is combined with chemical flocculation. Autoflocculation of microalgae using dissolved oxygen which is photo-synthetically produced was studied after flocculation with alum or C-31 polymer (Koopman and Lincoln, 1983; Uduman et al., 2010). It was observed that algae removal of 80-90% can be achieved with algae float concentrations more than 6%. However, dissolved oxygen concentration was limited to above 16 mg/l for successful autoflocculation.

Edzwald (1993) found that dissolved air floatation is more successful in microalgae removal as compared to settling, although dissolved air floatation required pretreatment by flocculation. The major advantage is that microalgae removal can be done at large scale using dissolved air floatation, but they have a few disadvantages. The use of flocculants can prove to be a problem in the downstream processing of microalgae (Hoffmann, 1998; Greenwell et al., 2010). The operational cost is high as they involve energy intensive air compression (Feris and Rubio, 1999; Haarhoff and Steinbach, 1996).

Dispersed air floatation

This method uses large bubbles that are produced by a mechanical agitator combined with an air injection system (Rubio et al., 2002). A study performed by Chen et al. (1998) compared three collectors to test the dispersed air floatation efficiency and found that the cationic CTAB was the most effective in removing microalgae species, *Scenedesmus quadricauda*. The optimum pH was found to range from 5-8.

Electrolytic floatation

In this process, air bubbles are created through electrolysis, which attaches itself to the microalgae cells and carry them to the surface (Azarian et al., 2007; Alfafara et al., 2002). Active metal anodes are used as flocculating agents for electro-floatation. However, it is the inactive metal cathode that generates hydrogen bubbles from water electrolysis. The removal of microalgae through electrolytic floatation in batch and continuous reactors was studied by Alfafara et al. (2002). The results indicated that increasing the electrical power in batch reactors increased the rate of chlorophyll removal thus, decreasing the electrolysis time. Some of the benefits of electrolytic floatation method include safety, versatility, environmental compatibility and energy efficiency (Mollah et al., 2004).

The major advantage of using electro-floatation is that, no chemicals are added for the separation of microalgae from the solution; however, the difficulty in scaling the cathodes and the high energy requirements makes this process unappealing for harvesting microalgae (Uduman et al., 2010). Nevertheless, it was noted by Svarovsky (1979) that electrolytic floatation is cost effective for small scale production of microalgae as when compared to Dissolved air floatation. Although electro-floatation is not the preferred choice for microalgae harvesting, it may be the preferred method for harvesting marine microalgae (Sandbank and Shelef, 1987).

2.4.4 Centrifugation

It is a process of separating the solids and liquids using centrifugal force (Shelf et al., 1984). Moraine et al. (ed. 1980) conducted a study on high speed centrifugation and concluded that this technique was effective in the recovery of microalgae biomass. However, centrifugation is expensive and requires high maintenance (Heasman et al., 2000; Bosma et al., 2003). Nevertheless, centrifugation is the preferred choice as the recovery rate of algae biomass is high (Aitken and Antizar-Ladislao, 2012) and it provides for an extended shelf-life concentrates for aquaculture (Grima at al., 2003).

The choice of harvesting depends on the cell density and the size of the particles; as the larger the size of the particles, the more effective is the filtration. Moraine et al. (ed. 1980) and Shelf et al. (1979) tested the potential of various centrifugal devices for the separation process and concluded that some of the centrifuges were effective in removing microalgae in a single step while the others required pre-concentrated slurry feed. Golueke and Oswald (1963) tested the efficiency of centrifuges in the dewatering process and concluded that three out of the four centrifuges were effective in removing 79% of the microalgae with 11.5 - 18.2% of solid biomass content.

The drawbacks of using centrifugation for biomass recovery include the high energy cost in processing a large amount of culture and time consumed to complete harvesting (Bosma et al., 2003; Grima et al., 2003). Knuckey et al. (2006) states that "exposure of microalgae cells to high gravitational and shear stress can damage the cell structure".

2.4.5 Filtration

This method of separation of microalgae cells was investigated first in the early seventies (Sim et al., 1988). Filtration requires a pressure drop that acts as a driving force which causes the fluid to flow through the medium. Based on the magnitude of pressure required, the following forces may be applied: vacuum, pressure, gravity or centrifugal (Shelf et al., 1984). Two basic types of filters are used namely Surface filters and Depth filters/Deep bed filters.

Filtration which operates under pressure or vacuum is ideal for harvesting large microalgae species, such as *Spirulina* and *Coelastrum* (Brennan and Owende, 2010; Grima et al., 2003), but this is not applicable for microalgae species with low cell sizes such as *Scenedesmus, Dunaliella and Chlorella* (Mohn, 1980; Brennan and Owende, 2010). Membrane microfiltration and ultra-filtration can be used in the recovery of smaller microalgal biomass (Petrusevski et al., 1995). These membranes could be used for fragile microalgae cells that require low trans-membrane pressure and relatively low cross-flow velocity conditions (Borowitzka, 1997).

Screening involves passing the feed suspension through a filter mesh with a specific pore size that retains the solid biomass allowing the liquid to pass through (Uduman et al., 2010). The two main types of filters used in the harvesting of microalgae are the micro-strainers and vibrating screen filters (Shelf et al., 1984). Micro-strainer filters are only suitable for algae strains of cell size larger than 70µm (Aitken and Antizar-Ladislao, 2012; Brennan and Owende, 2010). The size of the openings determines the amount of pressure required to facilitate the separation process which in turn influences the energy efficiency (Uduman et al., 2010). Larger openings can result in faster flow rate and a lower cost. The efficiency can also be influenced by the concentration of microalgae in the feed suspension (Aitken and Antizar-Ladislao, 2012). High microalgae concentrations can result in blocking of the filter, while a low concentration can result in ineffective capture (Wilde et al., 1991). Filtration provides for an energy effective and cost-efficient harvesting process as long as the algae strain used for harvest has a large cell size and optimum concentration level (Aitken and Antizar-Ladislao, 2012).

2.4.6 Ultrasonic Aggregation

Ultrasonic separation is a relatively new technique that is used in the separation of microalgae biomass. This method uses ultrasonic sound that induces aggregation followed by enhanced sedimentation (Bosma et al., 2003). The separation efficiency of this process is determined by the ingoing flow rates and the biomass concentration. Research by Bosma et al. (2003) concluded that high efficiency of more than 90% can be achieved at inflow rate of 4-6 L/day with high biomass concentrations. Higher efficiencies are difficult to achieve due to the low density and small size of the microalgae that is used for harvesting. Separation efficiencies of 92% can be achieved at high concentration factors, up to 20 (Tsukahara and Sawayama, 2005). Ultrasonic aggregation has the benefit of continuous operation without evoking any sheer stress due to the absence of freely moving part. Also, occupational space for the entire system is very less. Therefore, this method is best suited on small scale or in the production of high value products (Bosma et al., 2003).

2.5 Algae extraction methods

2.5.1 Drying / cell disruption

Production of biodiesel requires the extraction of lipid content from microalgae cells. The harvested microalgae biomass slurry typically consists of 5-15% dry solids that need to be processed immediately (Grima et al., 2003). The microalgae biomass contains high water content (80-90%) that if left unprocessed, can perish (Patil et al., 2008). This can be achieved by dewatering and drying the microalgae, for an extended shelf-life. Drying requires a lot of energy accounting for about 70% of the total cost involved in the production of biofuels (Singh et al., 2011). This is considered to be a major economical bottleneck in production of biofuels. Several methods have been adopted for drying like solar drying, spray-drying, drum drying, freeze drying, fluidized bed drying, flash drying, low-pressure shelf drying (Prakash et al., 1997) and Refractance Window technology drying (Nindo and Tang, 2007). The choice of drying methods depends on the scale of operation and the desired properties of the end product (Grima et al., 2003). The high water content in the biomass makes solar drying a not very effective process for producing algae powder and spray drying too expensive for low value-added products, such as fuel and feed.

Solar drying is the simplest and cheapest option for algae drying, but this method has a few disadvantages. It is a slow process and requires large surface area for drying (Brennan and Owende, 2010; Prakash et al., 1997). According to Desmorieux and Decaen (2006), spray drying is ideal for high value products where the entire biomass is desired. However, this dehydrating method of drying is an expensive process and can significantly deteriorate the algal pigments. Freeze drying is a commonly adopted technique in the recovery of biomass; however, it is too expensive for large scale operations (Brennan and Owende, 2010). It is therefore important to strike a balance between the drying efficiency, cost and the impact on the desired end products (Li, 2008). For example, high drying temperatures (greater than 60ºC) during lipid extraction has a direct impact on the lipid yield and chemical composition of the algal biomass (Grima et al., 2003).

It is rather difficult to extract oil from wet biomass without disrupting the algae cells (Melis, 2005). Cell disruption is therefore necessary for maximizing lipid extraction (Ruane, 1977). This can be achieved by mechanical means such as autoclave; bead mills, homogenizers and ultrasounds, or non-mechanical means such as osmotic shock, organic solvents and freezing (Mendes-Pinto et al., 2001). The selection of disruption method is based on the strength of the microalgae cell wall and the nature of the desired end product.

Cell homogenization is a process of subjecting the biomass to a rapid pressure change and a high shearing action, by pumping it through an orifice (Mercer and Armenta, 2011). The degree of disruption depends on the amount of pressure applied and the strength of the cell walls (Greenwell et al., 2010). Agitation of biomass at high speeds in the presence of small glass beads in bead mills, results in the disruption of cells (Hedenskog et al., 1969). The level of disruption is dependent on the size, shape and composition of the beads. Cell wall strength and the level of contact between the biomass and beads will also affect the performance of the device (Doucha and Lı´vansky, 2008). Studies by Greenwell et al. (2010) showed that bead milling was found to be most effective for biomass concentration of 100-200 g/L. Ultrasonication of biomass that uses a cavitation shear forces can also be used to break the cell walls (Gerde et al., 2012), but this method is not applicable on large- scale.

Autoclaving uses a strong pressurized steam-heated vessel to process the biomass at high temperature and pressure, causing the cells to rupture (Grima et al., 2003). Different cell disruption techniques have been assessed in recovering astaxanthin (an antioxidant supplement that helps fight the signs of aging), from encysted cells of *Haematococcus pluvial* (Mendes-Pinto, 2001). It was found that, disrupting the biomass using autoclaving and homogenization yielded three times as much astaxanthin as compared to other disruption methods (Mendes-Pinto et al,,2001).

Lee et al. (2010) investigated the various methods of cell disruption and found that microwave treatment provided the highest lipid yield of 28.6%. It was also concluded that rupturing the algae cell produced more lipids than extraction without disrupting the cell. Freeze drying or Lyophilization allows for ready extraction of lipids, making other treatments unnecessary (Grima et al., 1994). While treatment using chemicals are effective in the disruption of the cell walls, it is generally not recommended in the production of protein.

2.5.2 Extraction

For biodiesel production, the lipids have to be extracted from the microalgal biomass (Lee et al., 2010). There are several approaches to extracting the algae oil from the biomass, such as expellers/oil presses, enzymatic extraction, solvent extraction, osmotic shock, ultrasonic extraction and supercritical point CO_2 extraction (Demirbas, 2011; Bajhaiya et al., 2010). Oil press is a simple process to extract a large percentage of algae oil (Demirbas, 2011). Expellers use pressure to rupture the cells and compress out oil. This method can extract nearly 75% of the oil but due to the longer extraction times, it has been considered less effective (Popoola and Yangomodou, 2006).

Another commonly used technology in the lipid recovery from dry biomass is solvent extraction where organic solvents such as hexane, benzene, methanol etc are added to the microalgae paste allowing the algae cell walls to degrade and the oil can be extracted from the aqueous medium (Harun, 2001) by means of distillation (Scott et al., 2010). Hexane is the most popular chemical solvent used in the extraction process, known for its high extraction capabilities and low cost (Bajhaiya et al., 2010; Demirbas, 2009; Serrato, 1981). According to Packer (2009) and Muhs et al. (2009), more than 95% of the lipids can be derived using hexane. Other preferred characteristic of the solvents are that, they should be volatile, inexpensive, non-toxic, non-polar and poor extractors of cellular compounds (Rawat et al., 2010). Additionally, the efficiency of this solvent extraction process is highly dependent on the microalgae strains (Lam and Lee, 2012) and the properties of the cell membrane (Brennan and Owende, 2010; Mercer and Armenta, 2011). According to Shen et al. (2009) disrupting the algae cells mechanically prior to exposing them to the solvents has shown to enhance the efficiency of solvent diffusion and improve the recovery rate of lipids, as compared to soxhlet extraction (a commonly used solvent extraction method).

A two-stage extraction process where ethanol is used to extract the oil and hexane is added to purify the extracted oil has been reported to recover about 80% of the lipid content (Fajardo et al., 2010). Nevertheless, such an approach has its disadvantages. The use of solvents such as n-hexane, methanol and chloroform are capable of denaturing the cellular materials, as they are highly toxic (Greenwell et al., 2009). Additionally these solvents (n-hexane and methanol) are derived from non-renewable fossil fuels, which make them unsustainable. On the other hand, ethanol is derived from renewable plant sources, but they have poor extraction efficiency (Lam and Lee, 2012). They can also extract cellular components such as sugar, amino acids, salts and pigments, which are not desired in the process of lipid extraction (Mata et al., 2010). Butanol is effective in extracting lipids from freeze-dried biomass; however it is rather difficult to evaporate the solvent due to its high boiling point. Also, more impurities are extracted due to the high polarity of butanol (Xiou and Xu, 2005).

Alternatively, the extraction procedure can be enhanced by using organic solvents at high temperatures and pressures, typically above their boiling point. This process is known as the accelerated solvent extraction (ASE) and it requires the algal biomass to be dried prior to the extraction process (Richter et al., 1995). The chloroform- methanol mixed solvent, known as the Bligh and Dyer method, is known to have high extraction efficiency as compared to other solvents (Lam and lee, 2012; Mercer and Armenta, 2011). Nevertheless, solvent usage and recycling becomes rather expensive for large scale processes, as there is a significant loss of solvent during the extraction process (Sahena et al., 2009).

Another commonly employed method used in the extraction of high-value products from microalgae is supercritical fluid extraction (SFE) (Macias-Sanchez et al., 2005), which generates solvent-free extracts and is environmentally compatible as compared to the conventional use of harmful solvents (González-Delgado and Kafarov, 2011). This technology works on the principle of exposing the algal biomass to solvents under supercritical conditions. The low critical temperature and pressure of carbon-dioxide makes it a popular extractant (Mercer and Armenta, 2011), especially in food-directed applications (Sahena et al., 2009; Mendes et al., 2006). Additionally, supercritical- CO_2 is inexpensive, non-toxic, safe to use and can easily be separated from the extracts (Wisniak and Korin, 2005). A study by Bligh and Dyer (1957) indicates that supercritical- CO_2 when used in combination with ethanol as a co-solvent has shown to increase the lipid yield (Mendes et al., 2006). Supercritical fluid extraction, although a benign technology, is associated with a high investment and operational cost (Lam and Lee, 2012). In a study conducted by Halim et al. (2011), the use of supercritical- CO_2 was found to be more effective in extracting lipids from wet biomass as compared dry biomass. The use of this technology could make significant savings in cost as the energy required for drying the biomass can be eliminated. However, the moisture content in the sample biomass could be a barrier against the diffusion of CO_2 into the sample and diffusion of lipids out of the cells (Sahena et al., 2009).

Another technique used in the recovery of lipids from microalgae biomass is the ultrasonic extraction. In this method, the biomass is exposed to high-intensity ultrasonic sound waves that create tiny cavitation bubbles around cells (Pernet and Tremblay, 2003; Surendhiran and Vijay, 2012). These bubbles collapse near the cell walls, emitting shock waves that facilitate the extraction of lipids (Bajhaiya et al., 2010; Packer, 2009). The use of this ultrasound technology has shown to reduce the extraction time with improved efficiencies and higher oil yield (Mata et al., 2010; Mercer and Armenta, 2011). However, this technology has been difficult to scale up as it is not cost effective (Bajhaiya et al., 2010).

2.6 Conversion of algae biomass to biodiesel

The extracted oil is converted to biodiesel via a process known as transesterification (Brennan and Owende, 2010; Mata et al., 2012). The lipid feedstock which is comprised of mainly triglycerides are treated with alcohol (methanol or ethanol), in the presence of a catalyst to form fatty acid methyl esters (FAME), commonly known as biodiesel (Sharma and Singh, 2009; Lam and Lee, 2012). Complete conversion of the triglycerides however, involves three consecutive chemical reactions, where the triglycerides are converted to di-glycerides, which are further converted to mono-glycerides and finally to esters (biodiesel) and glycerol (by-product) (Mata et al., 2012). Transesterification utilizes acidic, basic or enzymatic catalysts to carry out the reaction (Rawat et al., 2010). In some cases, transesterification can be carried out without the catalysts using just alcohol (methanol or ethanol) in their supercritical state (Bajhaiya et al., 2010; Warabi et al., 2004; Tan and Lee, 2011). Methanol is the preferred choice for it is economical and has the ability to quickly react with triglycerides at mild temperatures, while the use of ethanol results in the production of ethyl esters which are less stable along with a carbon residue (Romero et al., 2011).

The most commonly used catalysts are acidic or basic, which can be either homogeneous (same phase) or heterogeneous (different phase). Homogeneous base (alkaline) catalysts such as Sodium hydroxide or Potassium hydroxide can be used to speed up the reaction (Ma and Hanna, 1999). Base catalysts have faster reaction kinetics than acid catalysts (Fukuda et al., 2001; Chisti, 2007), but are selective with regard to the type of microalgae lipids that are transesterified. For example, the use of base catalysts in the presence of lipids with high free fatty acid (FFA) content (greater than 0.5% w/w) can result in the undesirable production of soap (Parawira, 2009; Canakci and Van Gerpen, 1999, 2001). Additionally, the water that is produced as a result of transesterification has a tendency to hydrolyse (Palligova et al., 2008), generating more FFA (Swart, 2012), thereby lowering the yield and also increasing production costs (Lotero et al. 2005). Furthermore, base catalysed reactions can be carried out at lower temperatures and pressures and cause less equipment corrosion as compared to acid catalysed processes (Moser, 2009). On the other hand, homogeneous acid catalysts be a better alternative, as they are not affected by the FFA content in the lipids. The most commonly used acid catalysts are Sulphuric acid (Miao and Wu, 2006) or Hydrogen Chloride (Tran et al., 2009). A study by Nagle and Lemke (1990) concluded that, the use of acid catalysts resulted in higher yields as compared to base catalysts. However, the use of acid catalysts can be toxic and will require significant waste treatment.

Biodiesel is usually prepared in the presence of homogeneous base and acid catalysts. It is a two-step process that involves the lipids being subjected to acid catalysts to reduce the FFA levels and then base catalysed transesterification (Lam and Lee, 2012). The efficiency of the homogeneous process, however, is dependent on various parameters such as alcohol to oil molar ration, type of microalgae lipids, temperatures and reaction time (Ma and Hanna, 1999; Fukuda et al., 2001). The reactions were carried out at temperatures ranging from 40-65 ºC and atmospheric pressure. According to a study by Plata et al (2010), 90% of biodiesel conversion could be achieved with alcohol to oil molar ratio of 14, at temperatures of 43 ºC and a reaction time of 90 minutes. Homogeneous catalysts dominate the biofuel industry for its ease of use and the minimal time it requires for lipid conversion. Nevertheless, the major drawback of using homogeneous catalysts is that, they require high purity feedstock that has a complicated downstream process (Borges and Diaz, 2012). Homogeneous catalysts suffer from the requirement of a neutralization step to remove the catalysts which increases the cost of production of biodiesel (Lam and Lee, 2012). Despite the significant costs associated with the use of extra base catalysts to neutralize the acid catalysts during transesterification (Lam and Lee, 2012), the two-step process is being increasingly used in the transesterification process of low-cost biodiesel feedstock with high FFA content (Lotero et al., 2005).

Unlike homogeneous catalysts, heterogeneous catalysts offer economic benefits in the production of biodiesel (Lam and Lee, 2012). One of the major advantages of using heterogeneous catalysts is that, they can be easily separated after transesterification, minimizing product contamination and purification processes thus lowering the overall production costs (Greenwell, 2010). Various types of catalysts such as calcined hydrotalcites, zeolites, magnesium and calcium oxides are commonly used in the transesterification process (Dossin et al., 2006). They exhibit a less corrosive nature and can be easily recycled, regenerated and reused for further transesterification reactions (Sharma et al., 2008; Lam and Lee, 2012), thus making it a more environmentally-friendly process (Dossin et al., 2006). However, longer reaction times are required for heterogeneous catalysts. According to a study, microalgae yield of 97.5% was achieved at temperatures of 50ºC, alcohol to oil molar ratio of 30:1 and a reaction time of 4hours (Umdu et al., 2009). Despite all the efforts, biodiesel produced using heterogeneous catalysts have been difficult to commercialize at an industrial scale. More research is required in to address the feasibility of heterogeneous catalysts in the production of microalgae biodiesel.

According to Haas and Wagner (2011), a single step extraction process known as the direct/ in-situ transesterification, unlike the conventional biodiesel production methods, allows for the conversion of the lipid-bearing biomass into biodiesel without prior extraction. The direct conversion has the advantage of providing an energy-efficient and economical way of producing biodiesel from microalgae biomass (Patil et al., 2012). Additionally, in-situ transesterification has a greater advantage of producing biodiesel since mechanical extraction is ineffective in lipid extraction. Also, methanol consumption can be reduced by introducing a co-solvent such as chloroform and dichloromethane (Xu and Mi, 2011) during in-situ transesterification. However, the use of wet biomass could inhibit the in-situ transesterification process, resulting in poor conversion efficiencies (Ehimen et al., 2010). This is because the water content in the biomass can hydrolyse, generating FFA. Therefore, it is important to dry the biomass prior to transesterification in-situ, which consumes a lot of energy increasing the production costs (Lam and Lee, 2012).

2.7 Main advantages of Algae Biofuels

The supplies of fossil fuels are dwindling and meeting the global oil demands requires a sustainable source of energy. Biofuels from algae can be a promising alternative solution because it is clean and environmentally friendly. Compared to biofuels from other vegetable food crops, algae biofuels offer several advantages.

- Renewable energy

  The concept of using microalgae as a fuel source is very old and its additional potential has been rediscovered. The greatest advantage of producing biofuel from algae is that, it is a renewable source of energy and they are easily biodegradable. The impact it has on the environment is a lot less compared to petroleum and other fossil fuels (Bajhaiya et al., 2010).
- Land requirements and growth rate

  Algae could be the global solution to the food vs. fuel debate. As opposed to crop-based biofuels, algae can grow quickly and they do not require fertile agricultural land and fresh water for cultivation. It can be cultivated on unused/non-arable land or on waste/unclean water or sea water (Demirbas, 2011).
- Sulfur content

  Biodiesel from algae are highly biodegradable and therefore, will not cause great damage to the environment, if they happened to be spilled or leaked (Rutz and Janssen, 2007). They are also non-toxic as they contain no sulfur (Al- Rajhia et al., 2012; Roman et al., 2011).
- Reproductive potential

  Algae, has a much higher productivity potential as compared to land-based biofuels. According to the U.S. Department of Energy, the per acre yield is estimated to be roughly 5,000- 20,000 gallons per year which is 30-100 times greater than land-based crops (Tabak, 2009).

- CO_2 fixation

  Algae, like plants, use the energy of the sun for the process of photosynthesis. The main components needed for the growth of algae are sunlight, water, CO_2 and nutrients (Chisti, 2007). Algae farms are coupled with industrial power plants, where they capture the CO_2 from flue gases from power plants and use it for the cultivation process, thus reducing the GHG emission. The concept of an integrated approach of capturing and using CO_2 is rather appealing and effective in CO_2 fixation (Demirbas, 2011).

- Useful by-products

  Algae primarily consist of lipids, proteins, carbohydrates and nucleic acid, in varying proportions. Some species of algae contain more than 50% lipids by weight and these species are generally used in the production of biodiesel (Wagner L, 2007; Chisti, 2007). In addition to biofuel, several other by-products can be generated from algae feedstock, which is high in nutrition. The protein and carbohydrates from algae can either be used in the medical/cosmetic industry or as animal feed (Spolaore et al., 2006).

- Lubricity

  Algae based biodiesel has better lubricating properties as compared to petro-diesel. This significantly enhances the efficiency of the fuel pumps causing lesser emissions (Roman et al., 2011). This property also makes it more suitable for use in cold climate.

- Ideal fuel for transportation needs

  Biofuel has recently been heavily promoted as the ideal fuel for transportation needs. It has the potential to replace a significant amount of diesel and jet fuel needed today.

2.8 Main disadvantages of Algae Biofuels

Although algae seem to be a promising alternative, there are a few drawbacks that needs to be addressed.

- Cultivation

  Although fresh water is not essential for algae growth, it demands large quantities of water, which could prove uneconomical. Other limiting factors of cultivating algae in open ponds include poor sunlight penetration, loss of water due to evaporation and utilization of large areas of land as ponds need to be kept shallow to allow penetration of sunlight (Carvalho et al., 2008).
- Threat of contamination

  One of the major issues encountered in the open pond system is contamination due to infiltration by local algae, micro-organisms and other airborne material. This could significantly affect the pH levels and alkalinity of the culture medium and therefore, care should be taken in maintaining conditions that prevent unwanted growth (Ben-Amotz, 2009).
- Temperature

  Climatic conditions play an important role in determining the best locations for algae production sites. It is important to maintain a certain temperature favorable for the growth of algae, which could be difficult in the case of an open-pond system (Chisti, 2007).
- Harvesting

  Harvesting algae is difficult and can be energy intensive as it is a relatively new technology. Besides filtration, which is simple and cost-effective, other extraction methods such as flocculation, flotation and centrifugation are energy intensive and expensive, though innovative forms of filtration can prove to be economical in the future. Therefore, the major challenge lies in the effective balance between the selection of algae strains for cultivation and a cost-effective extraction process.
- Energy intensive

  One of the major disadvantages in the production of biodiesel from microalgae is the relatively high amount of energy needed both directly and indirectly for farming and harvesting, pond construction, the production of fertilizers, as well as transport requirements.

2.9 Environmental impact of microalgae biofuels

Algae are an attractive source of biofuel with high yields and appreciable lipid content. Nevertheless, recent studies have suggested that large-scale production of microalgae biofuels could have an impact on the environment. The demand for land, water, nutrients, CO2 and fertilizers are the main reasons for the large environmental footprint (Aitken and Antizar-Ladislao, 2012).

Large-scale production of microalgae biofuel requires large expanses of land. The topography and soil characteristics could limit the land availability for raceway ponds as the construction will require a flat terrain and a need for pond lining and sealing depending on the soil conditions (Lundquist et al., 2010). This could contribute to environmental burden.

Additionally, high amount of water is required for open-pond systems and PBRs. The environmental impact is largely dependent on the type of water used and the production system. A reliable and low-cost water supply is essential for microalgae biofuel productions as plenty of water is lost through evaporation, blow down and temperature maintenance in the closed PBR system (Lundquist et al., 2010). However, unlike terrestrial crops, microalgae can be grown in water of poor quality such as saline water or brackish water. Brackish water, however, requires pre-treatment if it contains chemical constituents that could inhibit microalgae growth, which in turn could increase energy demand (Darzins, et al., 2010). Nevertheless, using waste water from agricultural, industrial or municipal sources can greatly improve the final outcome of LCA (Clarens et al., 2010).

Another area of concern is the nutrient requirements for the cultivation of microalgae. Algae cultivation requires the use of fertilizers containing primarily Nitrogen, Phosphorous and Potassium for enhanced growth (René and Maria, 2010). The potential impact of biofuels on water supply due to the increased use of fertilizers and chemicals remain a major concern (Moreira, 2006). However, nutrients can be recycled and/or recovered from wastewater which could reduce the demand for fresh water for the cultivation of microalgae (Andersson et al., 2011). Also, locating the cultivation system near wastewater treatment could have additional benefits of wastewater remediation along with fuel production.

Transportation is an important factor to be considered from an economic as well as an environmental point of view. The proximity of the cultivation site to a carbon source has been identified by various experts as one of the possible limitation, as transportation can increase the CO_2 emissions (Carlson et al., 2010). Locating the cultivation site close to carbon point sources could be more beneficial (Darzins et al., 2010). However, this area needs further investigation as such a requirement would need a large area of land near the power plant.

Algae growth can also be hindered due to temperature fluctuations caused due to diurnal cycle and seasonal variations (Chisti, 2007). Heating and cooling requirements are therefore essential in order to maintain a high level of productivity. This could require additional fossil fuel input contributing to environmental burden. However, this could be improved through an integrated system where the waste heat from power plants is used to dry microalgae biomass (Garofalo, 2011).

Studies have indicated that there are a wide range of toxins found in microalgae that can have a negative impact on the environment (Thompson, n.d). The toxicity of algae is a concern particularly where the co-products are used for animal or human consumption (Garofalo, 2011). The toxins produced by algae range from simple ammonia to complicated polypeptides and polysaccharides. Certain species of algae are capable of inducing carcinogenic and ulcerative tissue changes over a long period of time (Collins, 1978). However, from an economic perspective, algal toxins may find use in the medical and toxicological industry (Garofalo, 2011).

It can be concluded that although microalgae can cause environmental problems, the impacts are location specific. Environmental monitoring is therefore an important requirement in the production of microalgae biofuels. Sheehan et al. (1998) concluded that although the technology faces several hurdles, resource limitation is not a valid argument against future development.

2.10 Genetically modified organisms (GMOs): opportunities and threats

Algae grow at an exponential rate and with the ability to double in size in less than 24 hours by feeding just a little CO_2, nutrients, water and sunlight; they have become a great attraction for researchers around the world. However, they pose a lot of restrictions in terms of adaptability, tolerance to contamination and temperature variations (Brennan and Owende, 2010). Genetically modified algae are now being investigated with an aim of increasing productivity. According to a report published in 2012, significant biological and engineering innovations could enhance the production of algae biofuels (Sustainable Development of

Algae Biofuels, 2012). Scientists are developing Genetically Modified Algae strains that can grow faster, yield more oil and resist contamination (Gunther, 2012). But this manipulation has its advantages and risks. Although these engineered strains have the ability to produce specific substances, critics fear that the economic gain could be at the cost of ecological health (Lacey, 2011). There is limited knowledge of the risks of genetically modified algae.

However, there are a few improvements made by researchers that have received significant attention. The dependence on high intensity light for photosynthesis has been optimized by reducing the antenna size, thus improving the photosynthetic efficiency (Ort et al., 2011). Solazyme's technology allows for the production of oil by feeding sugar to genetically engineered algae through fermentation (Bullis, 2008). Studies are being conducted to find out what is the triggering factor in the accumulation of lipids when exposed to stress (Sheehan et al., 1998).

Controversial studies have suggested that such genetically modified strains could pose a threat to human health and environment. While there is a huge potential for advancement through genetic modification, large scale application does not seem viable because there is a certain level of uncertainty about the impact it has on the environment (Snow and Smith, 2012). Researchers also fear that there could be a potential chance of undesired mutation and evolution of species that are uncontrollable in nature and pose a threat to biodiversity (The International Civil Society Working Group on Synthetic Biology, 2011).

2.11 Current state of technological development of the source – World Scenario

It was during the oil crisis of the late 1970's that algae received considerable attention by the U.S Department of Energy. From 1978 to 1996, the Aquatic Species Program, under the U.S Department of Energy conducted research on algae biofuels and concluded that the cost of algae-based biofuels was too high. Figure 2.4 provides the energy demand per use and the energy supply by fuel as predicted up to year 2025. Nevertheless, scientists continued their research on algae biofuels and several companies have been established ever since.

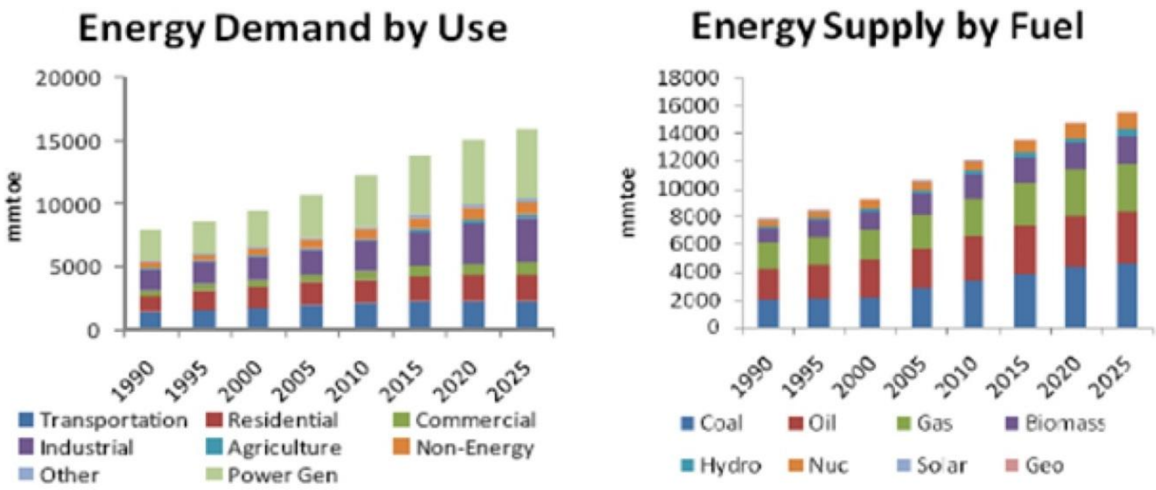

Figure 2.4: The energy demand per use and the energy supply by fuel as predicted up to year 2025. Source: (PFC Energy, 2009).

Algae have been brought into the spotlight with the recent technological advances in the science of production, cultivation and extraction of oil, together with large-scale investments in algae projects. Research is mainly concentrated in the growth and extraction process of algae. There are cases, where innovation in the existing technologies that have led to the development of new technologies. Some of the companies currently involved in algae biodiesel research are Algenol Biofuels, Solazyme, Sapphire Energy, OriginOil, Solix Biofuels, Seambiotic, Aurora BioFuels etc.

Algenol Biofuels in Florida introduced the 'DIRECT TO ETHANOL' technology, which uses blue-green algae to produce ethanol. The method involves using a flexible photobioreactor film made of plastic with special additives and coatings. Algae is fed with CO_2, seawater and exposed to sunlight, producing freshwater, ethanol and oxygen.

This technology can produce a much higher yield per acre per year. For every 2 gallons of seawater, 1 gallon of ethanol and 1 gallon of freshwater is produced. Algenol Biofuels is expected to produce 6000 gallons of ethanol per acre per year. Algenol Biofuels entered into partnership with Dow Chemical Company and The Linda Group, to develop CO_2 capture and produce low-cost ethanol.

Solazyme is a synthetic biology company in the United States that uses genetically modified algae to extract oil. These algae are capable of growing in dark fermentation tanks without sunlight, by consuming a variety of sugars and producing oil. The oil produced is generally used in the cosmetic industry and to fuel jet planes. Solazyme announced the first commercial passenger to be fuelled with 40% of Solazyme's algae biofuel in 2011. They claim to produce 20 million gallons of jet fuel per year from 2014 onwards and also bring down the cost from 80$ to 60$ a barrel in a few years. Solazyme is in collaboration with Chevron, UOP Honeywell and other leading industries to produce 'Soladiesel' to fuel ships and jets.

Sapphire Energy is an energy based company in San Diego, which produces algae-based crude oil. The company focuses on 'Green Crude' technology, which is the conversion of algae in the presence of CO_2 and sunlight into green oil which is further refined to produce 3 distillates- gasoline, diesel and jet fuel. The liquid transportation fuels are completely fungible with the existing oil, refineries and vehicles. Sapphire's sustainable technology is scalable, economic, and meets the ASTM standards.

In 2008, the company announced the production of 91-octane gasoline, 89-centane diesel and jet fuel using this technology. Sapphire Energy is expected to produce 1 million gallons of oil from algae by 2012.

OriginOil developed a technology that can sustainably enhance the growth rate of algae and also increase the efficiency of the extraction process. The company uses a 'Helix BioReactorTM', an advanced bioreactor that has a rotating vertical shaft arranged in a helix pattern, where the helix delivers the nutrients and CO_2 required for the growth of algae. The design utilizes very low energy light that can penetrate every algae cell. This technology significantly reduces the footprint as the system can grow multiple layers of algae. OriginOil claims that their technology can reproduce exponentially doubling in mass every few hours.

Solix Biofuels is a biofuel company in Colorado that offers integrated technology and solution for cultivation and extraction of algae biofuels. The Solix's AGS (Algae Growth System) technology uses thin photobioreactor tubes that are vertically oriented in order to maximize the surface level exposure allowing deeper sunlight penetration, thus enhancing the efficiency of the system. The technology is scalable, economic and covers a lower footprint. With the current state of technology, the cost of producing biofuel is 150$ per barrel, which is expected to reduce further in 2-3 years.

Solix uses its proprietary extraction process to convert the harvested algae biomass into biocrude, which can be further refined to produce biodiesel, green diesel, bio-jet and other products. Solix Biofuels is closely working with Los Alamos National Laboratory, a Mexicobased company that uses acoustic technology- a process of using sound waves to concentrate algae cells to extract oil from it. This method does not require the use of a chemical solvent and is found to use less energy for extraction.

Established in 2003, Seambiotic's main focus was on producing Omega3 fatty acids from microalgae. However, with the advancement in technology over the years, the company is now producing algae biodiesel as well. It uses the traditional method of growing algae in shallow open ponds to allow maximum sunlight penetration.

Being the first company to use flue gases from coal-fired power plants, they are advanced in the technology for gas transfer, cleaning and control. It is reported that NASA is partnering with Seambiotic to research on algae as a source for fuelling jets.

Aurora BioFuels is a renewable energy company focusing on the production of bio-oil from algae which can be converted into biodiesel. The company has generated a cost-effective and scalable technology for fuel generation from microalgae strains that are highly productive. The company uses only $1/25^{th}$ the land space and claims to be 70-100 times more productive than traditional food crops. In 2007, the company was able to overcome the issues of contamination by using new technologies. Aurora BioFuels can sequester nearly 90 percent of the carbon dioxide fed into the system. The investors include Oak Investment Partners, Noventi Ventures and Gabriel Venture Partners.

2.12 Limitations currently facing biofuel production from microalgae

- Technical and economic barrier

  The major issue restricting the implementation of the algae biofuel technology is the technical and economic factors. The high capital and operating costs makes it unappealing for potential investors. The open-pond system is the least expensive method to produce algae biofuels, however, susceptibility to contamination, low productivity and loss of water due to evaporation can make it unattractive (Benemann, 2009). On the other hand, the PBRs reduce the chances of contamination as they are a closed system and increase the productivity rate, but the high initial cost limits the commercialization of such systems (Chisti, 2007).

The factors affecting the economic viability of algae biofuels are the biomass productivity, oil extraction, the level of technology and the oil prices (Singh and Gu, 2010).

- Commercial scalability

  While the concept of algae biofuels as a renewable source of energy has been explored, the development of a cost-effective, sustainable and commercially scalable system is yet to emerge. With the current state of technological development, it is not economically viable to produce algae biofuels (Hannon et al, 2010).

- The challenge of carbon neutrality

  CO_2 plays an essential role in the photosynthesis process which will significantly increase the growth rate of algae, but the production of algae require large amounts of CO_2. Such high concentrations of CO_2 cannot be obtained from the atmosphere, demanding burning of some fuel to capture concentrated CO_2, which is energy intensive. Providing a reliable and steady source of CO_2 can pose major limitation in the production of algae biofuel, unless scientists find cost-effective ways to add CO_2.

  It is rather difficult to find an economically viable method to prevent GHG emission while generating clean energy and oxygen as waste.

- Land availability

  Land use and land value affect land affordability. Physical characteristics such as soil conditions and topography could be a limiting factor for algae biofuel production. The porosity and permeability of soil are important characteristics that need to be taken into consideration during the design of open systems. Also, the construction and installation of large open ponds require a flat terrain. Areas that have a slope of more than 5% will require time and a lot of money for preparation and leveling (Chisti, 2007).

  Additionally, highly desirable land set aside for agricultural development or development of publicly beneficial projects may not be considered for algae cultivation and production.

- Cheap and abundant oil

  In India, where fossil fuels are cheap and readily available, alternative energy sources like algae biofuels may seem like an odd suggestion. The economic feasibility will never be reached unless the environmental and economic cost of using fossil fuels increases.

2.13 Unknown factors

Scientists, investors and companies are looking at algae as a source of biofuel and an efficient substitute to fossil fuels. However, with any new technology, there remains significant doubt on the social, economic and technical potentiality of algae biofuels (Potter et al, 2010). The sustainability of biofuels is still a matter of debate. The Natural Resource Defence Council (NRDC) analysed the potential of algae as a fuel source, and identified the known and unknown impact it has on the environment associated with the production of biofuels.

- Water use
  There is limited data on the amount of water used in the cultivation of algae in the closed and open cycle.
- Effect of Genetically Modified Organism and toxic substances
  The impact of genetically modified organism (GMO) on the ecosystem and the environmental consequences of material toxicity and waste water treatment, during the cultivation on algae on a large scale are unknown.
- Oil spill
  The potential environmental impact of an oil spill is unknown.
- Environmental impact of Algae fuel
  There are concerns regarding the potential toxicity of using chemicals to separate biomass from wastewater during harvesting.
- The energy input and the environmental impact of adding a solvent for the extraction of algae oil are unknown.

In order to mitigate environmental impact and achieve sustainability, it is important for algae industry to meet the environmental objectives. This can be done by conducting life-cycle analysis, energy and carbon balance tests and adopting low-impact development, operation and maintenance practices.

2.14 Future challenges

Despite Algae's potential as a source of biofuel, their development is limited by many factors, which must be addressed in order for algae biofuels to be commercialized. Few of the challenges faced by the algae biofuel industry are discussed below.

Notably, one of the major barriers is the commercialization of algae, which is dependent on the technical and economic process. Commercialization of algae-based fuels has the potential to increase energy security, environmental quality by reducing GHG emissions and improve the economy by creating jobs (IEA, 2011). However, algae-based biofuels are currently not recognized in the tax code as other advanced biofuels. Therefore, it is extremely difficult for companies to attract the capital required to construct large-scale facilities. The high cost associated with the production and extraction of algae oil is an obstacle to commercialization.

Achieving commercial viability will require overcoming a variety of technical barriers. These include several scientific and engineering issues such as poor conversion efficiency from biomass to fuel, reliance on unproven technology, large energy requirements for operation etc. Other critical elements like recycling of nutrients, resource requirements, efficient water management and availability of algae strains needs to be studied. Sustainable development of the algae industry will require technologically advanced systems combined with effective implementation of economically viable integrated production and extraction techniques (Hannon et al., 2010).

The critical issue, after the technical feasibility, is to produce oil at a reasonably low rate. Although economic feasibility analysis suggests that algae may become a solution for biofuels owing to its high availability and yield, production of biofuel from algae has not yet been undertaken on a commercial scale. This is largely due to the high initial and operational cost (US DOE, 2010). Additionally, siting is an important factor in determining the economic feasibility of the algae-to-biofuel process. The proximity of resources such as land, water and CO_2 could be the limiting factors in the contribution of algae biofuels to liquid transportation (U.S. DOE, 2010).

According to Rodolfi et al (2008), not all kinds of algae are compatible with the engines used today for oil extraction which poses a limitation on the algae species that can be used for cultivation. One of the solutions proposed by Prakash et al. (1997) is to combine the two technologies i.e.; the photobioreactor and the open pond system which proved economical. It has been reported that, by 2020, the cost of algae biodiesel grown in ponds will be 9-25 per gallon and those harvested in photobioreactors will cost 15-40 per gallon (Singh, 2010).

2.15 Conclusion

Producing low-cost algae biofuels will require innovation in technology and improvements in algae biology. The recent advances in photobioreactor systems could enhance the economic viability of algae biofuel production. Photobioreactors provide for a controlled environment and the production can be tailored to specific demands. The harvesting and concentration of biomass contribute heavily to the operation cost of biofuel production. A number of studies are being conducted to make harvesting an efficient and cost-effective process. Due to the availability of a large variety of microalgae species with unique characteristics, it is difficult to decide on a harvesting technique that will provide optimum results. The choice of harvesting technique is dependent on the algae species and the desired end product. Microalgae species that have "a large cell size, high specific gravity compared to the medium and reliable autoflocculation" are desirable for microalgae harvesting (Garofalo, 2011). Centrifugation is considered the most efficient method for harvesting microalgae, but the high capital investment and energy required make it unappealing for commercial production (Shelef, 1984). The solvent extraction method combined with oil press is the most popular and widely adopted method for extraction of lipids from microalgae. However, this method is cost-intensive on a large scale. With significant research and development, it is possible to achieve commercial success in the near future.

3. METHODOLOGY

The previous chapter gives an overview of the intent of this thesis along with its aim and objectives. The goal of this section is to introduce the research method adopted in order to achieve the research objective.

3.1 Selection and Justification of method chosen

The main aim of this study is to identify the technical and economic challenges faced by the algae industry and present possible solutions for the successful commercialization of biofuel in India. For this approach, the research will focus on the key drivers such as energy security, technical and economic issues, regulations and mandates that promote use. The methods chosen to carry out this study is a combination of literature-based data collection (Chapter 2) and a survey-based research (questionnaire distribution and interviews). The survey method allows for data collection from questionnaires supplemented by interviews to get in-depth information. The study intends to identify the various algae technologies, the issues associated with it, assist in creating a strategy for research, development and demonstration priorities.

There were hardly any papers that focused on identifying industry issues on algae production and presenting possible solutions. Literature shows that most of the studies on the techno-economic analysis of microalgae-to-biofuel process focused on reducing the cost of production. The findings suggest that the methodologies predominantly used were either simulation or experimental method. Davis et al. (2011) used the Aspen Plus simulation software to evaluate the rigorous mass and energy balance, estimate the hydrogen demand and power generated in order to establish the overall cost of lipid-to-fuel production. Similarly, in order to reduce cost and energy requirements, Zamalloa et al. (2011) conducted an experimental study for over a year. Amer et al. (2011) created a techno-economic model called SAFEER (Sustainable Algae to Fuel: Environmental and Economic Realities) to study the economic viability of producing biofuels from microalgae feedstock.

Survey is the chosen method for this study for the ease and efficiency is offers. Data could be gathered from a larger group quickly as the survey was created online. Additionally, this can be performed at zero cost with no extra manpower. The survey asked for the opinion and future projections on the industry’s growth, barriers in the development and policies that spur economic growth. The questionnaire was e-mailed and circulated among researchers in the algae industry.

3.2 Evaluation of literature review

The balance between research and development and production is an important issue. The primary step involved in the large scale microalgae production pathways was to evaluate the technical and economic process in order to identify their strengths and weaknesses. It was also important to identify the stakeholders and their development pathways as there was little networking among the algae stakeholders. As work progressed, it was important to invest in finding the microalgae species that could produce commercially viable biomass products. In practice, the work was focused on creating questionnaires and conducting surveys to assess the relevant techno-economic issues, environmental and social impact of algae biofuels. Therefore, a literature-based overview of sustainability issues and assessment challenges is provided.

The companies, institutes and research centres in India producing/researching on microalgae biofuels were identified and contacted in order to conduct the survey. Extensive data was collected from academic websites, research papers and published books. A literature review helped in providing details of the state of technological development and current practices followed in India. This was studied in conjunction with the practices and technologies used in other parts of the world in order to identify the positives and negatives.

This review was necessary to set the basis for the next part of the project, whose objective was to help and support researchers, producers of algae biofuels and policy makers in their way to achieve large scale development of microalgae biofuel production. The main objective was to identify the major challenges and limiting factors and indicate future research and development needs in order to commercialize microalgae biofuels.

3.3 Data collection

The choice of data collection is a critical point in the research process. A successful research involves gathering data, examining and statistical processing of data, interpretation and drawing conclusions and making recommendations about the research data. There are two main issues that need to be assessed prior to choosing a particular data collection method. First is to identify the various methods that can help deliver the required information. Second is to find out from literature about the methods used previously in research. This has been discussed in section 3.1. Choosing the right collection method is an important process as mistakes at this stage could have an impact on the findings apart from wasted time and effort.

To perform a research study on the “Technical and economic feasibility of commercial biodiesel production from algae, both quantitative and qualitative approach to data collection is adopted. Quantitative data is concerned with testing hypothesis derived from theory and are easy to compare, generalize and summarize. Data is expressed in the form of numbers and analysed using statistical techniques to test the validity (Naoum, 2007). Qualitative data on the other hand are non- numerical and helps provide in-depth information on people’s perception that is beyond the observer’s results. Various techniques are used to collect and analyse quantitative and qualitative data. Typically quantitative data collection methods include observing, recording and obtaining relevant data from the information system as well as conducting surveys using questionnaires that use a close-ended question format. The qualitative method relies on reviewing documents, observation and interactive interviews using open- ended questions. In conclusion, both quantitative and qualitative data collection approaches are needed to improve an evaluation by ensuring that the limitations of one type of data are balanced by the strengths of another.

The research strategy adopted for this study is to survey policies, programs and practices that will help in the development and commercialization of algae biofuels that are beneficial to the environment, society and the economy. Theoretically, sustainable development into practice has proven to be cost-effective while preventing an increase in the global GHG emissions and reducing the risk of depletion of natural resources. In practice, sustainable biofuel development evolves around the efforts to balance goals and focus on addressing the potential environmental and social impacts and meeting the energy needs. In reality, a zero-impact or zero-risk option does not exist.

3.4 Instruments used for Data collection

In order to select a suitable method for data collection, it is important to consider the type of information needed to answer the research question; the method’s validity and reliability and the resources available, such as time, money and manpower. This section provides details of the technique used in the collection of data for this study.

Questionnaires were used to conduct surveys in order to gather quantitative data. The key to a good survey is its design. Therefore, the questionnaire is carefully designed to produce the data needed to answer the research question. The main advantage of the survey method is that there is minimum cost involved in the amount of data that can be collected. However, there is a risk of significant error due to lower response rates which occurs when the surveys are conducted by mail. To avoid this, the respondents were pre-notified about the survey. According to a study by Fox et al. (1988), it was found that a pre-notification to the respondents increased the response rate suggesting that follow-up mails and repeated reminders can help speed-up the process (Yammarino et al, 1991). Additionally, interviews via telephone and Skype were conducted with experts in the field in order to collect valuable information. The high response rate and the flexibility it offers are some of the advantages of conducting interviews.

3.4.1 Sample size, subject selection and mode of contact

Survey designs involve two steps – sampling plan and procedure for obtaining population estimates and to estimate the reliability of those estimates (Levy and Lemeshow, 1999). The sampling plan will be used to select the sample from the population. The sampling plan will determine the size of the sample and the mode of contact through which the survey will be administered. The mode of contact includes electronically mailing the survey as well as telephonic and Skype interviews.

Determining the right sample size is an important step in a statistical study. The size of the sample for survey must be related to the goal of the study. Undersized surveys could be a waste of time and resource as they will not have enough data for conclusion, whereas an oversized survey could end up using more resources than necessary. The sample size chosen for this study is small due to limited resources and accessibility of the respondents. Given the limited time and manpower, the researcher decided to target nearly 30 surveys.

The target population for this study was defined as individuals with an in-depth knowledge in the field having an onsite experience. The key participants of this survey were algae biofuel producers and other industry professionals working on microalgae biofuels in India. About 70 individuals were selected for participating in the survey out of which 36 responses were received. The sample size was increased to compensate for the non-response rates that are bound to occur in such surveys. A brief interview with a few individuals helped provide a better insight into the new technologies and methodologies adopted in enhancing the production of microalgae biofuels. A list of organizations and research institutes were identified online for conducting the survey. This is discussed in section 1.3. In order to avoid sampling error, no two subjects are selected from the same organization or industry. The subjects are chosen from different parts of India namely Maharashtra, Chandigarh, Delhi, Tamil Nadu, Kerala, Andhra Pradesh, Madhya Pradesh and Karnataka.

The survey was created online using software called SurveyMonkey. This web-based survey helps to create, distribute and analyse results instantly. The number of non-sampling error and coding errors are almost none as the results are analysed online. This improves the overall quality of data. The advantage of an internet based survey is that the cost of collecting data is virtually nil. The link to the online survey is provided in the Appendix A. The answers given by the respondents are accepted as final and no changes are allowed to be made once the survey is submitted. This could be one of the limitations of the online survey and the respondents are made aware of this at the beginning of the survey.

Approval for implementation of the survey was obtained from The British University in Dubai prior to initiation of project. The individuals were identified through a professional network called "LinkedIn" and invitations were sent by e-mail requesting them to participate in the survey. The e-mail also contained the URL that linked the respondents to the SurveyMonkey web-site that hosted the survey. The survey was conducted from mid February 2013 to April 2013 for a period of 1.5 month. Follow up e-mails, reminders and calls were made to non-respondents to speed up the process. The survey was pretested to check for potential problems in clarity and navigation.

3.4.2 Electronic Self-completion questionnaire

A questionnaire was used to identify sustainable biofuel activities in the southern region of Tamil Nadu. The questionnaire was designed to assess the current state of technological development, the limitations and challenges faced by the industry, the policy measures being implemented and to explore the overall feasibility of algae to biofuels production chains.

Additionally, follow up interviews were conducted in order to gain more information. This will be discussed in detail in section 3.4.3. The survey aims to be simple and a clear tool for algae stakeholders by putting together all members of the emerging community.

Questionnaire design

The questionnaire is split into two parts; where the first part consists of general basic questions followed by more specific detailed questions in the second part.

Part one contained some basic but essential questions about the institution or organization, the core business process such as the kind of technology employed or researched upon, the targeted end use of algae and their project involvement. The questions are straight-forward and does not require much of the respondent's time. The information from this section will provide an understanding of the criteria adopted in the selection of algae strains, the kind of end uses targeted by the industry and the kind of technology incorporated in the production of microalgae biofuels.

The second part of the questionnaire contains more open-ended questions regarding the economic aspects of the algae biomass sector, the policies implemented, the challenges faced by the industry and their future projects. Information from this section will provide an understanding on the research and development requirements to promote algae biotechnology, the gaps in the algal research chain in India, the technological issues and the changes in regulations and policies required for the successful commercialization of microalgae biofuels. On the longer term, this information will form the basic picture of the industry practices in India, taking stock of the evolution of the technological innovation from research to commercial production at large scale. A better picture of the industry practices will help in the development of technology and research.

The report highlights the key driving forces behind the development of the algae-biofuel market and documents unresolved supply challenges. It compares the advantages and disadvantages of producing algae biofuels, the technology involved in cultivating, harvesting and extraction of lipids and end-user market opportunities. The report also includes details of the key industry players in the algae biofuel sector.

Questionnaire development

The pattern of questionnaire is important when designing for a survey as a well- formatted survey will make it easier for the respondents to read and complete it (Bradburn et al., 2004). The questions follow a logical pattern in order for the respondents to be able to work through the survey without going back or forward for reference. Ordering the questions of the survey is important as they establish the survey's logic and flow (Dillman, 2000; Bradburn et al., 2004). The survey consisted of closed and open-ended questions to gather information from the respondents. Open-ended questions give respondents the freedom to answer the way they want and this could help provide an unpredictable insight into the topic. Open-ended questions provide rich and detailed information. However, analysing the response is a tedious process. The researcher will have to make sense of the data and analyse it statistically.

The questions are grouped by content in order to make it easier for the participant to focus his/her thoughts, opinions and reactions (Knowles, 1975). The first half of the survey consists of easy and less sensitive questions in order to keep the respondents motivate to complete the survey. Open-ended questions are kept to the end of the questionnaire design. Personal questions and confidential information are consciously avoided to gain the participant's trust and motivate them to complete the survey.

The length of the survey is another important criterion that needs to be taken into consideration as they have a direct influence on the response rate and data quality. Questions are therefore simple, short and concise for ease of reading and understanding. Long and unorganized questions could make the respondents unwilling to answer. Studies by Yammarino et al., (1991) state that the longer the survey the lower the response rate. Also, long surveys could result in a diminished quality of response as the respondents lose interest out of fatigue (Dillman, 2000). The language used in the questionnaire is simple and clear to avoid taxing the participants.

The questionnaire included a total of 20 questions (as shown in Appendix B) where 15 of them are multiple choice questions where participants are required to tick their answers. Most of the questions are made mandatory to answer except for a few open-ended questions which the respondents are allowed to skip if they could not or did not want to answer. The options to write additional responses was provided for the following closed-ended questions: the criteria for strain selection; the kind of production/ harvesting and extraction system employed or researched upon; targeted end uses; the technical and economic challenges in making cost-competitive algae based biofuels. These additional responses are later analysed by the researcher to determine whether they fit into a predefined category of the survey. If so, then they are added to the total for the specified items. The remaining responses were summarized in tables under the heading “others”. The questionnaire is easy to use and could be completed in less than 10 minutes. A good covering letter is added to give a personal touch.

3.4.3 Interview

While data for a large population can be collected in the numerical form using the quantitative method, qualitative research provides a greater insight and an in-depth knowledge into the participant attitude, thoughts and actions (Kendall, 2008). The most common method of qualitative data collection includes interviews, observation and reviewing documents (Patton, 2002). The purpose of interviews is to provide rich details, data and perspectives of the participant’s experience and knowledge in the field. Interviews also decrease the number of questions going unanswered as compared to questionnaire surveys. Qualitative interviews provide a deeper understanding of the subject as compared to a quantitative method of data collection (Silverman, 2000). However, processing of information requires critical analysis, insightful interpretation and challenging synthesis. The in-depth information provided by qualitative research helps in understanding the complex reality of the given subject.

Unstructured and semi-structured interviews which are open-ended and informal provide for a qualitative analysis as compared to structured-interviews which provide for a quantitative analysis. Coolican (1994) states that it is important for the interviewer to have effective listening and understanding skills and also adopt a non-judgmental approach in order to obtain critical data. Since face-to-face interviews were highly impractical and uneconomical as it required travelling to the respondent’s location; telephonic and Skype interviews were the preferred choice.

A total of 5 respondents were interviewed: 2 telephonically and 3 over Skype. The 5 participants were given prior notice about the interview and a date and time was decided based on their convenience. The questions were mailed to them in advance for the purpose of better understanding and preparation. The interviews were informal and semi-structured with open-ended questions. Semi-structured interviews are flexible as they do not limit the respondents to pre-determined set of answers. Yin (2009) states that unlike in-depth interviews that are time consuming, semi-structured interviews are much shorter. Data collected through such interviews are useful for comparative listening to various individual's perspectives.

The five interviewees were experts in the field of algae biofuels out of which two members had more than 15 years of experience in the field. The list of interviewees is provided in Appendix C. The interview was carried out in the month of April 2013. The interview schedule consisted of questions on: criteria of species selection for biofuel production, targeted end products and potential applications of algae biomass, technical and economic barriers faced by the algae biofuel industry, policies and procedure and the risk and opportunities of genetically modified algae.

3.5 Ethical issues in survey research

The purpose of the study was explained to the subjects before being asked to participate in the survey. Respondents were fully aware that the survey research conducted is part of the dissertation and is for academic purpose only. Details about the researcher were provided to reassure that the survey conducted is a genuine one. In addition to that, assurance of confidentiality was given to each individual who participated in the survey. A letter was sent to all the individuals at the very beginning of the survey stating that the confidentiality of their response will be maintained unless permission was given to do so otherwise. According to Singer et al. (1995), assurance of confidentiality has shown to improve the rate of response and the quality of it, especially when the subjects are asked sensitive questions. The confidentiality was maintained from data collection, to analysis till the final presentation of the report.

The covering letter also contained information as to who is conducting the survey, the purpose of this survey, confidentiality of their response, online link to the questionnaire and contact details of the researcher. The covering letter is provided in Appendix D. Since the survey is being conducted by a research student, gifts in the form of money or prizes could not be offered to the respondents for participating in the survey. However, in order for the respondents to co-operate with the researcher by making them believe their response would add value to the report, the researcher decided to present the feedback from the findings once the research was complete; with a hope that it would be of use to them in their field of work. A thank you letter was sent to all the individuals for their participation.

3.6 Limitations

Despite the scope of this methodology, it also presents certain limitations that need to be taken into consideration.

- Errors of two kinds can occur in the sample selection process: Systematic error and Random error. Systematic error occurs when the selection of participants are random. For example, there is a chance of bias that occurs when there are more than two subjects from the same organization or industry. Random error on the other hand is related to the size of the sample. Such an error is common in this type of methodology. The problem with small sample sizes is the interpretation of results, which could affect the reliability of the study. Sampling error will decrease with increase in sample size. The sample size chosen was relatively small due to limitations in resources such as time, money and manpower.
- Low response rates are another concern for researchers when surveys are sent by e-mail. This could be because the respondent's overall attitude towards the survey may be unfavorable. Respondents could feel that participating in the survey is unproductive and a waste of time as it is conducted by a student for her dissertation. Poor understanding of the question, lack of knowledge and poor memory could lead to inaccuracies in the data.
- Limited selection of options to multiple choice questions could result in non-response or incorrect response. In the case of close-ended questions, there is little room for unanticipated discoveries where the participants feel that their response does not fit into the choices provided.
- Another major limitation of this methodology is the error introduced in surveys due to sensitivity. Refusal to answer certain questions and providing inaccurate data because the respondents believed they are protecting their integrity could lead to bias in the estimates. For example, if the respondents are faced with sensitive questions such "what is the current cost of biofuels per gallon (in Rupees) and by what percentage

have you managed to reduce the cost in the last five years”, could prevent them from answering the question or providing the researchers with incorrect data.

- The study is an exploratory one and does not intend to explain the success or failure of the algae biofuel industry, nor suggest policy changes for the deployment of advanced biofuels. Also, the conclusion of the study is limited to the period of time the survey was carried out and thus, the conclusions must be interpreted within the context of these limitations.

3.7 Data coding and analysis

The final stage is coding and analysing the data from the questionnaire. Analysis delivers the value from the survey data and this can be done in several ways. The data needs to be coded before processing it. Coding involves simplifying the responses by sorting the data into various categories and converting them into numbers. This is done by the inductive and deductive method. In the inductive method, in-depth data is collected and recorded whereas in the deductive method, a predetermined classification is done using the coder. This method has both advantages as well as disadvantages. The advantage of using the inductive method is that, it allows for flexibility and new categories can be easily developed. However, the process can be exhausting as a lot of time is required for coding the data. This can be overcome using the deductive method, but the major shortcoming of this method is that they do not allow for new ideas and insights. According to Kumar (2006), it has been suggested that both inductive and deductive methods be used for small size surveys.

Coding can be carried out at three stages: before the survey, during the interview and after the survey. Since the survey was conducted electronically, the responses are ready for data entry as the questions are already pre-coded. However, there is an important distinction between quantitative and qualitative questions. Unlike closed-ended questions, open-ended questions are more difficult to code as a range of responses are received and it requires human expertise to analyse the responses. Qualitative data is collected from responses to open-ended questions from questionnaire-based survey and transcripts from individual interviews (Taylor-Powell and Renner, 2003). Most of the qualitative data collected was from responses to interview questions. As with qualitative data, investment of time is required to analyse and interpret the data in order to better understand the work.

Coded answers can be easily analysed using computer software such as Computer Aided Textual Markup & Analysis (CATMA), Coding Analysis Toolkit (CAT) and Compendium. This allows for the data obtained from the questionnaire to be easily summarized in the form of numbers. The researcher however decided to process the data by hand as the number of open-ended questions and respondents were few. The rest of the processing was done by the web-based software called SurveyMonkey. The software is capable of transforming the respondent's data into charts, graphs and pie charts. Numerical data in the form of tabulation and frequency distribution in the form of bar chart and graphs are used in the result analysis.

During analysis, it is also important to make sure that the trend of data is regular and consistent in order to avoid outliers or freak values. Outliers are identified after the data has been processed and passed through validation and editing. Non-representative outliers that are unique and inconsistent in nature can be easily identified and edited whereas representative outliers that have genuine values cannot be identified. Therefore, each of the individual's response is thoroughly checked to avoid inconsistency in results. Additionally, measures were employed to prevent duplication of entries by the same individual. The software SurveyMonkey is designed in such a way that once the URL is used to complete the survey, the web system will prevent the user from another submission from the same URL.

4. RESULTS AND ANALYSIS

4.1 Introduction

This section of the report presents and discusses the results of the survey that was carried out in India. The survey was designed to assess the technical and economic challenges faced by the algae industry in India. Information was collected on: personal qualifications, the algae strains researched upon, the technology used in the cultivation, harvesting and extraction of biomass from microalgae, the targeted end products, cost of biofuels, policies and procedures, the technical and economic challenges faced by the organization. In addition, the respondents were also asked about the challenges in commercialization of algae biofuels and how it can be solved.

The questionnaire included a total of 20 questions; where defined choices were provided for 15 questions with the exception of the name of the organizations, number of years of experience, the algae strains employed or researched upon, the projected cost of biofuels and the percentage of reduction in cost of biofuels over the years, each of which required the respondents to fill in. A total of 36 responses were obtained from the 70 surveys that were sent out. The responses were filtered to avoid duplicating the results and remove responses from outliers. The filtering eliminated only 1 such responses which reduced the sample size to 35. The 35 responses that were received were consistent and did not reveal unusual results. The analysis and results presented in this section are based on the analysis of the responses of the 35 individuals.

Due to the small sample size and the wide range of participants in the research, the analysis was confined to descriptive statistics and charts and tables. The survey findings and the associated discussion are organized under the following headings:

- Demographics
- Species selection
- Algae production (Cultivation/ Harvesting/ Extraction)
- Cost competitiveness
- Policy and procedure

- Challenges faced by the algae biofuel industry
- Genetically modified algae

These areas, which cover the various issues and challenges faced by the microalgae biofuel industry, will provide a better understanding of the changes that need to be made for the successful commercialization of the this technology.

4.2 Demographics

Question #1, #2 and #3 consists of basic details of the respondents such as the name of the organization or personal name in case of self-employment along with their location; the field of activity; number of years of experience in the field and project involvement. The survey was targeted at a wide range of organizations/ individuals from different parts of India to get a broader perspective.

Responses were obtained from 12 states in India. Table 4.1 provides details of the name of the organization/ individual along their location and the number of years of experience in the algae biofuel industry. Of the 35 participants, 8 respondents (23%) were from Tamil Nadu, followed by 5 respondents (15%) from Delhi, 4 respondents (12%) from Gujarat, 3 respondents each (8%) from Maharashtra and Andra Pradesh, 2 respondents each (6%) from Chandigarh, Kerala and Karnataka and 1 respondent each (3%) from Rajasthan, Madhya Pradesh, West Bengal and Assam (Figure 4.1). Two respondents failed to mention their location.

Table 4.1: Name of the organization/ individual and location

Name of organization/ individual (n)	City/ State	Years of experience
Green Bubble	Bangalore, Karnataka	3
The Energy and Resource Institute	Delhi	3.5
Albert Einstein Science Institute	Delhi	5
R. Sivakumar	Chennai, Tamil Nadu	18
D.R. K Dev	(skipped)	5
Ram	Mumbai, Maharashtra	12

Kadambari Consultants Pvt. Ltd	Hyderabad, Andra Pradesh	9
Aban Infrastructure Pvt. Ltd	Chennai, Tamil Nadu	15
Abellon CleanEnergy	Ahmedabad, Gujarat	3
Hash BioTech Labs Pvt. Ltd	Chandigarh	5
Vivekananda Institute of Algae Technology	Chennai, Tamil Nadu	6
Synthetic Biology & Biofuel Group	Delhi	7
Energy Microalgae	Cochin, Kerala	7
Krishna	Calcutta, West Bengal	2
SNAP Natural and Alginate Products	Ranipet, Tamil Nadu	12
Algae Bio-tech India Pvt Ltd	Hyderabad, Andra Pradesh	5
National Institute of Ocean Technology	Chennai, Tamil Nadu	6
Enhanced Biofuels & Technologies India (P) Ltd	Coimbatore, Tamil Nadu	5
Beckons Industries Ltd	Chandigarh	4
Krishnamurthy Institute of Algology	Chennai, Tamil Nadu	3
Altret Greenfuels Limited	Bhuj, Gujarat	9
EWBiofuel	Vadodhara, Gujarat	12
Shiva Iyer	(skipped)	2
Dr. MGR Algae Biofuel Research Center	Sivakashi, Tamil Nadu	6
Central Food Technological Research Institute(CFTRI)	Mysore, Karnataka	5
Nivedita B	Trivandrum, Kerala	1.5
Amit Agarwal	Nagpur, Maharashtra	3
Central Salt and Marine Chemicals Research Institute	Bhavnagar, Gujarat	16
The Defence Research Laboratory, (DRL)	Tezpur, Assam	5
Centre for Conservation & Utilization of Blue Green Algae	Delhi	13
Birla Institute of Scientific Research	Jaipur, Rajasthan	7
Vivek Kumar	Delhi	3
Shirke Biohealthcare Pvt. Ltd	Pune, Maharashtra	9
Surendra Singh	Bhopal, Madhya Pradesh	5
M. Thomas Kiran	Hyderabad, Andra Pradesh	5

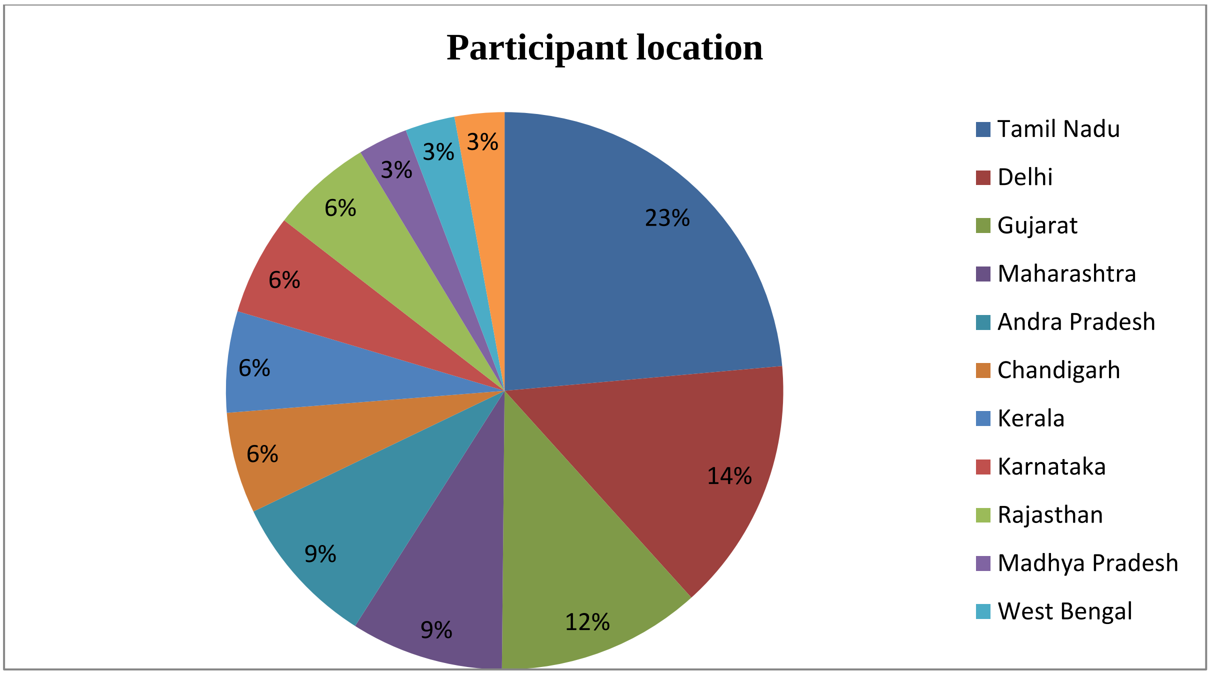

Figure 4.1: Participant location

The number of years of experience of the respondents varied between 1-15 years. Figure 4.2 shows that, a little more than half (54%) of the respondents (n=19) had between 1-5 years of experience and a quarter (26%) of the group (n=9) had between 6-10 years of experience.

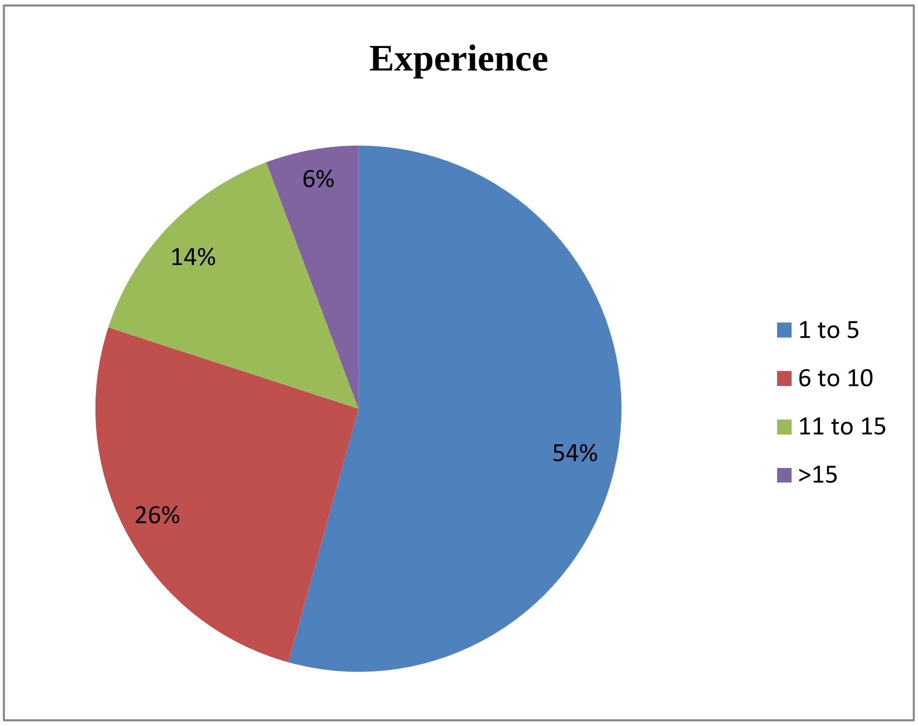

Figure 4.2: Years of experience in the field

A small percentage (14%, n=5) had between 11-15 years of experience with only 2 respondents (6%) with more than 15 years of experience. Individuals with less than a year's experience in the field were not qualified to participate in the survey.

When asked about the field of activity, respondents seemed to be focused on all types of activities except investment. Figure 4.3 shows that all the 35 respondents were into research while none of the organizations/ individuals focused on investment in microalgae biofuels. Results show that, nearly three-quarter (74%) of the respondents (n=26) focused on industrial development out of which 34% of the respondents (n=12) said that their organization provided for technology solutions and services. As can be seen in Table 4.2, 37% of the respondents (n=13) used microalgae for aquaculture production while more than a quarters (26%) of the respondents (n=7) focused on producing feed from algae. According to researchers, only a few strains of algae can be cultured in aquaculture hatcheries, based on their availability, cell characteristics, nutritional benefits, digestibility and absence of toxicity (ed. Muller-Fuega et al. 2004; Guedes and Malcata 2012). Results indicate that only 9% of the respondents (n=3) focused on food related issues.

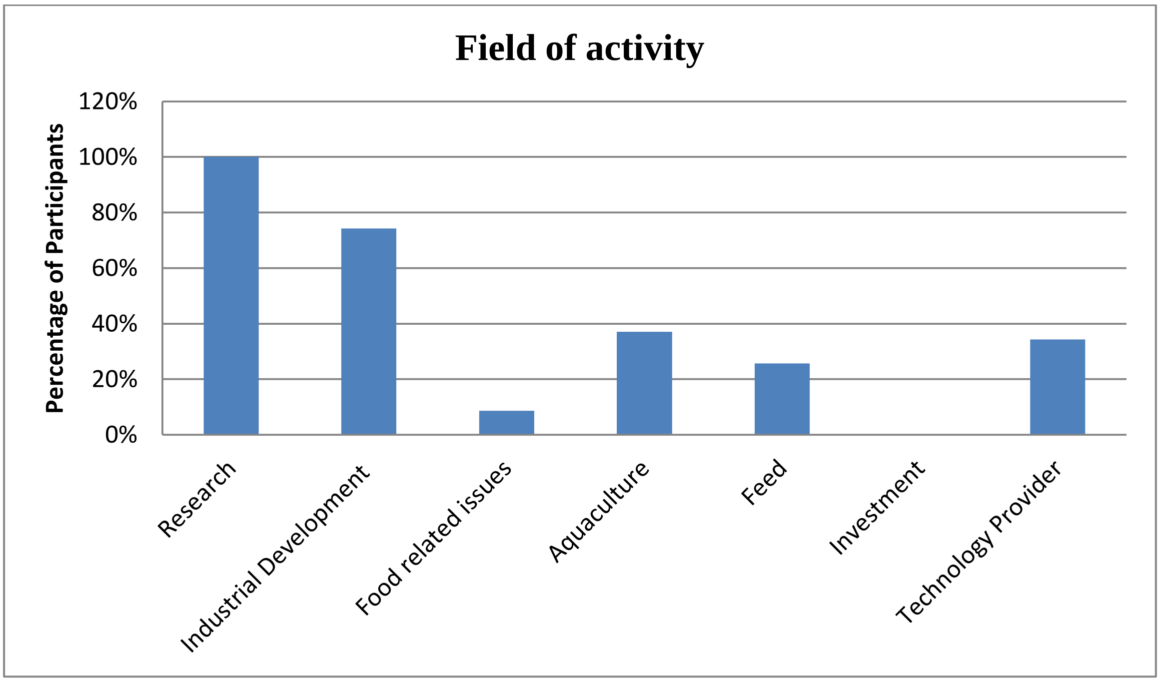

Figure 4.3: Field of activity of respondents

Table 4.2: Field of activity

Field of activity	Response Percent	Response count
Research	100%	35
Industrial Development	74%	26
Food related issues	9%	3
Aquaculture	37%	13
Feed	26%	9
Investment	0%	0
Technology Provider	34%	12d
Others	0%	0
TOTAL		35

4.3 Species selection

India's long coastline is known for supporting a diverse group of marine algae species. Nearly 844 different species of algae are found along the coastline of India (Oza and Zaidi, 2001). A major factor to be considered during strain selection is the availability of water (Mata et al., 2010). A major factor that makes microalgae biofuel production an attractive option in India is because of the country's tropical climate that favours the growth of various microalgae species.

4.3.1 Algae strains researched upon

Survey results show that respondents researched on 19 different species of algae comprising of green algae, blue-green algae, brown algae, red algae and diatoms. Figure 4.4 shows that out of the 19 different species of algae listed by the respondents, 14 are found in marine waters while 8 are freshwater algae. 4 of the 19 species are known to grown on both freshwater and seawater. There is a general preference for cultivation in seawater as it can be used directly instead of freshwater sources (Amaro et al., 2011). According to Sarma et al. (2005), most of the marine species are identified along the coastline of Tamil Nadu.

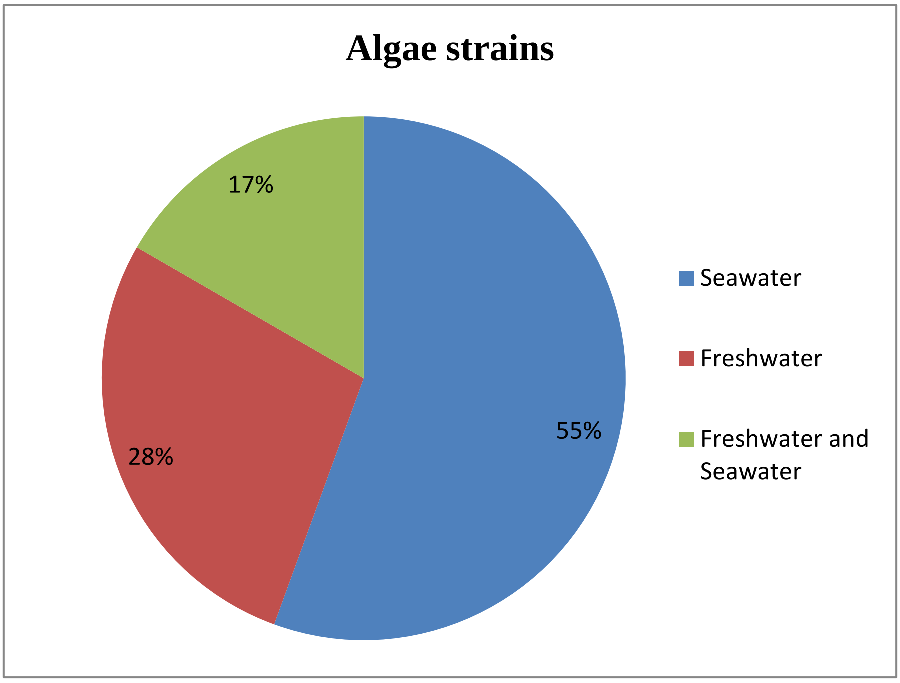

Figure 4.4: Algae strains researched upon

Analysis of survey data discloses that 5 out of the 8 respondents (63%) from Tamil Nadu researched on marine species of algae. However, the high evaporative rates can increase the salinity causing the cell to rupture due to osmotic shock (Mata et al., 2010). Also, marine production plants are restricted to coastal regions due to the availability of seawater. Therefore, cultivation of freshwater microalgae may be appropriate in inland areas. Cultivation of freshwater microalgae also allows a more diverse group of species to be propagated.

When asked to list some of the main algae species that were produced or researched upon (Question #4), all the participants showed a significant preference for naturally occurring algae species instead of genetically modified ones. However, this did not stop them from researching on genetically modified algae (Discussed in section 4.8).

The freshwater green algae Chlorella was the preferred choice by 40% (n=14) of the researchers, followed by freshwater blue-green algae Spirulina which was preferred by 34% (n=12) of the researchers (Table 3). Chlorella and Spirulina are high in proteins, nutrients and other minerals which can be a potential source of food and energy (Belasco, 1997; Maheshwari et al., 2010).

Cyanobacteria, also known as blue-green algae have high biomass productivity and are capable of growing in wastewater (agriculture, industrial and even seawater) by utilizing CO_2 from flue gases and industrial steams (Markou and Georgakakis, 2011).

The marine green algae Dunaliella species and the freshwater green algae Botryococcus braunii were preferred by almost a quarter of the respondents (n=9 and n=8 respectively). Other popular species that were of interest are the marine green algae Chodatella (n=6), the freshwater green algae Scenedesmus species (n=5) and the marine brown algae Turbenaria species (n=4). Table 4.3 lists the different species of algae that are researched upon.

Table 4.3: Algae strains produced and/or researched upon

Algae strains	Groups	Found in	Response count (n)
Chlorella	Green algae	Freshwater	14
Spirulina species	Blue-green algae	Freshwater	12
Dunaliella species	Green algae	Marine	9
Botryococcus braunii	Green algae	Freshwater	8
Chodatella	Green algae	Marine	6
Scenedesmus species	Green algae	Freshwater	5
Turbeneria species	Brown algae	Marine	4
C. closterium	Diatom	Marine	3
Cylindrotheca fusiformis	Diatom	Marine	3
Sargassum	Brown algae	Marine	2
Tetraselmis suicica	Green algae	Marine	2
Chaetoceros species	Diatom	Marine	1
Porphyridium cruentum	Red algae	Marine	1
Oscillatoria species	Blue-green algae	Freshwater	1
Nitzschia frustulum	Diatom	Marine	1
Thalassiosira indica	Diatom	Marine	1
Chroococcus turgidus	Blue-green algae	Freshwater/Marine	1
Chlamydomonas	Green	Freshwater/Marine	1
Nannochloropsis oculata	Diatom	Freshwater/Marine	1

4.3.2 Algae strain selection criteria

Selection of appropriate algae species is the primary step in the successful culturing of microalgae at large scale (Chisti, 2007; Ahmad, 2011). There are over 30,000 different strains of algae in the world, each with different properties that allow it to survive in wild conditions (Sanchez et al., 2008). Therefore, selection of microalgae species are based on a number of characteristics such as the growth rate, lipid content, adaptability to local conditions, harvest ability and the resistance to contamination (Amaro et al., 2011). Ideally, the algae strains are selected based on the ability to produce biofuels along with the extraction of valuable co-products.

Results show that the criteria for selecting the microalgae species is based on many factors, of which lipid content (91%, n=32), harvest ability or growth rate (66%, n=23) and lipid productivity (60%, n=21) are primary (lipid productivity is different from lipid content), followed by resistance to contamination (46%, n=16) and adaptation to local conditions (40%, n=14). Lipid productivity is the product of the cell lipid content multiplied by biomass productivity (Sakthivel et al., 2011). Two respondent (6%) added strain robustness to the selection criteria (Table 4.4).

Table 4.4: The criteria for strain selection

Criteria for strain selection	Response percent	Response count
Oil content	92%	32
Adaptation to local conditions	40%	14
Lipid Productivity	60%	21
Resistance to contamination	46%	16
Harvest ability	66%	23
Others	6%	2

There was a high level of agreement among all the interviewees that the characteristics of a good algae strain should consists of high oil content, fast growth rate and resistance to contamination. Dr. Senthil Chinnasamy, Chief Technology Officer at Aban Infrastructre Pvt Ltd, Chennai and the author of several books during the interview said that:

“The possibility of finding a strain that has a rapid growth rate and resist contamination is an expensive research task”.

He suggested that the selection of microalgae stains be restricted to native species as they can resist contamination quite well.

4.4 Algae production

4.4.1 Cultivation system

Choosing the right algae strain coupled with the right production system is important in the quest to commercialization of microalgae biofuels. Microalgae can be grown in open systems like ponds, lakes and lagoons, or in an enclosed system like a photobioreactor that allows for greater control over environmental factors (Bajhaiya et al., 2010). When asked about the kind of production system employed, 80% of the respondents (n=28) represented the open-pond system (Table 5). Open-pond systems are the most attractive for cultivation of microalgae biofuels because of its low-operating cost as compared to other closed-systems (Sakthivel et al., 2011). Microalgae species such as Spirulina, Dunaliella and Chlorella can be grown in open-pond systems, as they are capable of surviving in extreme environment such as high pH and high salinity. However, the main disadvantages of using this system are that they are susceptible to evaporative losses and contamination by other microalgae species and organisms (Chisti, 2007).

31% of the respondents (n=11) reported using the photobioreactor system. Photobioreactors are more suitable for microalgae species that can get easily contaminated by other micro-organisms. The main disadvantage of using this system is the high capital and operational costs and the difficulty in scaling up (Eriksen, 2008; Sakthivel et al., 2011). However, this cost can be offset if the targeted end products are of high value. Hybrid system on the other hand combines the benefits of both open-pond system and photobioreactors making the process cost-effective (Schenk et al., 2008). But only a small (6%) percentage of the respondents (n=2) reported using the hybrid system.

Table 4.5 show that almost half of the respondents (43%, n=15) are actively doing laboratory testing and less than a quarter (20%) are in the pilot demonstration stage. Lab testing and pilot testing are done for algae identification, toxicity testing of algae strains, etc. While 14% of the respondents (n=5) reported production in industrial system, none of the respondents reported using lagoons. Although lagoons provide an ideal solution for wastewater treatment, biomass yield requires the use of specialized harvesting techniques (Rahman et al., 2012).

Table 4.5: The kind of production system employed and/or researched

Cultivation system	Response percent	Response count
Open ponds	80%	28
Photobioreactors	31%	11
Hybrid design	6%	2
Laboratory	43%	15
Pilot Demonstration	20%	7
Industrial system	14%	5
Lagoons	0%	0
Others	0%	0

The interviewees showed a strong support for the open pond system for its low capital investment and operating costs. Vivek Kumar, founder and director of an international organization called Albert Einstein Science Institute, located in New Delhi believes that there is a clear barrier that exists between laboratory studies and large-scale industrial production, as all the outdoor variables cannot be produced in the laboratory.

4.4.2 Harvesting technique

Recovery of algae biomass from the culture is an energy intensive and complex process (Wang et al., 2008). The harvesting process is said to account for nearly 20-30% of the total cost of production of microalgae biomass (Gudin and Therpernier, 1986). The method chosen for harvesting depends on the properties of microalgae like the algae species, cell size and density, the desired end product and the growth medium (Brennan and Owende, 2010).

Respondents reported using all kinds of harvesting techniques. Table 4.6 shows that more than fifty percent of the respondents (55%, n=19) reported using the flocculation for harvesting microalgae followed by filtration which was chosen by an equal number of respondents (52%, n=18). One of the respondents reported using ‘Reversible flocculation’, a process that occurs when the slurries are treated with chemical flocculants. The flocs after being broken down begin to form again to the same degree by strong agitation. The flocculation process is generally applied to concentrate a large range of microalgae species and is said to have efficiencies ranging between 80-90% (Sukenik et al., 1988). Algae size is an important factor when choosing filtration for harvesting microalgae as it requires fairly large microalgae (Shelef et al., 1984).

Nearly a quarter (20%, n=7) chose centrifugation while floatation was the method chosen by 17% of the respondents (n=6) among which one of the respondents reported using ‘Dissolved air floatation’ for harvesting microalgae. Centrifugation is chosen when the end products are of high value such as food, feed or aquaculture (Mata et al., 2010). Analysis of survey data discloses that 6 out of 7 respondents employed centrifugation to produce one of the high value products.

Smaller percentages were reported for manual or mechanical (11%, n=4) and sedimentation (9%, n=3). Gravity sedimentation is typically used for treating wastewater and to produce low value-added products (Grima et al., 2003). Only 1 respondent reported using a technology called ‘e-zeta process’ for harvesting microalgae. This technology uses catalytic electrodes composed of ‘Poly Oxo Metallates’ (POMs) to remove algae cells from the culture medium and concentrate the biomass for downstream processing.

Table 4.6: The harvesting technique adopted and/or researched

Harvesting technique	Response percent	Response count
Centrifugation	20%	7
Filtration	52%	18
Flocculation	55%	19
Sedimentation	9%	3
Manual or mechanical	11%	4
Others	23%	8
Floatation	17%	6
E-Zeta process	3%	1

4.4.3 Extraction technique

Once harvested, the slurry which consists of 5-15% of dry solids needs to undergo energy-intensive drying prior to extraction of lipids when using traditional extraction methods (Grima et al., 2003). One of the major hurdles in algae biodiesel production is the cost associated with dewatering large quantities of algae biomass. Harvesting and dewatering processes together is said to contribute nearly 20-30% of the total production cost (Uduman et al., 2010). Depending on the microalgae wall and the nature of the product, mechanical or non-mechanical methods of extraction are chosen. Non-mechanical methods of extraction include enzymatic extraction, Solvent extraction and Osmotic shock and mechanical methods include expeller/oil press and Ultrasonic extraction etc. The choice of extraction technique largely depends on the nature of the photosynthetic organism in the culture.

Table 4.7 shows that the respondents used all kinds of extraction techniques, either alone or in combination with other methods for better efficiencies. The largest segment, 63% (n=22) reported using the solvent extraction method, closely followed by expellers/ oil press extraction (51%, n=18). Mechanical press is the simplest form of extraction and is often used in combination with chemical solvents to recover oil (Mercer and Armenta, 2011). Analysis of survey data shows that nearly a quarter (23%) of the respondents (n=8) reported using mechanical press in combination with solvent extraction. Less than a quarter (17%) of the respondents (n=6) reported using enzymatic extraction with an equal percentage (14%, n=5) using ultrasonic extraction and osmotic shock for extraction of microalgae biofuels. Survey data shows that 14% of the respondents (n=5) used ultrasonic extraction in combination with enzymatic extraction. Ultrasonic extraction used in conjunction with enzymatic extraction can accelerate the extraction process while yielding more oil (Yatish, 2012).

Table 4.7: The extraction process employed and/ or researched

Extraction technique	Response percent	Response count
Expeller/oil presses	51%	18
Enzymatic extraction	17%	6
Solvent extraction	63%	22
Osmotic shock	14%	5
Ultrasonic extraction	14%	5
Others	0%	0

4.4.4 End products

Following the extraction process, the lipids, fats, triglycerides etc. can be processed to a variety of value added products. Unlike other energy crops, most part of the algae biomass produced can be used to obtain valuable end products. Algae, with its number of characteristics can have a potential application in several industries. Algae biomass can be used to produce biodiesel, bioethanol, bio-hydrogen, biogas etc. while the protein and carbohydrate part of algae can be used in the pharmaceutical industry and as a food source, including feed for livestock and aquaculture (U.S. DOE, 2010). Non-food compounds of algae can be extracted to produce chemicals that can have application in the cosmetic industry or produce organic fertilizers and bio-plastics (FAO Aquatic Biofuels Working Group, 2010). Targeting high value end products or co-products is viable from an economic perspective.

It is also important to choose algae strains with specific characteristics for desired type of final products. Depending on the algae species, various compounds can be extracted, with valuable application in different industries. For example, Spirulina and Chlorella which are rich in proteins, vitamins, fat and polyunsaturated fatty acids are used to produce dietary supplements, while Chlamydomonas is used both as a dietary supplement and in the pharmaceuticals industry. Nannochloropsis on the other hand is widely used in the aquaculture industry as feed as it has a high nutritional value and Botryococcus is a potential source of biofuels (FAO Aquatic Biofuels Working Group, 2010).

When asked about the kind of end uses targeted, most (91%) of the respondents (n=32) said they focused on producing biofuels with almost three-quarters (69%, n=24) of the respondents produced feed (Table 4.8). More than half (54%) of the respondents (n=19) reported manufacturing pharmaceuticals and 34% (n=12) reported extracting algae for aquaculture. More than a quarter (29%) of the respondents (n=10) focused on producing fertilizers while only 9% (n=3) produced bio-plastics. Results indicated that there were no respondents who focused on energy generation.

Table 4.8: Which kind of end uses are you targeting?

End Products	Response percent	Response count
Biofuel	91%	32
Feed	69%	24
Aquaculture	34%	12
Pharmaceuticals	54%	19
Fertilizers	29%	10
Bio-plastics	9%	3
Biomass for electricity generation	0%	0
Others	0%	0

There is a high level of agreement among all the interviewees on the production of medical and food applications as key co-products of algae biomass. All the interviewees underlined the need for co-production of high-value products along with biofuels for the economic feasibility of biofuel production. As reported by Senthil Chinnasamy:

> "Targeting non-energy products such as feed, medicine and fertilizers from algae biomass is the best way to make large-scale production of biofuels a feasible option".

But despite their high potential, significant investment is needed in order to commercialize algae biofuels, he added.

4.4.5 Project involvement

Figure 4.5 shows that more than half (51%) of the respondents/ organizations (n=18) said that they were involved in algae biofuel projects with national partners while less than a quarter (23%) of the respondents/ organizations (n=8) said they were involved with international partners. Another quarter (26%) of the respondents/ organizations (n=9) said they were involved in projects locally. Analysis of the survey data shows that organizations in Chennai, Delhi, Gujarat and Andra Pradesh are involved in algae production at international level.

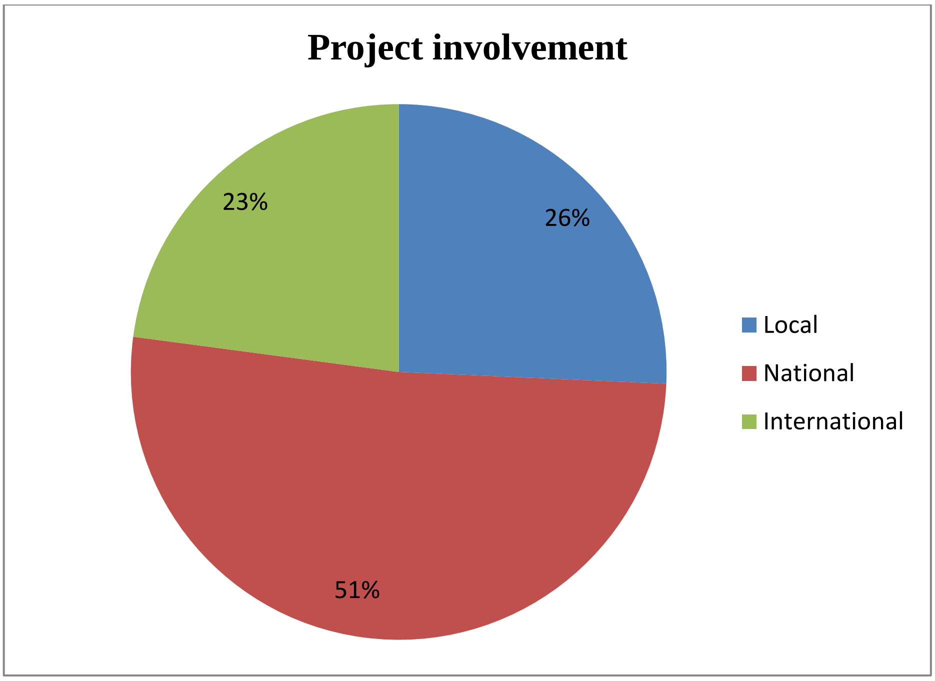

Figure 4.5: Research project involvement

4.5 Cost competitiveness

One of the major hurdles in the commercialization of algae biofuel production is the economic viability of the technology. The main cost in the production of algae biofuels is associated with algae harvesting, dewatering and extraction of lipids (Singh and Gu, 2010). Additional there is cost involved in infrastructure preparation and installation, O&M costs which includes water replenishment to substitute for evaporative losses, CO_2 distribution and labour cost. There is also a significant cost involved in land and leasing (Singh and Gu, 2010).

Q #11, #12 and #13 are pertaining to economic issues where the respondents were asked if they have managed to reduce the cost of biofuels. If so, by what percentage and what will be the cost of biofuels by the year 2020. Most of the respondents are positive about algae biofuels becoming commercially viable within the next 10 years.

Despite the high potential of algae biofuels, in terms of productivity and sustainability, significant investment is required to make algae biofuels commercially viable. Several companies, NGOs and government agencies are investing and providing incentive to algae biofuel companies in an effort to reduce cost to make algae productivity economically feasible and commercially viable. Figure 4.6 shows that the most of the organizations/ individuals in India have managed to reduce the cost of biofuels over the years. 94% of the respondents (n=33) reported that they have reduced the cost of biofuels with only 6% (n=2) who did not know the statistics.

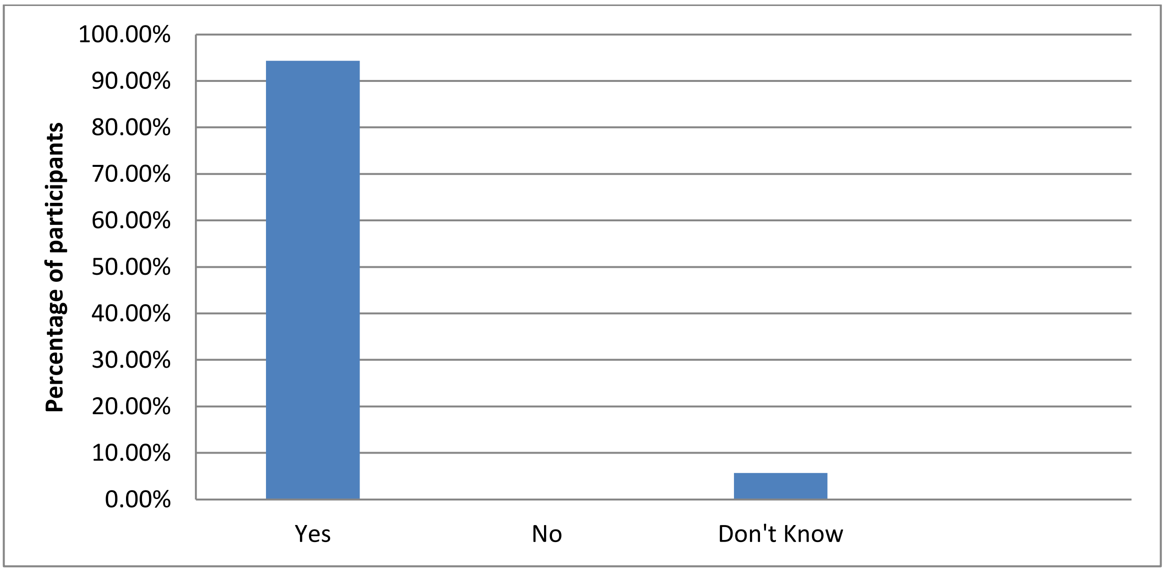

Figure 4.6: The number of respondents who have reduced the cost of biofuels over the years

When asked by what percentage they have managed to reduce the cost of biofuels, more than a quarter (26%) of the respondents (n=9) reported having reduced cost by 21-30%, closely followed by another 20% (n=7) who have managed to reduce cost by 31-40% (Figure 4.7). Nearly 17% (n=6) of the respondents said that they have reduced cost by 11-20% while 14% (n=5) managed to reduce cost by 41-50%. There was only one respondent (3%) who had reduced cost by more than 50% and one who reduced cost by less than 10%.

Analysis of the survey data shows that 6 out of the 35 respondents (17%) declined to mention the reduction in cost achieved over the years. One out of the 6 respondents said that he had not calculated the percentage as the technology is still at the incubation stage.

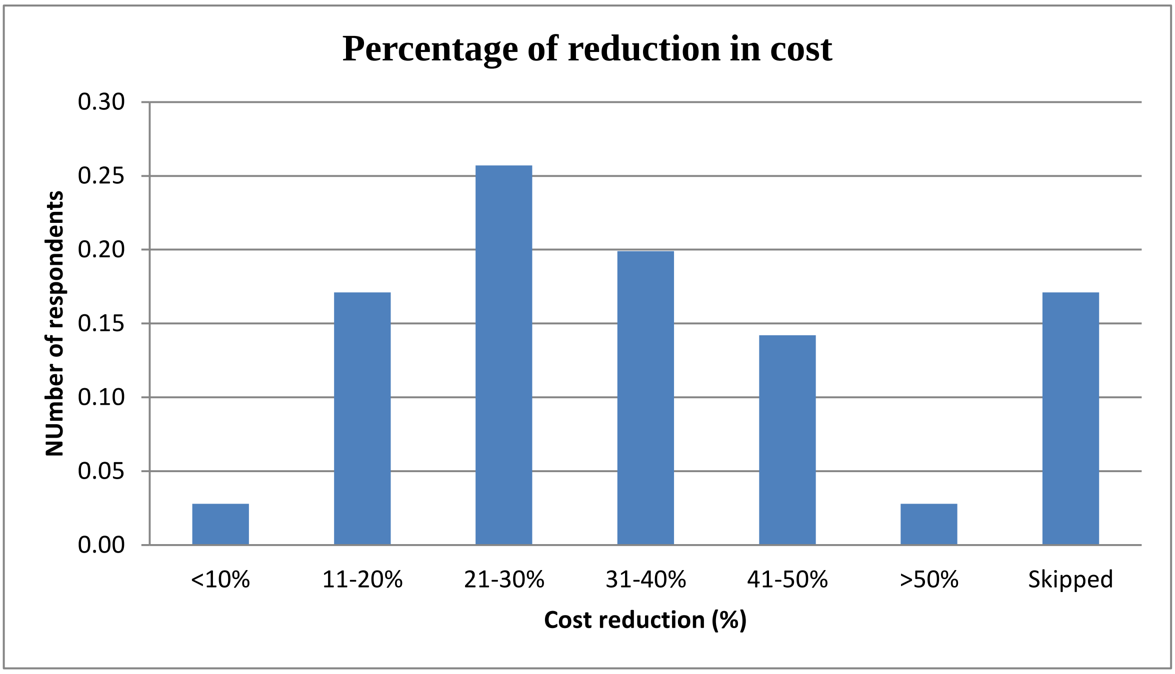

Figure 4.7: The percentage reduction in cost of biofuels

The survey also requested the respondents to make projections of the cost of algae biofuels in the year 2020. The survey data reported that most of the respondents believe that the cost of algae biofuels will be within the range of less than 1$/ gallon – 3$/ gallon. Table 4.9 shows that the largest segment (34%, n=12) believe that the cost will range between 1.1-1.5$/gallon, followed by a 20% (n=7) who believe the cost will range from 1.6-2$/ gallon. 9% (n=3) believe that the cost will range from 2.6-3$/gallon, and a 3% (n=1) believe that the cost will range between 2.1-2.5$/gallon. Only 1 respondent indicated that the cost will be less than 1$/gallon by the year 2020. More than a quarter (31%) of the respondents (n=11) did not make any projections.

To date, the production of algae biofuels has been successful only on a small-scale. The current research and development in the field has not been adequate in facilitating the development of a robust algae biofuel industry (Darzins et al., 2010). The cost of algae biofuels using current technology in the year 2010 was estimated to be U.S $300- $2600 per barrel, as compared to diesel oil rates which were U.S $40-$80 in the year 2009 (Hannon et al., 2010). But with improvements and innovations in technology, a significant reduction in cost can be achieved making algae biofuels commercially viable (Singh and Gu, 2010). Additionally, government funding, investment and policy changes can accelerate the development of algae biofuels nationally and globally (discussed in section 4.6).

Table 4.9: What is the projected cost of biofuel per liter (by the year 2020)

Cost (/litre)		Response percent	Response count
Less than 1$/L		3%	1
1.1- 1.5$/L		34%	12
1.6-2$/L		20%	7
2.1-2.5$/L		3%	1
2.6- 3$/L		9%	3
Skipped		31%	11

One of the major challenges comes in making the algae biofuel system price competitive with fossil fuels. Survey results show that the respondents are optimistic about the prospects for cost-competitive algae biofuels. Table 4.10 shows that more than half (63%) of the respondents (n=22) believe that it is 'likely' for algae-biofuels to compete with fossil fuels by the year 2020, followed by a 37% who believe that it will be 'very likely'.

Table 4.10: In your opinion, how likely is it that algae based fuels will be cost competitive by 2020

		Response percent	Response count
Very likely		37%	13
Likely		63%	22
Not likely		0%	0

It is widely reported that microalgae have several advantages over first and second generation biofuel crops such as fast growth rate and higher yield with the ability to grown in non-arable land. Although economic viability of the technology is a barrier in the commercialization of algae biofuels, the net cost of biofuel production can be reduced by focusing on end products such as wastewater treatment apart from producing biofuels. Additionally, companies like ExxonMobil and Airbus are investing heavily in the development of algae biofuels. According to Vivek Kumar, such large scale investment along with a few improvements in R&D can make algae biofuels price competitive with fossil fuels by 2020.

Dheeban Chakravarthi Kannan, fellow at The Energy and Resource Institute in New Delhi, when interviewed said:

> "Biodiesel price in general is not at competitive market take-back value given the inflated prices of petroleum gasoline", although he still believes that it is likely that algae biofuels will be cost competitive by 2020.

According to Senthil Chinnasamy, it is possible to meet the total energy demand of the country by using only 20% of India's wasteland. But for this to happen, it is essential to reduce the production cost. With an aim to reduce production cost, he is planning to focus on algae strains that have a fast growth rate rather than one with high lipid composition and cultivate them on wastewater, brackish water and seawater. He also added that he plans to begin commercial production of algae biofuels by 2020.

4.6 Policy and procedure

There has been an increased interest in algae biofuels due to government incentives and subsidies, industry investment and new renewable policies. Policies are designed to promote biofuels that seek to reduce GHG emissions as part of the overall target. According to the International Renewable Energy Agency (2013), the government is currently providing mandates and tax incentives favouring the blending of biofuels with fossil fuels that will contribute significant to the growth of biofuels in the country. However, policy measures should be selective in promoting only advanced technologies that can be undertaken on non-arable degraded wastelands, substantially reduce greenhouse gas emissions, avoid adverse use of water and have a positive socio-economic impact (IEA, 2013). As access to water and arable land is a growing concern in India, priority should be given to those energy crops that require little or no irrigation.

In India, 'The National Policy on Biofuels' was released in 2009 with an aim to mainstream the biofuels by setting a target of blending 20% with fossil fuels in the transportation industry by 2017 (GOI, 2009). The National Policy on Biofuels sees biofuels as a potential to stimulate rural development by creating employment opportunities and aspires to reap economic and environmental benefits arising out of the large-scale use (GOI, 2009). The policy states that the biofuel programme is to be carried out only the non-food feedstocks, such as algae that are grown exclusively on non-arable degraded wastelands in order to avoid conflict between foods vs. fuel security.

Table 4.11 shows that nearly fifty percent (49%) of the respondents said that they continued to receive support from the government in the form of incentives, subsidies, carbon nutrient credits and other funds. However, an equal (51%) group of respondents said they did not receive any support from the government. Analysis of the survey data shows government support is not provided to organizations/ individuals that are involved in projects locally. 7 out of 8 respondents/organizations involved in international projects were provided support by the government, while only 9 out of the 18 respondents involved with national projects reported receiving support. Results reveal that government support was offered to only 1 out of the 9 organizations that are involved in projects locally.

Table 4.11: Are you being provided with any incentives/ carbon nutrients credits/ subsidies/ funds etc by the government to expand the industry?

	Response percent	**Response count**
Yes	49%	17
No	51%	18
Don’t know	0%	0

When asked about policies that might accelerate commercialization of biofuels, Harshith Sirigeri, the Managing Director at GreenBubble Algalworks Pvt Ltd said that:

> “Favourable policies like ensuring government support in the form of subsidized inputs, providing technical assistance, buy-back agreements and minimum support prices in marginal lands, enhancing community participation in cultivation and encouraging private sector involvement in growing the feedstock crops and setting-up of processing and marketing infrastructure could have a catalytic effect.

Dheeban Chakravarthi Kannan had a different take on the policy environment in India. He said that government funding opportunities and reach for private institutions are limited.

> "If research is undertaken by private institutes, they have to bear a substantial percentage of investment. The Principal Investigator and other senior research professionals are not compensated by project funds, only research associates and lab technicians are paid for manpower. Only 10% overheads are funded for R&D activities, whereas for other consultancy/application activities 76% overheads are funded. It is different in places like the US and European Union".

Ramalingam Sivakumar, a private Spirulina consultant in Chennai and Vivek Kumar believe that long term contracting for biofuels will establish price certainty for biofuels while also providing the biofuel market more stability. Long term contracting is also expected to stimulate more private investment in biofuels, resulting in a more robust biofuel industry.

4.6.1 Do elected official visit facility

The respondents were asked if elected officials (policy makers) at any level (local, state, national) ever visit their facility. Table 4.12 shows that while 37% of the respondents (n=13) said yes, nearly half (49%) of the respondents (n=17) reported that elected officials do not visit their facility. A small (14%, n=5) percentage of respondents said they did not know if officials visit their facility.

Analysis of the survey data discloses that elected officials visited 6 out of 8 international facilities, 6 out of the 18 national level facilities and only 1 out of the 9 local facilities.

Table 4.12: Do elected officials (policy makers) at any level (local, state, national) ever visit your facility

	Response percent	Response count
Yes	37%	13
No	49%	17
Don't know	14%	5

4.6.2 Expand facility

Respondents were asked if they planned to expand their facility in order to promote biofuels. Results show that there is a positive view on the prospects of expansion of the algae biofuel industry. Table 4.13 shows that majority (69%) of the respondents (n=24) reported they would be expanding the organization to increase production while less than a quarter (20%, n=7) said no. A small (11%) of the respondents (n=4) said they were not sure.

Table 4.13: Are you planning to expand your organization in order to promote biofuels?

	Response percent	Response count
Yes	69%	24
No	20%	7
Don't know	11%	4

The need to move from laboratory to large-scale industrial production is elicited by all of the interviewees. It is the main factor for future deployment of algae biofuels. When asked about the delay in moving to an industrial-scale production, Dheeban said that the main reason is the lack of knowledge. He believes that the researchers are unable to imagine how a large-scale industrial facility might work. There are also serious doubts about the current technological capacity to move to a large-scale biomass facility. But he believes that large-scale production will soon begin with technology innovation and investment.

4. 7 Challenges faced by the algae biofuel industry

The main issue restricting the implementation of algae biofuel technology is the technical and economic barriers. There are technical inefficiencies in the cultivation, harvesting and extraction of algae biofuels (NREL). Some of the challenges are strain selection, algae production system, dewatering methods, lipid extraction, temperature/light management and contamination in the case of open pond systems (Pienkos, 2007). Algae strain selection and cultivation require special skills and demand special attention.

Survey results show that the biggest challenge in making algae biofuels cost-competitive with other fuel sources was a cost effective production system and harvesting and extraction systems.

Table 4.14 shows that 80% of the respondents (n=28) reported that the biggest challenge faced by the algae industry is the cultivation growth system, closely followed by component separation or dewatering as reported by 69% (n=24) of the respondents. More than half (66%, n=23; 60%, n=21) of the respondents reported algae species selection followed by extraction of algae oil as major challenges respectively. Another half (54%, n=19) reported contamination as a major challenge and less than half (46%) of the respondents (n=16) reported light/temperature management to be a barrier in making cost-competitive algae based biofuels. None of the respondents felt that there was a lack of trained professionals.

Table 4.14: The biggest challenge in making cost-competitive algae based biofuels

Technical challenges	Response percent	Response count
Production system	80%	28
Lack of trained professionals	0%	0
Algae strain selection	66%	23
Component separation	69%	24
Light/temperature management	46%	16
Extraction	60%	21
Contamination	54%	19
Others	0%	0

According to Dheeban Chakravarthi Kannan, algae harvest methodology remains the main barrier for algae biofuel enterprises throughout the world and a viable methodology is needed to harvest the grown cells. When asked about the major challenges faced by the algae biofuel industry, he added that the mass cultivation growth system also pose several challenges that are barriers to commercialization of microalgae biofuels. He said:

> "Although high productivity numbers have been reached in lab, replicating it in real world large scale conditions requires improved growth system designs. It would depend on the growth components available outside – light, water type, temperature, etc".

Vivek Kumar and Harshith Sirigeri also believe that the biggest technological challenge is the downstream process- harvesting, dewatering and drying. Innovation in technology and integrated systems are necessary to overcome these challenges. According to Vivek Kumar, finding or engineering the right species of algae and integrating it with the best suited downstream processing is important to create an optimum system for microalgae cultivation. He said:

> "The choices made at this stage will decide the affordability, scalability and sustainability of algae biofuels".

Ramalingam Sivakumar also believes that the toughest challenge is to find the right algae strain. He believes that the choice of the downstream processing will depend upon the algae species selected.

Dr. Senthil Chinnasamy considers the extraction system to be the biggest challenge faced by the algae biofuel industry. He believes that the Hexane extraction is currently the most cost-efficient process but only on a small-scale. In the words of Dr. Senthil Chinnasamy:

> "Hexane extraction is presently the most economical option to recover lipids from algae. But even that becomes cost-prohibitive since very large-capacity processing plants would need to be built, and this would increase the transportation cost. Hence, new on-site smaller-capacity processing technologies are required".

He also said that there has been no clear roadmap for research and development:

> "There has been no vision on land demarcation needed for such purposes. The water intensive nature and its dependence on various types of regions have not been addressed".

He suggested that an integrated approach of combing biofuel production with wastewater treatment will reduce the cost significantly.

In order for algae biofuels to become cost-competitive with petroleum products, it is important to provide assistance in the form of production grants, loan guarantees, and incentives such as tax credits and fuel subsidies to encourage biofuel production. Incentives and funding programs can spur wide scale investment in the development of algae biofuel industry. Integration of sustainability schemes with biofuel policies is essential in order to provide market stability and improve public acceptance, which will attract investors for sustainable biofuel projects.

When asked to list the policies that would help in building a robust algae biofuel industry, more than three-quarters (77%) of the respondents (n=27) felt there was a need for Cleantech investors, followed by a 69% (n=24) who said government funds/incentives. More than half (63%) of the respondents (n=22) reported tax credits, another 49% of the respondents (n=17) reported fuel subsidies and 31% of the respondents (n=11) reported loan guarantees (Table 4.15).

Table 4.15: According to you, what are the policies that are important in building a robust algae biofuel industry?

Policies	Response percent	Response count
Government funds/grants	69%	24
Loan guarantees	31%	11
Cleantech investors	77%	27
Tax credits	63%	22
Fuel subsidies	49%	17
Others	0%	0

Achieving economic feasibility in generating algae biofuels is the biggest challenge faced by the industry. According to the respondents, the main challenge facing innovation is government funding and investment. When interviewed, Dheeban said that:

> "The space/infrastructure allocation is a problem for private institutes as the government does not provide any overhead support".

He believes that it is important to create and manage policies in order to attract government/ private funding and investment as it can help improve the biofuel industry while providing jobs in rural communities. Above all, it is time to become active in all disciplines, discuss possibilities instead of problems, develop a vision/roadmap and team up with the industry.

Harshith Sirigeri and Senthil Chinnasamy agree that, with government funds and incentive programs, it is possible to reduce the cost of biofuels to cost-competitive levels by 2020. To speed up a breakthrough in technology, it is essential to get the support of the government to enable continued investment in research and development of biofuel production in India. According to Senthil Chinnasamy, government should initiate and pursue policies that will encourage the private sector to invest into large-scale production of algae biofuels- for proven technologies, including incentives to scale-up technology from demonstration projects to industrial scale. Harshith Sirigeri emphasized that a multidisciplinary approach dealing with the engineering issues, cell biology, upscaling, logistics and sustainability issues is needed to reduce the cost and enhance productivity.

Vivek Kumar believes that a public-private partnership can bring the biofuels into the market, where innovation in research and development and the capital to support it will be provided by the private sector and the policies to support its growth will be provided by the public sector. He said:

> “Building investor’s confidence is no easy task.. Investors willing to take a change on algae may find it more profitable to focus on the byproducts of algae and not biofuels and this could hinder the development of algae biofuels as an alternative to petroleum”.

Therefore, the need for investor confidence is essential to commit the funds needed in order to take the industry forward. This can be done by getting into a stable and long-term policy contract. According to Ramalingam Sivakumar, policy measures that address the market risks associated with scaling-up innovative technologies and the insecurity of product markets for advanced biofuels is essential in attracting large-scale investment. He also believes that algae biofuels have the potential to significantly boost the economy that will lead to millions of new jobs. As he reflected:

> “India is capable of displacing the fossil fuel consumption entirely by 2030 and produce another 4 billion liters for export”.

4.8 Genetically modified algae

The future of genetically modified algae species is the question dominating the researchers in the algae biofuel industry. Genetically modified algae (GMOs) come with their benefits and risks. Although genetic modification improves the productivity rate by two-fold, critics fear that the economic gain could be at the cost of environment and human health (Lacey, 2011).

The survey results show that there is a high level of agreement that genetically engineered algae can make a significant impact on the production of biofuels and also improve the economic situation. Table 4.16 shows that while 46% of the respondents (n=16) said no, 26% of the respondents (n=9) said they plan to research/focus on genetic modification of algae strains. Some (29%) respondents (n=10) said they may focus on GMOs.

Table 4.16: Do you plan to research or focus on algae genetic modifications GMOs

	Response percent	Response count
Yes	26%	9
No	46%	16
Maybe	29%	10

For Dheeban Chakravarthi Kannan, Harshith Sirigeri, Senthil Chinnasamy and Vivek Kumar, genetically modified algae are not justifiable. The interviewees see more risk than opportunities in GMOs and emphasized that microalgae cultivation should rely on existent biodiversity. Vivek Kumar argued that the introduction of modified species into the environment could have a potential impact on the environment and biodiversity as there is little knowledge about the genetics of the algae species. Also it would be rather difficult to monitor their growth and spread in the natural ecosystem due to their microbial nature.

"Genetically engineered algae will have a positive impact on the biofuel production", says Ramalingam Sivakumar.

He believes that GMOs have the capability of growing under high CO_2 concentrations and have the ability to withstand the presence of contaminants in the wastewater. Advances in this area of research can make algae biofuel production feasible in the near future. However, the current regulations and technical complications limit its development.

5. PROPOSED STRATGIES FOR ALGAE BIOFUEL DEVELOPMENT IN INDIA

Environmental perspective

The survey reconfirms the obvious that there is an increased interest in developing microalgae feedstock for biofuel production for the economic and environmental benefits it has over fossil fuels. One of the primary environmental benefits of microalgae cultivation is its ability to mitigate CO_2. According to the U.S. Department of Energy, the production and consumption of biodiesel has resulted in a 78.5% reduction in CO_2 emission, as opposed to petroleum diesel (National Biodiesel Board, 2009). Microalgae are capable of utilizing high levels (300-400ppm) of CO_2; higher than atmospheric CO_2 levels for algae biomass production (Chanakya et al., 2012). The ability of microalgae to fix CO_2 via various sources such as the atmosphere, through flue gases from industries and from soluble carbonates, makes them an attractive alternative to other fuels (Wang et al., 2008). Additionally, using microalgae strains that have a high CO_2 tolerance have several benefits such as the CO_2 released during nighttime can be stored for conversion during daytime; contaminant control is relatively easy as only a few strains can survive in elevated CO_2 concentrations (Table 5.1) and such strains also exhibit high pH optima ranging from 9.0-11, making contamination control easier (Wang et al., 2008; Ginzburg, 1993). Therefore, an integrated system of combining microalgae cultivation with CO_2 capture from power plants can serve as an effective CO_2 mitigation system along with the production of algae biomass. Table 5.1 lists some of the algae species that are researched upon in India that can tolerate high CO_2 concentrations.

Table 5.1: CO_2 tolerance of various algae species researched upon in India. Source: (Goswami et al., 2012).

Species	**CO_2 tolerance**
Scenedesmus sp	80%
Chlorella	40%
Dunaliella sp	15%
Nannochloropsis	15%
Chlamydomonas	15%
Tetraselmis	14%

The research findings also concur with the literature studies which reported that the cultivation of algae is more prominent in the southern and eastern parts of India. This is because of the availability of water for most part of the year which facilitates microalgae growth. Figure 5.1 shows that a large part of south and eastern India is suitable for algae cultivation particularly Tamil Nadu, Karnataka, Andra Pradesh, Gujarat, Rajasthan and Punjab-Haryana (Chandigarh). It is important to take into consideration the evaporative losses and the total annual precipitation for that geographic location, when choosing an area for algae cultivation. According to Chanakya et al. (2012), the water lost through evaporation should not exceed the annual rainfall for that location, in order to increase the cultivation period.

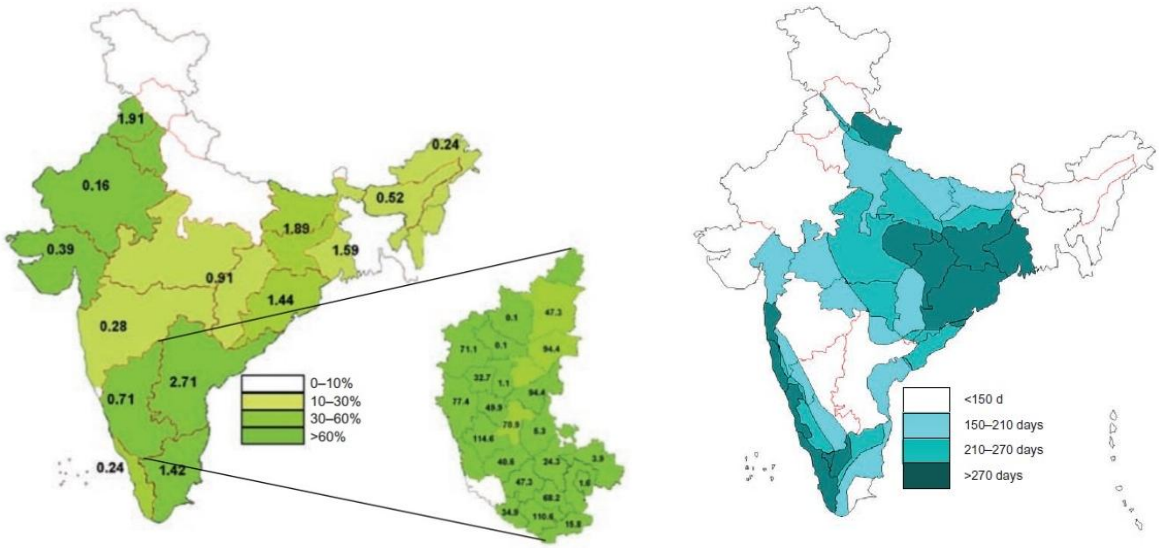

Figure 5.1- Algae cultivation (left) and the availability and supply of water after meeting the needs of a single or double crop (right). Source: (Chanakya et al., 2012).

Large quantities of micro and macro nutrients particularly Nitrogen (N), Phosphorous (P) and Potassium (K) are essential for the large scale cultivation of microalgae (Garofalo, 2011). The nitrogen requirements are currently being met by fertilizers, which on a large scale can burden the already high levels of fossil fuel dependence (Chanakya et al., 2012). A sustainable alternative to minimize the dependence on fertilizers is to cultivate algae in wastewater as they are a rich source of nutrients. In addition to generating substantial quantities of algae biomass, this process can also be used for wastewater treatment. Microalgae are also capable of removing chemicals and other heavy metals from wastewater, while producing biomass (Munoz and Guieysse, 2006). Such an integrated process will not only provide savings on fertilizer requirement, but will also minimize the dependence on freshwater sources for algae cultivation (Li et al., 2008). However, the major drawback associated with growing microalgae in wastewater is that, they are difficult to harvest (Tang et al., 1997). *Phycospectrum Consultants Pvt Ltd.* in Chennai is currently focusing on wastewater treatment using microalgae where algae biomass is harvested using a combination of auto-flocculation and chemical flocculation. Considerable R&D efforts are required for this technology since most of the research on microalgae wastewater treatment in India is based on the analysis of a small laboratory-based and pilot pond scale culture.

Techno-Economic perspective

Biofuels produced from algae certainly has its benefits, but there are certain techno – economic issues that require attention for the successful commercialization of algae biofuels. There are several challenges that exist from cultivation to harvesting of microalgae and extraction of lipid for biofuel production. The survey findings complement the literature study on the cultivation of microalgae in open-pond systems for their low capital investment and relative ease in construction. Photobioreactor systems are largely based on laboratory-based results and require high capital and operating costs (Kumar, 2011; Benemann, 2009; Carvalho et al., 2006). Although photobioreactors provide greater control over culture parameters and have a higher harvesting efficiency (Suh and Lee, 2003), the complexity of operation of PBRs and the high cost associated with it limit their use on a large-scale. There are currently no reports of commercial-scale production of microalgae in India using photobioreactor systems. At present, most (~98%) of the commercially produced microalgae biomass is cultivated in open-pond systems (Benemann, 2009). The use of hybrid design that combines the benefits of both open-pond and closed-photobioreactor systems could provide a cost-effective solution.

Other major technical and economic bottleneck in the production of microalgae biofuel is in the downstream processing which includes dewatering/ drying and extraction of algae biomass, which is energy intensive and expensive. Dewatering and drying the biomass is a standard procedure prior to extraction of the lipids which contributes to nearly 80-85% of the total production cost (Lardon et al., 2009). Direct extraction of lipids from wet biomass however is less energy intensive and seems to be an attractive solution. The ‘Simultaneous

Distillation and Extraction Process' (SDEP) is a newly developed procedure for extraction of lipids directly from wet algae biomass without pre-drying (Dejoye-Tanzi et al., 2013). Results show that a high lipid yield along with a substantial savings in extraction cost was achieved using microalgae species such as the Nannochloropsis oculata and Dunaliella salina (Dejoye-Tanzi et al., 2013). According to Yoo et al. (2012), osmotic shock can be used to extract lipids from wet algae biomass and by manipulating the cell structure of the algae strain, can double the lipid recovery. Extraction of wet algae biomass using subcritical co-solvents (combination of hexane and ethanol) have also shown to increase lipid yield while reducing cost (Chen et al., 2012). For higher lipid recovery, a solvent known as 2-ethoxyethanol (2-EE) has been used which has shown to be more effective in extraction of lipids from wet biomass compared to dry biomass (Jones et al., 2012). Studies show that using near-critical dimethylether (DME) solvent can extract lipids from both wet and dry biomass, leading to higher yields (Catchpole et al., 2010). Further research in the wet-lipid extraction system along with investment in technological development is needed for the large-scale commercial production of microalgae biofuels. When introducing new technologies, it is important to take into consideration the ease of implementation.

The survey findings seem to concur with the literature studies which reported that solvent extraction is the most widely used method to recover lipids from algae. Solvent extraction is popular for its economic and environmental benefits, but large-scale production will require infrastructural demands and transportation, which could increase the overall cost. Standardization of harvesting and extraction techniques could be the solution for the large scale production of microalgae biofuels. But regardless of the advances in technology and research, the commercialization of algae biofuels will ultimately depends on the economic viability of the technology.

Socio-Economic perspective

Algae biofuel production faces several economic challenges. The main issue faced by the country is the lack of sufficient financial resources, which is preventing the spread of new technology and development. Survey results indicate that there is limited public-private investment. The private sector will make huge investments only if the concept or technology is good enough to make profit from the investment. It is evident in the survey results that the organizations focusing on algae biofuels do not receive much support from the government, particularly the ones at the national and local level. It is important for the national government to provide loans, grants and incentives and also support and initiate policies that will stimulate investment in algae biofuel sector for their commercial success. Non-governmental organizations (NGO) should monitor the progress of biofuel development, policy changes and other biofuel related issues and publish results on a regular basis to keep a check on industries and governments.

In order for algae biofuels to enter the international market, it is essential for both the fuel and vehicle to comply with international standards. Government should work towards the development of international markets by elimination of trade barriers and implement sound sustainability criteria based on internationally agreed standards. International collaborations can help create a sustainable biofuel sector by stimulating large-scale investment. Joint R&D efforts and involving developing countries in technology development can accelerate the successful deployment of large-scale biofuel production.

India being a developing country, the cultivation of microalgae in rural areas will have several benefits, from an economic perspective. Expenses for nutrient and water replenishment, infrastructure preparation, component replacement, cost of land and labor in India will be low. The production of microalgae biofuels can generate new opportunities for income in rural communities while eliminating the expenditure involved in importing petroleum products. Government should make sure that biofuel policies are in-sync with policies in the rural and agriculture sector.

Developing an integrated algae processing (IAP) of producing algae biofuels along with the generation of high value-added co-products using a biorefinery approach, can substantially reduce the overall cost of production. Algae biomass is capable of yielding various co-products such as omega-3 fatty acids, proteins, nutrients, feed and fertilizers from the same biomass which makes them an ideal candidate for biorefinery approach (Subhadra and Grinson-George, 2010). Several companies in India are targeting co-products such as feed, pharmaceuticals and aquaculture apart from producing biofuels. Such a process can contribute significantly to rural development where nutrients, feed, fertilizers and other co-products can be customized to local needs. Additionally, industries should focus on improving the feedstock flexibility to allow the production of a wider range of feedstocks that will reduce the feedstock competition.

Estimated cost of algae biofuels using current technology as predicted in the year 2010 is U.S $300- $2600 per barrel (Hannon et al., 2010), reaching prices as low as U.S $84 in some regions (Huntley and Redalji, 2007). According to a recent report by Parmar, (2012), scientists from Central Salt and Marine Chemicals Research Institute (CSMCRI), India have recently developed B100 biodiesel from microalgae at a cost of Rs.175 per liter (U.S $382 per barrel), which is expected to go as low as Rs.75 per liter (U.S $167 per barrel) with advanced extraction techniques. In the present scenario, it is difficult, rather impossible for algae biofuels to replace diesel oil as the current price of diesel in India is in the range of U.S $110- $120 per barrel ($0.9- $1.1 per liter) (NDTV, 2013). However, the price of diesel is expected to increase to meet the growing demands of the ever increasing population (Figure 5.2). As per the survey results, the cost of biofuels in the year 2020 is predicted to be between U.S $120- $360 per barrel ($1.1- $3 per liter), according to conversion rates in May 2013. With policy changes, investment and innovation in technology, the cost of algae biofuels can be reduced further to an extent where it can completely replace diesel fuels. Eliminating subsidies for fossil fuels and establishing a price for CO_2 emission can help promote the use of biodiesel.

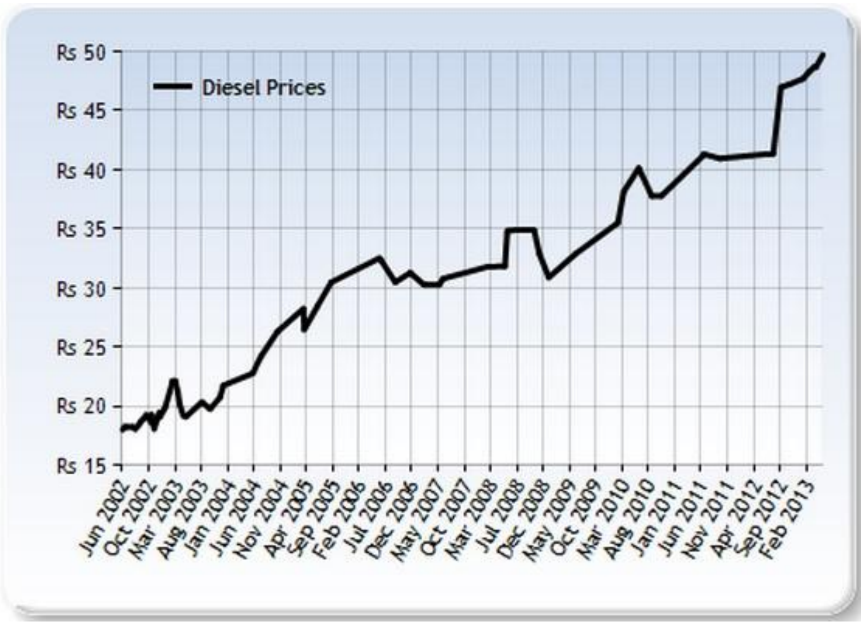

Figure 5.2: Shows the consistent increase in diesel price in India between 2002 and 2013. Source: (Kumar, 2013)

Concluding remarks

Cost reductions can be achieved by reducing the number of complex steps (such as cultivation, harvesting, dewatering, drying and extraction) that are involved in the production system. A major savings in cost and energy can be achieved by adopting the wet-lipid extraction process. Coupling wastewater treatment with algae biofuel generation and adopting a method to directly extract lipids from wet-biomass without pre-drying can help reduce the cost of biofuel production significantly. In addition to that, adopting a biorefinery approach can further improve the economics of biofuel production.

There are several factors that need to be taken into consideration when discussing cost such as the algae species selected (as the productivity is based on the lipid content and other parameters of the strain), the cultivation system employed and infrastructure installation (which will decide the capital investment needed), site location (since operating costs are site dependent), resource availability (water, other nutrients and CO_2 sources which can add to operational costs), downstream processing which includes harvesting, dewatering/drying, extraction (contribute to the operational costs) and other categories such as labour, maintenance, supervision, wastewater treatment, marketing, tax, etc. (which add to the O&M costs). For example, assuming that the achievable biomass productivity is approximately 22 tons/acre-year; employing algae strain that has 25% oil content is capable of producing approximately 1,500 gallons/acre-year (48 barrels of oil/acre-year). Based on the current scenario, this would translate to approximately U.S $18,000/ ton of oil, which is significantly high. Improved productivities and technological advances can largely overcome this gap. But there are additional costs involved in the production of algae biofuels which are difficult to analyse as they are site dependent.

6. CONCLUSION

Algae could be the future for a carbon-neutral biofuel feedstock. Algae have several advantages such as high growth rate and yield as compared to other traditional biofuel crops, the ability to grow on non-arable land and thrive on wastewater (industrial, agricultural, saline, brackish), recycle nutrients from waste streams and mitigate CO_2 (Darzins et al., 2010). However, the production of biofuels from algae faces several challenges – both technological and economic, that require further research and development for the successful commercialization of the industry.

Most of the respondents mentioned the high energy and cost requirements of production of biofuels as a major obstacle in the commercialization of biofuels. Scaling up of technology is yet another major concern. Although most of the respondents remain optimistic about the future developments in technology, they are aware that the production of huge amounts of usable biomass for microalgae has not yet been tested on a large scale. There are some respondents who are unsure about the large-scale production of biofuels in the near future and stressed the need for investment in R&D, despite knowing the challenges faced by the industry. However, a large majority of the respondents believe that development in strain selection and innovation in cultivation and harvesting techniques can solve the challenges. This will require engineering innovation and advancement in algae harvesting and downstream processing, while also focusing on several biological issues such as finding or engineering the right algae strains. Several challenges and opportunities lie ahead.

Several challenges exist in the cultivation, harvesting, dewatering and extraction of lipids from microalgae. Commercial algae production employs both open ponds and closed bioreactor systems that have its advantages and disadvantages. Although open ponds are easy to build, ideal for the climatic conditions in India and require a low capital, they are subject to contamination from other microalgae species and organisms. Photobioreactors on the other hand provide a controlled environment for microalgae growth and can be tailored to specific demands; but they require a huge capital investment. Respondents showed a strong support for the open pond system and a favourable attitude for closed systems recognizing the need for improvements in technology as it is in the early stage of development. The cost-effectiveness of using the closed bio-rector system was questioned by some respondents as they were more familiar with the open systems. Results highlight that intensive laboratory-scale studies are being conducted to determine a pathway for large-scale cultivation of algae. One of the respondents suggested that a dual-use cultivation system combining wastewater treatment with biofuel generation can be adopted for positive returns. It provides a pathway for removing nitrogen, phosphorous and other toxic metals from the wastewater and produce algae biomass which can be further processed to algae biofuels. Algae cultivation in wastewater faces a lot of challenges such as contamination and unstable biomass production which requires further research (Cai et al., 2013).

Of all the hurdles, dewatering/ drying of the biomass prior to extraction have been identified as the major bottleneck in the biofuel industry. Most respondents feel that efficient and economic harvesting and extraction technologies should be developed in order to make algae biofuels cost-competitive with other fuels. The main hurdle in the commercialization of microalgae biofuels is in the energy and cost associated with dewatering/ drying and extraction of lipids from algae biomass, which is substantially high demanding innovation in technology for cost-effective solution. There is critical research in developing wet processing technologies for converting wet biomass to biofuels, which has proven to be more energy efficient compared to the dry route (Xu et al., 2011).

There is a strong focus on genetically engineered algae species with efforts aimed at increasing productivity. There were mixed reviews when respondents were asked if they would focus on GMOs. While some respondents showed strong disapproval, an equal number favoured the idea of researching on genetically engineered algae. Respondents believe that genetic engineering is likely to make a significant impact on microalgae biofuel production by improving the economics of production. One of the respondents added that:

"The current regulations and limitations in technology needed for genetic modification are a serious obstacle to the development of genetically modified strains".

The few who objected see more risk than opportunities and stressed that algae cultivation rely on existent biodiversity. Advancement and innovation in technology can bring a significant breakthrough in the production of algae biofuels.

Significant investment in technological development is needed before large-scale production of algae biofuels can become a reality. As highlighted by one of the respondents:

"Public discussions on biofuels providing critical data on the good and bad of biofuel production, based on state-of-the-art research results can avoid creating market uncertainty and attract investors".

Additionally, to get access to the international market, it is crucial for the biofuels to comply with international standards- both fuel and vehicle standards. To avoid infrastructure barriers and allow for a smooth entry into new markets, it is essential to exchange experience and knowledge between upcoming markets and large-scale biofuel producing countries.

Algae is the perfect choice for future processing in bio-refineries because of its unique features such as the availability of a large range of species with different characteristics that allows for a spectrum of different products to be synthesized from it. Respondents emphasized the need for commercial production of high value-added products combined with algae biofuel production. An integrated approach of processing biofuels along with various high-value co-products such as food, feed and fertilizers, can bring financial sustainability to the production facility. The use of the bio-refinery concept along with technological advance is expected to lower the cost of biofuel production significantly.

However, in view of the challenges the world faces today in terms of limited resources such as arable land, access to fresh water and most importantly fossil fuels; the opportunities provided by algae biofuels are much greater than the technological challenges it currently faces. Large-scale research and efforts are underway to achieve commercialization of algae biofuels likely to be possible in the near future.

7. RECOMMENDATIONS AND CONSIDERATIONS

Biodiesel from microalgae is a goal that requires further research to reach commercialization. The economic feasibility of biofuel production is directly proportional to algae productivity and any improvements in the yield will increase the economic gain. Although technological improvements may be expected in the near future, optimization of the biological process can play an important role in the economic viability of algae biofuel production.

International collaborations can be promoted to reduce cost. Government should provide long-term targets and introduce specific policy measures that address the economic risks involved in scaling up of the technology and the insecurity of product markets to attract large-scale investment to ensure algae biofuels reach commercial production. Policies that support research and development of algae biofuels should focus on the whole production chain beginning from cultivation, to transport to end use products in order to avoid barriers at any stage of production, which could slow the entire process of technological development. Additionally, to enrich international biofuel trade, government should ensure that sustainability criteria adhere to internationally agreed principle and standards. Intergovernmental organizations and development agencies should work on biofuel standardization to enhance international trade.

Other aspects that are recommended for further research are the large-scale testing of hybrid system that combine the benefits of both open pond and closed photobioreactor systems. It is recommended that photobioreactors use seawater for cooling, especially in regions where freshwater supply is limited. Furthermore, cultivation of algae on non-arable land should receive more attention as such a process will not pose a threat to the environment and food security.

To make the process more economical, it is recommended that the microalgae cultivation process be integrated with CO_2 sequestration from coal-fired power plants and/or be coupled with wastewater treatment which can minimize the dependency on external sources of nutrients.

From an economic perspective, industries should develop concepts for an integrated approach of targeting high value co-products along with energy production with a bio-refinery approach. Algae production can contribute significantly to the development of rural communities by an integrated approach of co-producing energy with value added co-products such as nutrients, feed, fertilizers, biofuels and many other products that can bring overall economic feasibility. Industries should also engage in public-private partnerships to foster private sector investment in new technologies.

Non-governmental organizations (NGO) should monitor the progress of biofuel development, policy changes and other biofuel related issues by publishing the results on a regular basis to keep a check on industries and governments. They should also provide objective information on the potential of sustainable biofuels to mitigate climate change, increase energy security and provide economic benefits for rural communities.

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APPENDIX A: Link to the survey

1. http://www.surveymonkey.com/s/938D2B7
2. http://www.surveymonkey.com/s/93VW65N

APPENDIX B: Algae Biofuel Questionnaire

1. **Name of your company/institution or personal name in case of individual. (please specify location)**

2. **Field of activity**

   - Research
   - Industrial Development
   - Food related issues
   - Aquaculture
   - Feed
   - Investment
   - Technology Provider

   Other (please specify)

3. **Years of experience in the field**

4. **Algae strains produced and/or researched upon (please list the main ones)**

5. **Criteria for strain selection**

   - Oil content
   - Adaptation to local conditions
   - Lipid Productivity
   - Other (please specify)
   - Resistance to contamination
   - Harvest ability

6. **The kind of production system employed and/or researched**

   - Open ponds
   - Pilot demonstration

- [ ] Photobioreactors
- [ ] Hybrid design
- [ ] Laboratory
- [ ] Other (please specify)
- [ ] Industrial system
- [ ] Lagoons

7. **The harvesting technique adopted and/or researched**

Centrifugation
- [ ] Filtration
- [ ] Flocculation
- [ ] Other (please specify)
- [ ] Sedimentation
- [ ] manual or mechanical

8. **The extraction process employed and/ or researched**

Expellers/oil presses
- [ ] Enzymatic extraction
- [ ] Solvent extraction
- [ ] Other (please specify)
- [ ] Osmotic shock
- [ ] Ultrasonic extraction

9. **Which kind of end uses are you targeting**

Biofuel
- [ ] Feed
- [ ] Aquaculture
- [ ] Pharma
- [ ] Other (please specify)
- [ ] Fertilizers
- [ ] Bioplastics
- [ ] Biomass for electricity generation

10. **Project involvement**

○ Local ○ National ○ International

11. **Have you managed to reduce the cost of algae biofuels over the years**

○ Yes ○ No ○ Don't know

12. **If yes, by what percentage have you managed to reduce the cost of biofuels per litre**

13. **What is the projected cost of biofuel per litre (by the year 2020)**

14. **In your opinion, how likely is it that algae based fuels will be cost competitive by**

- [ ] Very Likely
- [ ] Likely
- [ ] Not likely

15. **Are you being provided with any incentives/ carbon nutrients credits/ subsidies/ funds etc by the government to expand the industry**

- [ ] Yes
- [ ] No
- [ ] Don't know

16. **Do elected officials (policy makers) at any level (local, state, national) ever visit your facility**

- [ ] Yes
- [ ] No
- [ ] Don't know

17. **Are you planning to expand your organization in order to promote biofuels**

- [ ] Yes
- [ ] No
- [ ] Don't know

18. **What is the biggest challenge in making cost-competitive algae based biofuels**

Production system

- [ ] Lack of trained professionals
- [ ] Algae strain selection
- [ ] Component separation
- [ ] Other (please specify)
- [ ] Light/temperature management
- [ ] Extraction
- [ ] Contamination

19. **According to you, what are the policies that are important in building a robust algae biofuel industry**

- Government funds/ grants
- Loan guarantees
- Cleantech investors
- Other (please specify)
- Tax credits
- Fuel subsidies

20. **Do you plan to research or focus on algae genetic modifications GMOs**

Yes No Don't know

APPENDIX C: The list of interviewees.

1. Dheeban Chakravarthi Kannan - The Energy and Resources Institute, Delhi
2. Vivek Kumar- Albert Einstein Science Institute, Delhi
3. Harshith Sirigeri - GreenBubble, Bangalore
4. Senthil Chinnasamy - Aban Infrastructure Pvt Ltd / Chennai
5. Ramalingam Sivakumar - Private Spirulina consultant, Chennai

APPENDIX D: Covering letter

Dear Mr/ Ms,

Thank you very much indeed for your time and effort.

My name is Nithya and I am a student at The British University in Dubai. As part of a Masters dissertation, I am carrying out a survey on the 'Techno-economic analysis of microalgae for biofuel production in India' and would greatly appreciate if you could participate in it.

The survey consists of 20 questions in total, split into two parts. It will not take more than 2 minutes of your time. I will present the feedback from the findings when the research is completed and hope it will provide some support for you in this area of your work. Confidentiality of your responses will be completely protected unless you have given permission otherwise.

Below is the link to my survey.

1. http://www.surveymonkey.com/s/938D2B7
2. http://www.surveymonkey.com/s/93VW65N

Thank you once again and look forward to hearing from you.

Regards

Nithya Srinath