Theoretical Estimation the Potential of Algal Biomass for Biofuel Production and Carbon Sequestration in Ethiopia

Abraham M. Asmare*‡, Berhanu A. Demessie**, Ganti S. Murthy***

*Chemical and Biochemical Engineering, Addis Ababa Institute of Technology

**Chemical and Biochemical Engineering, Addis Ababa Institute of Technology

***Biological and Ecological Engineering, Oregon State of University, USA

(abraham.mebrat@aau.edu.et, hmberhanu@yahoo.com, murthyg@onid.orst.edu)

‡ Corresponding Author; Abraham Mebrat, P.O.Box:385, Tel: +251-911-104685, Fax: +251-111-239480, abraham.mebrat@aau.edu.et

Received: «received» Accepted: «accepted»

Abstract- Five regions of Ethiopia were identified as potential sites for the algal biomass cultivation considering both sunlight and local climatic conditions. The meteorological data, sunlight and air temperature information for the identified potential sites were used as a basis to estimate annual biomass production, lipid production and carbon sequestration potential. An average upper biomass, oil yield and carbon fixation potential were calculated to be 291.6 ton/ha/yr, 101,249.2 L/ha/yr. and 82.7 ton_{CO2}/ha/yr. This study provides a baseline data for theoretical estimates of open pond microalgae production systems in Ethiopia. This study will support the Ethiopian government in its Energy and Food Security policy to promote the use of indigenous and renewable sources of energy for transportation fuels and income generation

Keywords- Biomass productivity, lipid productivity, Microalgae, Carbon dioxide fixation, solar radiation

1. Introduction

Demand for energy is increasing every day due to the rapid growth of population and urbanization [1]. According to International Energy Agency (IEA) [2] data from 1990 to 2008, the average energy use per person increased 10% while world population increased 27%. About 80% of this energy demand is delivered from fossil fuels with the consequence of an increase of greenhouse gas emissions in the atmosphere that provokes serious climate changes from global warming. The world today is heavily dependent on fossil fuels. The global increase in carbon dioxide concentration is due primarily to fossil fuel use and land use change, while those of methane and nitrous oxide are primarily due to agriculture [3].

Ethiopia belongs to the non-oil exporting less developed countries of Africa. Ethiopia imports all of its petroleum products and the demand for petroleum fuel is rising rapidly due to the growing economy of about 10% GDP growth and infrastructure development. In the second quarter of 2007/08, petroleum imports exceeded exports earnings by 30%. With the recent trends and volatility of oil prices, the country has been forced to develop a biofuels strategy to mitigate the impacts of imported oil on its economy. The strategy encourages the diversification of energy supplies in the transport sector; therefore, biofuel offers significant opportunities for Ethiopia [4].

Ethiopia's demand for electricity and petroleum fuels will grow at 11.6 and 9.3% per year, respectively. The demand growth will have serious economic, social and environmental implications and repercussions [4].

All microalgae as renewable source energy for biofuel production primarily comprise of the following, in varying proportions: proteins, carbohydrates, fats and nucleic acids. While the percentages vary with the type of microalgae, there are microalgae types that are comprised up to 40% (20%-80%) of their overall mass by fatty acids [5], and it has higher growth rates and the capability to accumulate higher amounts of lipids [6,7,8,9,10] than conventional oil crops those are not more than 5% of dry weight [11] and therefore the oil yield per hectare obtained from microalgae can greatly exceed the yield over the next best oil producing crop, oil palms.

Algae can grow in a wide variety of conditions from freshwater to extreme salinity, non-arable land or in dirty water [12, 13]. They are more efficient converters of solar energy than terrestrial plants and take carbon dioxide out of the atmosphere as they grow [14]. Algae are the most optimum organisms for sequestration of CO_2 because of their ability to fix carbon by photosynthesis. The cultivation of algae has been suggested for carbon capture because of its ability to fix CO_2 into biomass and thereby to produce carbon neutral fuels. The prospects of CO_2 mitigation by microalgae is inhibited because of the lack of viable technologies at large scale [15]. The preference towards microalgae is due largely to its less complex structure, fast growth rate and for high oil content.

It is believed that there are hundreds of thousands of species of microalgae, although only about 40,000 individual species have been described to date [16]. They use starch as their primary storage component. However, nitrogen deficiency promotes the accumulation of lipids in certain species. Green microalgae are the evolutionary progenitors of higher plants and, as such, they have received more attention than other groups [17]. Common microalgae found in Ethiopia: *Anabaena, Botryococcus braunii, Chlorella, Chroococcus, Gloeocapsa, Haematococcus pluvialis, Lyngbya, Oedogonium sp., Oscillatoria, Scenedesmus, Synechoccystis, Spirulina and Synedra,* etc. Some of these algae strain may contain up to 75 % lipids making them very suitable for the production of liquid fuels [6, 7].

Microalgae presents one of the most exciting possibilities as a future solution to our energy problems, especially that of transportation fuel. There are several different studies conducted on the theoretical photosynthesis efficiency [18, 19, 20], but they have not been applied specifically to algal photosynthesis on specific Ethiopian climate conditions. Algal productivity based on small-scale experiments were also estimated and reported in different literatures [8, 17]. Maximum efficiency and annual algae biomass production yield were calculated based on numerous assumptions without addressing lowest possible yield [21].

Biofuel production from algae has the potential to improve food security, and incomes for Ethiopian families. Crops not used for food can also be considered for biofuel production. Algae have been shown to be very promising as a biofuel; with it is not share the crop land and grow with wastewater and stress handling abilities. New research could even develop ways to use only the non-food feedstock like microalgae. The need to have renewable energy technologies for Ethiopia is guided by: sustained economic growth and food security, energy security, rising investment pressure and sustainable environment.

The objective of the present study is to investigate biomass and lipid productivity, and carbon dioxide sequestration using weather data for the selected locations climates and in order to generate baseline data under optimum growing conditions of Ethiopian context. These values provide a benchmark against which to gauge predicted and achieved yields both to the designers of algae production systems and those seeking to implement the technology.

2. Methodology

2.1. Site Selection

According to Maxwell et al. [22], the selected sites for microalgae cultivation have to meet the following criteria such as, availability of sunlight throughout the year, favorable climatic conditions, temperature, relative humidity, precipitation and evaporation, land topography and assess to nutrients, carbon sources and water. For the above reasons, microalgae production will be possible in some regions of the world which have optimal temperature and solar radiation [23], among them Ethiopia is one of the potential areas.

Sites suitable for algal cultivation should have a basic requirement of abundant sunlight. This is undoubtedly an important consideration since insulation directly linked to biomass yield. Barsanti and Gualtieri [24] stated that about 6224.34 μmoles/m^2/s of light energy reaches the outer atmosphere of earth and on average only 1096.8 μmoles/m^2/s reaches the earth's surface.

2.2. Climate and Weather Data (Sunlight and Air Temperature Data)

The sites selected for this study are based on availability of adequate sunlight, air temperature, number of the population, and proximity to industrial area. The average ambient temperature greater than 15°C are selected for this study [25]. The meteorological data such as solar radiation intensity and air temperature of potential sites are obtained from NASA maps/RETScreen software [26]. As the productivity of algae is determined by the available solar radiation levels, is important in assessing the potential of algae growth.

Annual solar radiation within the world generally varies between 3199 and 11425 μmoles/m^2/s**.** This is undoubtedly an important consideration since insulation is directly linked to biomass yield. Tropical countries like Ethiopia experiencing more intense sunlight are ideally suited for microalgae cultivation. However, to identify the variation in productivity of each region, the hypothetical algae biodiesel production facility for this study is considered to be located in five Ethiopian regional climates as shown in Figure 1.

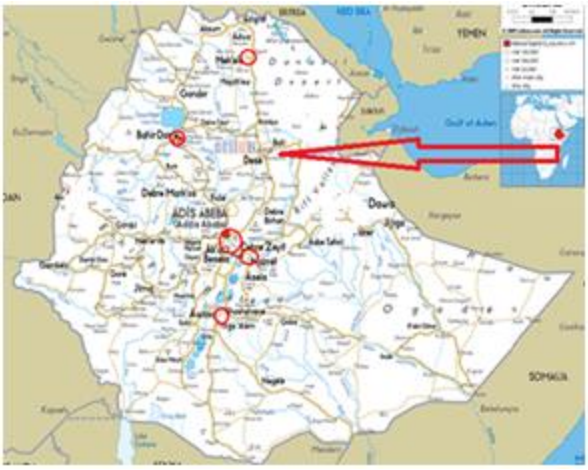

Fig 1: Selected Sites Map Location

Five different locations were considered for the microalgae biodiesel facility presented in this paper: Addis Ababa (8.9^o N, 38.8^o E), Awasa (7.1^o N, 38.5^o E), Bahir Dar (11.6^o N, 37.4^o E), Mekele (13.5^o N, 39.5^o E), and Nazret (8.6^o N, 39.3^o E). The hypothetical large-scale open pond algae production facility is considered to be located in different cities of Ethiopia. The sites are assumed to be adjacent to fossil fuel generation plant for access to the CO_2 in flue gas.

2.3. Photosynthetic Efficiency of Microalgae

The process by which green plants and algae form carbohydrates from carbon dioxide and water through the agency of sunlight acting upon chlorophyll is called photosynthesis. These organisms are able to harness the energy contained in sunlight, and via a series of oxidation-reduction reactions, produce oxygen and carbohydrates, as well as other compounds, which may be utilized for energy as well as the synthesis of other compounds [27, 28, 29]

$$6CO_2+12H_2O+\text{photons} \rightarrow C_6H_{12}O_6+6O_2+6H_2O \quad (1)$$

The solar energy available for photosynthesis is called Photosynthetically Active Radiation (PAR) which ranges from 400 to 700 nm of the entire solar spectrum. PAR varies with latitude, seasonality and geographical factors [30], supplies the energy for photosynthetic conversion of carbon dioxide to carbohydrates. Not all of the solar energy is suitable for photosynthesis.

As the average energy of PAR photons is roughly 217 kJ [31, 32], the maximum efficiency for converting solar energy into stored chemical energy is 33% with PAR accounting for 45.8 % of incident sunlight on the earth's surface and because 10–20% of the solar energy is lost by surface reflection, only 12.8–14.4% of solar energy can theoretically be converted into algal biomass [33, 34]. Percent of PAR was assumed to be constant, though it does vary a small amount depending on the ratio of direct to diffusion solar irradiance. The quantum limit of photosynthetic efficiency is roughly about 11.6% [34]. This efficiency limit is important to judge claims of the heating value of plants in a given area, in particular algae for which high biodiesel production figures are sometimes quoted.

A total of eight photons are required for complete photosynthesis to capture or fix one molecule of CO_2 into carbohydrate (CH_2O_n) [35, 36]. In equation 1, CH_2O represents the basic form of chemical energy captured by photosynthesis. Its actual form is triosephosphate ($C_3H_5O_3P$), but the energy content is often calculated from glucose ($C_6H_{12}O_6$). The light energy absorbed by algae is first stored as intermediate bio-chemical reductants ($NADPH_2$ and ATP) which are then used by the algal cells to produce new biomass (CH_2O) (Tillett, 1988). Since, the energy content of one mole CH_2O is ~468 kJ [35, 37, 38]. This maximum theoretical photoconversion efficiency of PAR energy applies to any photosynthesizing organism (carbohydrates) is 27% (468 kJ/ (8 x 217 kJ)).

2.4. Microalgae biomass production (g/m^2/d)

$$MB_{production\ (daily)} = \frac{\eta_{Transimission} * \eta_{Capture} * S_I(kWh/m^2/day)}{E_{microalgae}(\mathbf{MJ/kg})} \quad (2)$$

Where:

$MB_{production\ (daily)}$ is microalgae productivity in g/m^2/day, $\eta_{transmission}$ is the efficiency of light transmission to microalgae, $\eta_{capture}$ is the efficiency of conversion of incident sunlight to biomass in microalgae, S_I is the solar Irradiance falling on a horizontal surface (kWh/m^2/day), and $E_{microalgae}$ is Energy stored in the biomass (MJ/kg).

2.5. Microalgae lipid production (ml/m^2/d)

$$ML_{production\ (daily)} = \frac{f_L * MB_{Production}(g/m^2/day)}{\rho_L(kg/L)} \quad (3)$$

Where:

$ML_{production\ (daily)}$ is the lipid productivity from microalgae (ml/m^2/day), f_L is the microalgae Lipid fraction usable for biodiesel, $MB_{production}$ is the microalgae productivity in g/m^2/day, and ρ_L is the density of lipids usable for conversion to biodiesel (kg/L).

2.5.1. Energy stored in biomass

The primary compositions of microalgae are lipids, carbohydrates and proteins. Lipid content in microalgae ranges from 20% to 80% by weight of dry biomass [6]. The term biomass energy content describes how much biomass will be produced from the amount of captured energy, also called higher heating value (HHV) or heat of combustion Values cited in different literatures range from 20 to 23.75 kJ/g [17,39]. Energy content can also be calculated via a weighted average of proteins, carbohydrates, and lipid, with energy contents 16.7, 15.7, and 37.6 kJ/g, respectively [40].

The heating value of microalgae was estimated according to the assumed chemical composition with 30% lipid, 35% carbohydrate, 35% protein. HHV of microalgal biomass 36.6 MJ/kg [41]. The net calorific value (lower heating value) of the major composition of microalgae is summarized in Table 1 [42].

$$\mathbf{E_{microalgae}}\left({}^{MJ}/_{kg}\right) = \mathbf{f_L} * \mathbf{E_L} + \mathbf{f_P} * \mathbf{E_P} + \mathbf{f_C} * \mathbf{E_C} \qquad (4)$$

Where:

$E_{microalgae}$ is the energy stored in the biomass (MJ/kg) (L=lipids; P=proteins; C=carbohydrates), f_L is a microalgae lipid fraction usable for biodiesel, f_P is microalgae protein content fraction, and f_C is the microalgae carbohydrate content fraction.

Table 1: Biomass fractions and net calorific values [40].

Fraction	**Molar mass (g/mole)**	**Lower Heating Value (MJ/kg)**
Protein ($C_{4.43}H_7O_{1.44}N_{1.16}$)	100.1	16.7
Carbohydrate ($C_6H_{12}O_6$)	180	15.7
Lipid ($C_{40}H_{74}O_5$)	634	37.6

2.5.2. Photon Transmission efficiency of sunlight to microalgae

The term photon transmission efficiency accounts for losses in light distribution, absorption characteristics, land-use and PAR of sunlight. The land-use efficiency depends on the availability of the growth system for cultivation throughout the year. Light reflection or absorption by surfaces and materials will be minimized in an optimized design, but any design will have some reduction in the number of incident photons that reach the cells. In the theoretical case, the growing system was assumed to preserve total photon flux density, i.e., no reduction to 100% photon transmission efficiency [33]. For the best case, the reduction in photon flux density due to the growth system was estimated for an open pond scenario, where incident solar energy is lost due to reflection off the open water surface. Not all the incident photons will be absorbed by microalgae. The number of photons reaching the microalgal growth system depends on the light absorption coefficient of microalgae.

$$\boldsymbol{\eta}_{\mathbf{transmission}} = \boldsymbol{\eta}_{\mathbf{light\ distribution}} * \boldsymbol{\eta}_{\mathbf{land\ use}} * \boldsymbol{\alpha} * \mathbf{PAR_{component}} \qquad (5)$$

Where:

$\eta_{transmission}$ is the efficiency of light transmission to microalgae, $\eta_{light\text{-}distribution}$ is the optical light distribution efficiency, $\eta_{land\text{-}use}$ is land-use efficiency, and PARcomponent is photo synthetically active radiation of the sun and α is the light absorption coefficient of microalgae.

2.5.3. Solar energy capture efficiency

The capture efficiency of the open pond growth system depends on the efficiency of photosynthesis, absorption, respiration and photo inhibition characteristics of the microalgal culture. The energy required to fix CO_2 and produce chemical energy via photosynthesis is estimated to be 27 % as per the Z-Scheme or light-dependent reactions [18, 19, 32, 35]. While some researches might argue that higher values may be more realistic, because of our methodology of conservatism to produce an absolute maximum, eight was used because there is not yet consensus on a higher theoretical quantum requirement. Some portion of the captured energy is wasted due to respiration in microalgae during the night. The capture efficiency depends on the algae's ability to utilize the sunlight efficiently without photoinhibition.

$$\boldsymbol{\eta}_{\mathbf{capture}} = \boldsymbol{\eta}_{\mathbf{photosynthesis}} * \boldsymbol{\eta}_{\mathbf{photo\ utilization}} * (\mathbf{1} - \boldsymbol{r}) \qquad (6)$$

Where:

$\eta_{capture}$ is the efficiency of conversion of incident sunlight to biomass in microalgae, $\eta_{photo\text{-}\ synthetic}$ is photosynthetic efficiency, $\eta_{photo\text{-}utilization}$ is the fraction of captured photons utilized by microalgae and r is the fraction of energy consumed by respiration in microalgae.

2.5.4. Photon utilization efficiency

The term photon utilization efficiency accounts for reductions in perfect photon absorption due to suboptimal conditions of the algal culture. A cell under optimal conditions will absorb and use nearly all incident photons.

However, under suboptimal conditions such as high-light levels or non-optimal temperatures under which photoinhibition occurs, some absorbed photons will be re-emitted as heat or cause damage to the cells. Reduction in photon utilization due to high-light levels can be significant for outdoor production, and the magnitude of this effect varies with species, light, and other ambient conditions such as temperature. Light utilization efficiency could range from 50–90% under low-light conditions to 10–30% under high-light conditions [37].

$$\boldsymbol{\eta}_{\mathbf{Photo-utilization}} = \frac{I_s}{I_l}\left[\mathbf{ln}\left(\frac{I_l}{I_s}\right) + \mathbf{1}\right. \qquad (7)$$

Where:

I_s is the saturation light photosynthetic photon flux density on microalgae (µmole/m^2/s) quantum of energy at which microalgal photosynthesis attains saturation, I_1 is an incident light photosynthetic photon flux density incident on microalgae (µmole/m^2/s) quantum of energy available in natural sunlight.

In general, out of the total solar spectrum only 47% is available for photosynthetic applications [28]. Furthermore, fixation of one CO_2 molecule during photosynthesis necessitates a quantum requirement of eight, which results in a maximum utilization of only 27% of the PAR absorbed by the photosynthetic system [32]. An additional 10% loss is identified as photo transmission losses. On the basis of these limitations, the theoretical maximum efficiency of solar energy conversion into biomass is approximately 11.42% [43, 44].

However, the magnitude of photosynthetic efficiency observed in the field, is further decreased by factors such as poor absorption, transmission, reflection, respiration and photoinhibition [45]. Thus, it is shown that algae should obey the law of thermodynamics. Maximum possible algal biomass yield, oil productivity and carbon dioxide fixation were estimated for five regions of Ethiopia sites based on the theoretical and assumption data on Table 3.

2.6. Annual Biomass and Lipid Productivity

2.6.1. Photon utilization efficiency

$$\boldsymbol{MB_{production(annual)}}(T/ha/yr) = MB_{productio\ ((daily)} * n * 10^{-2} \quad (8)$$

2.6.2. Annual lipid productivity ($ML_{production\ (annual)}$)

$$\boldsymbol{ML_{production\ (annual)}}(L/ha/yr) = \frac{f_L * \boldsymbol{MB_{production\ (annual)}}\ (T/ha/yr) * 1000}{\rho_L(\frac{Kg}{L})} \quad (9)$$

Where: $ML_{production\ (annual)}$) is the annual average lipid productivity (L/ha/yr), f_L is lipid fraction of algae biomass, $MB_{production\ (annual)}$ is the annual average biomass productivity (T/ha/yr) and n is the number of operating days of open pond.

2.7. Carbon Mitigation Potential

The microalgae have the ability to fix carbon dioxide efficiently [44]. Carbon dioxide fixed through photosynthesis is converted to carbohydrates, lipids, proteins and nucleic acids. The carbon content varies with microalgae strains, media and cultivation conditions.

Several species have been tested under CO_2 concentrations of over 15%. For example, *Chlorococcum littorale* could grow under 60% CO_2 using the stepwise adaptation technique [46]. Another high CO_2 tolerant species is *Euglena gracilis.* Its growth was enhanced under 5-45 % concentration of CO_2. The best growth was observed with 5% CO_2 concentration. *Scenedesmus* sp. could grow under 80% CO_2 conditions but the maximum cell mass was observed in 10-20% CO_2 concentrations [47]. *Cyanidium caldarium* [48] and some other species of *Cyanidium* can grow in pure CO_2 [49]. It is also reported that *Chlorella* sp. can be grown under 40% CO_2 conditions [47]. Furthermore, Maeda et al. [50] found a strain of *Chlorella* sp. T-1 which could grow under 100% CO_2, despite the maximum growth rate occurred under a 10% concentration. The CO_2 fixation or removal efficiency varied from16 to 58% in an experiment conducted in a semi continuous photobioreactor [51]. Therefore, for this paper 15% is assumed for carbon dioxide fixation efficiency [51]. The CO_2 fixation rate can be calculated by applying the law of conservation of mass. Biomass molecular formula: $CO_{0.48}H_{1.83}N_{0.11}P_{0.01}$ [52].

$M_{biomass}$ = 23.2 gram/mol: MCO_2 =44 gram/mol

$$4CO_2 + \text{nutrients} + H_2O + hv \rightarrow 4CO_{0.48}H_{1.83}N_{0.11}P_{0.01} + 3.5O_2 \quad (10)$$

Rate constant K = $M_{CO2}/M_{biomass}$ = 44/23.2 = 1.89.

Total CO_2 fixation = K × biomass productivity × fixation efficiency (11)

2.8. Assumptions

Equations (2)–(11) can be solved the biomass productivity, lipid productivity and CO_2 sequestration, using the input data of sunlight available at a particular selected site and assuming optimum values for unknown variables. This paper uses the assumption of Ethiopian case use the average conversion efficiency of sunlight to algal biomass based on the theoretical value, the following optimum values of variables are taken from the literatures and few of them are assumed as listed in Table 3.

Table 3: Optimum values of parameters used in the calculation

Term	*Unit*	*Optimum Value*	*Reference*
$\eta_{Light\text{-}distribution}$		**0.96**	**[10]**
$\eta_{Land\text{-}use}$		**0.98**	**[10]**
$\eta_{photo\text{-}synthesis}$		**0.27**	**[53]**
$\eta_{photo\text{-}utilization}$		**1**	**Calculated from Equ. 7**
E_l	**kJ/g**	**37.6**	**[40]**
E_p	**kJ/g**	**16.7**	**[40]**
E_c	**kJ/g**	**15.7**	**[40]**
I_s	**µmole/m²/s**	**200**	**[54]**
I_1	**µmole/m²/s**	**200**	**[10]**
$Par_{component}$		**0.458**	**[31,32,37]**
α		**1**	**[10]**
r		**0.2**	**[10]**
ρ_l	**Kg/L**	**0.864**	**[55]**
n	**Day (d)**	**340**	**Assumed**
Fixation Efficiency		**0.15**	**[51]**
Rate Constant (K)		**1.89**	**Calculated from Equ. 10**

3. Results

3.1. Variations of solar radiation

The variations in solar radiation for the selected sites are shown in Figure 2. The average solar radiation received from Addis Ababa, Awasa, Bahir Dar, Mekele and Nazret are greater than 5.0 kWh/m^2/day except Addis Ababa (4.99 kWh/m^2/day). The maximum and minimum intensity of solar radiation was found to be 5.65 and 3.73 kWh/m^2/day, for Addis Ababa, 6.41 and 4.83 kWh/m^2/day, , for Awasa, 6.69 and 5.16 kWh/m^2/day, for Bahir Dar, 6.82 and 5.46 kWh/m^2/day, for Mekele and 6.57 and 5.23 kWh/m^2/day, for Nazret, respectively.

As the productivity of algae is determined by the available solar radiation levels, is important in assessing the potential of algae growth. All the sites selected for this analysis have high solar insulation, providing an ideal combination for algae open pond cultivation.

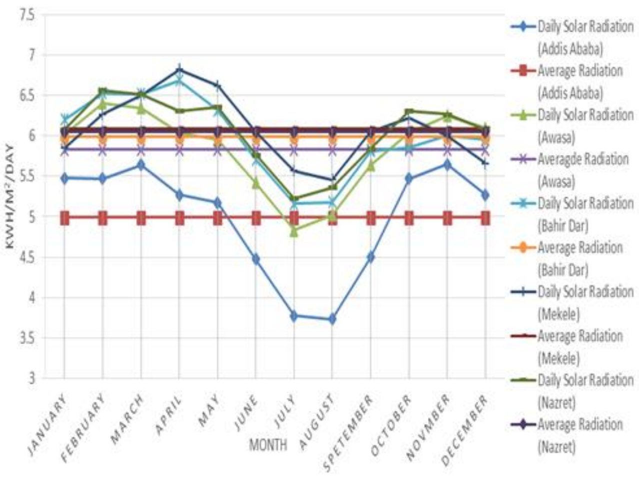

Fig 2: Solar Irradiation Variation in Selected Sites

3.2. Variations of Air Temperature

Fig 3 compares the average air temperatures for the selected locations. The temperature required for optimum growth of algae is around 20 to 35 °C [7] for some species like *C. vulgaris,* but *S. Dimorphus* strain the optimum temperature is around 10 to 40°C [56**].** The maximum and minimum annual average air temperatures in Addis Ababa were 17.9 and 15 °C, respectively, 20.37 and 15.73 °C, respectively for Awasa, 21.77 and 16.34 °C, respectively in Bahir Dar, 26.3 and 19.7 °C, respectively in Mekele and 21.5 and 17.9 °C, respectively for Nazret. All the sites selected have ideal air temperature for the growth of microalgae and to produce biodiesel, Mekele has the most optimal ambient temperature for microalgae cultivation than the others.

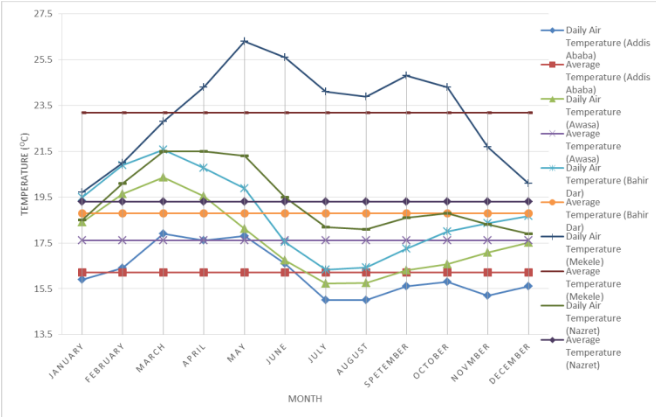

Fig 3: Air Temperature Variation in Selected Sites

3.3. Biomass, Oil Productivity and Carbon Dioxide Sequestration

By knowing the average solar intensity and substituting the values in the above model equations (2)–(11) [57, 58], the corresponding monthly average biomass productivity and oil productivity can be determined. The biomass and lipid based on the solar radiation available at the sites and various efficiency factors closely matches with the other literatures data. The daily biomass productivity for the selected sites are summarized in Table 4 giving an average of **73.91, 86.36, 88.73, 90.21 and 89.62** g/m^2 /day, for Addis Ababa, Awasa, Bahir Dar, Mekele and Nazret, respectively, and lipid productivity of **25.66, 29.98, 30.81, 31.32 and 31.12** ml/m^2/day, respectively, and an average daily carbon sequestration of the different sites are **20.95, 24.48, 25.15, 25.57 and 25.41** gCO_2/m^2/day, for Addis Ababa, Awasa, Bahir Dar, Mekele and Nazret, respectively.

3.4. Annual Average and Variation of Biomass Productivity

Figure *4 shows the variation of biomass productivity in different months for the selected experimental sites (Addis Ababa, Awasa, Bahir Dar, Mekele and Nazret) giving an average biomass productivity in the case of best possible scenario of **251.3, 293.6, 301.7, 306.7 and 304.7** ton/ha/yr, respectively.*

Algae are more efficient at utilizing sunlight than terrestrial plants [59]; Algae have higher growth rates than terrestrial plants, allowing a large quantity of biomass to be produced in a shorter amount of time in a smaller area [7]. The maximum annual biomass productivity of 284.5 ton/ha/yr. was possible in the month of November for Addis Ababa, 322.8 ton/ha/yr. was possible in the month of February for Awasa, 336.9 ton/ha/yr. in the month of April for Bahir Dar, 343.5 ton/ha/yr. in the month of April for Mekele and 330.9 ton/ha/yr. in the month of February for Nazret.

Table 4: *Average Daily Biomass productivity, Oil production and CO_2 sequestration for the selected sites*

Sites	***Solar Irradiation ($KWh/m^2/d$)***	***Solar Irradiation ($KJ/m^2/d$)***	***$Mb_{production}$ ($g/m^2/d$)***	***$Ml_{production}$ ($ml/m^2/d$)***	***CO_2 Sequestration ($gco_2/m^2/d$)***
Addis Ababa	*4.99*	*17964*	*73.91*	*25.66*	*20.95*
Awassa	*5.83*	*20988*	*86.36*	*29.98*	*24.48*
Bahir Dar	*5.99*	*21564*	*88.73*	*30.81*	*25.15*
Mekele	*6.09*	*21924*	*90.21*	*31.32*	*25.57*
Nazret	*6.05*	*21780*	*89.62*	*31.12*	*25.41*

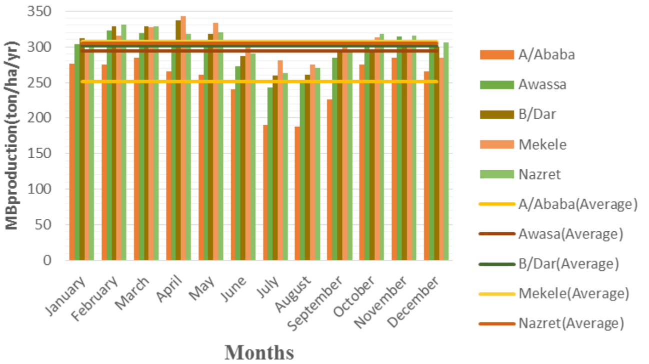

Fig 4*: Annual Average Biomass productivity in selected sites*

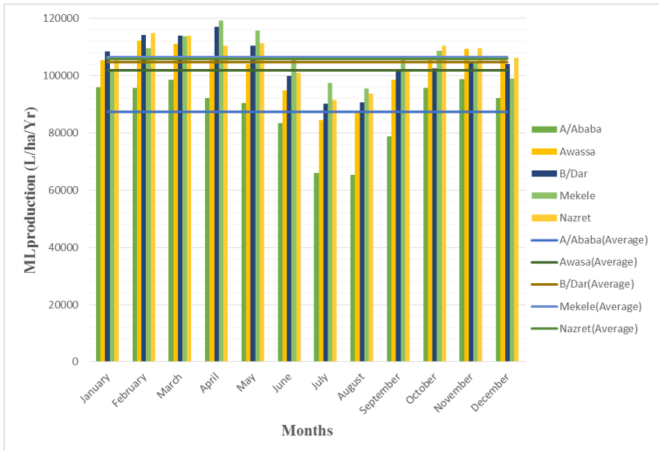

Fig 5: Annual Average Lipid productivity in selected sites

3.5. Annual Average and Variation of oil Productivity

The average potential oil yield for the selected different sites ranged from **87,259.6, 101,948.6, 104,746.5, 106,495.2 and 105,795.8** L/ha/yr. Under all sites, the oil productivity of algae could be significantly higher than other energy crops like jatropha, palm, sunflower and soya bean [7, 60]. However, if algal lipid productivity approaches even a fraction of the calculated minimum, they will be extremely productive compared to first and second generation biofuels [44]. Figure 5 shows the average and the variation oil productivity in different months for the given sites.

The maximum lipid production of 98,801.0 L/ha/yr was possible in the month of November in Addis Ababa, 112,091.0 L/ha/yr in the month of February for Awasa, 116,987.4 L/ha/yr in the month of April in Bahir Dar, 119,260.7 L/ha/yr in the month of April for Mekele and 114,888.9 L/ha/yr in the month of February in Nazret.

3.6. Variations of Carbon Sequestration Potential

Fig 6 shows annual average and variation of carbon sequestration potential in different months for the selected sites, giving an average carbon sequestration potential from possible photosynthesis efficiency of 71.2, 83.2, 85.5, 87.0 and 86.4 ton_{CO2}/ha/yr, respectively. The maximum carbon sequestration potential of 80.7 ton_{CO2}/ha/yr was possible in the month of November in Addis Ababa, 91.5 ton_{CO2}/ha/yr in February for Awasa, 95.5 ton_{CO2}/ha/yr in April for Bahir Dar, 97.4 ton_{CO2}/ha/yr in April for Mekele and 93.8 ton_{CO2}/ha/yr in February for Nazret.

However, the lowest projection in this paper was 53.3 ton_{CO2}/ha/yr for Addis Ababa. This estimate is higher than carbon sequestration capacity of terrestrial plants [61]. Despite any discrepancies among approaches, all estimates affirm the productive potential of algae as a sustainable source of carbon sequestration and energy production. Considering the CO_2 sequestration ability of microalgae, it would be ideal to locate algae production plants next to stationary emitters as a carbon capture and storage option [44].

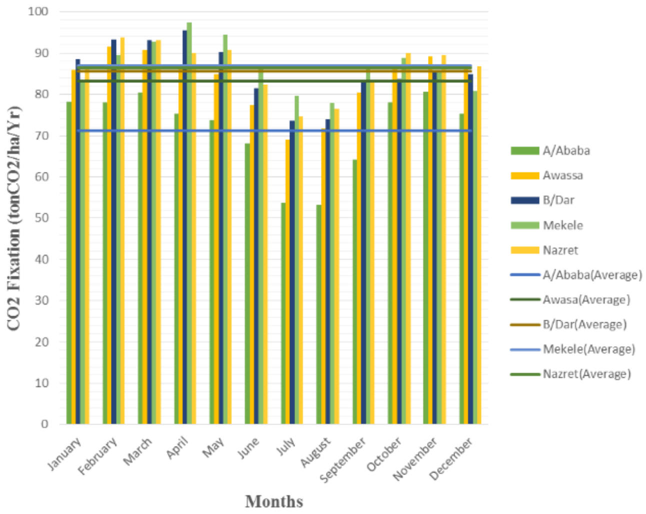

Fig 6: Average and annual Carbon Sequestration Potential of the selected sites

4. Discussion

The most ideal location to set up an algae farm would be tropical climates where the temperature is constantly above 15°C [25]. The estimates of biomass and lipid were evaluated for the potential sites. On average, 85.76 g/m^2/day and 29.78 ml/m^2/day of biomass and oil yield would be possible in the Ethiopian condition. Sudhakar et al. [10] estimated the annual average productivity of 75 g/m^2/day for the India condition. Slightly lower values of 20 g/m^2/day have been reported for the small-scale pilot pond system in Israel [62]. A total of 30g/m^2/day productivity of microalgal biomass was measured by the seventh year Aquatic species program project during 1986 and 1987 in the open pond system [17].

The productivity in theoretical case represents an unfeasible limit despite improved cultivation techniques and efficient algal strains. The production yield results presented here confirms its realistic potential and it will assist the biofuel industry to target maximum oil production. The main differences among approaches for calculating theoretical maximum involve reduction factors, thus presenting it as a true maximum optimum yield. A sustainable biomass yield of 100-200 ton/ha/yr can be achieved in practical condition and even with a shortened 10 month growing season, the algal system could produce 25,000-65,000 L/ha/year of oil yield. The most likely yield under practical conditions ranges from 65,768 L/ha/yr to50, 415 L/ha/yr. The lowest possible yield was calculated to range from 32,941 L/ha/yr to 25,269 L/ha/yr. The carbon assimilation capacities of microalgae range from 20 to 50 ton$_{CO2}$/ha/yr [44].

For the Ethiopian condition, the estimated biomass, lipid and CO_2 sequestration slightly greater than the other reported literatures and experimental data especially on Indian condition. To reduce the dependency on fossil fuels, producing energy from sustainable sources like microalgae can make the country to shift towards a low carbon economy. To produce 13.4 million tons of biodiesel as per the national target of 5% blending, 48 million tons of biomass needs to be produced. Based on our estimates of the algal biomass yield, only 0.2 million hectares of land is required which is just 0.06 % of the Ethiopian land area. The nation has huge potential to meet the biodiesel blend in target. Under Ethiopian conditions, microalgae can be grown abundantly on a large-scale in wastelands for biodiesel production and have the potential to replace a portion of gasoline fuels. Issues such as global warming, CO_2 sequestration and food security can be addressed with algal cultivation.

In this case, estimate of open pond microalgae production provides baseline information to assess the realistic potential of microalgae in various climatic conditions of the Ethiopian regions. High productivity rates may require good solar irradiance, sufficient land, suitable temperature and adequate water. However, locations where all these resources are available need to be identified. With algal biomass for sustainable energy production is not known in Ethiopia, there need be awareness creation in algal cultivation technology are required to achieve the most likely estimates of biomass and oil productivity.

The theoretical biomass and oil productivity in the Ethiopian condition was found to be 80.7 g/m^2/day and 101,249 L/ha/yr, respectively. These values can be used to explore the importance of the design features of large scale open pond cultivation system in the country. However, this upper limit of biomass and oil yield can never be improved upon very much in the open pond cultivation system irrespective of the optimum design of the pond and genetic improvements to algal strains.

In addition to many environmental benefits, algal biomass offers many economic and energy security benefits. By growing our fuels at home, we reduce the need to import oil, reduce our exposure to disruptions in day-to- day supply and thereby generate local employment. However, it was found that the social cost of producing algal biodiesel is higher than rapeseed biodiesel and fossil fuels in the world. Algal biodiesel can replace other fuels with further significant biotechnology development [63].

Therefore, it can be concluded based on the above results that there is a huge potential of algae for biodiesel in Ethiopia. Although there are many theories to support the use of algae biodiesel, further research and development activities are needed in large scale to firmly assess the potential of algae cultivation for biodiesel.

5. Conclusions

A process of employing basic physical laws, known values, and conservative assumptions has resulted in a robust calculation of theoretical maximum and best case algal oil yields. The equations, calculations, and discussion in this paper have shown that, presented here based on photosynthetic light efficiency can yield a rough estimate of the algae biomass potential in Ethiopia under the ambient condition. An effort was made to estimate algal biomass productivity, lipid productivity and carbon sequestration potential based on readily available input data. The biomass and lipid productivity in the Ethiopian condition was found to be 85.76 g/m^2/day and 101,249 L/ha/year, respectively and 82.7 ton$_{CO2}$/ha/yr of potential carbon sequestration.

The estimates obtained from the study confirm its realistic potential and will serve the biofuel industry to achieve this target and reduce the losses occurring in the large-scale open pond cultivation system. Therefore, the outdoor algae pond should be designed and operated efficiently to maximize algal product yield. It can be concluded from the results that there is a huge potential of algae biodiesel in Ethiopia.

However, if algal biofuel production systems approach even a fraction of the calculated theoretical maximum, they will be extremely productive compared to current oil production capability of agriculture-based biofuels.

Acknowledgements

The first author would like to thank Dr. -Ing Berhanu Assefa (Head, School of Chemical and Bio-Engineering, Addis Ababa University) and Dr. Murthy S. Ganti (Professor at Oregon State University, USA) for their support and proofreading.

References

[1] P. Kalayasiri, N. Jayashke, and K. Krisnangkura, “Survey of seed oils for use as diesel fuels” Journal of American Oil Chemical Society, 1996, 73, 471–474.

[2] International Energy Agency (IEA), 2009. Accessed 26 February 2013. http://www.iea.org.

[3] Intergovernmental Panel on Climate Change (IPCC), “IPCC Summary for Policymakers. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change”, Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller. *Cambridge University Press, Cambridge, UK and New York, USA,* 2007.

[4] Ministry of Mines and Energy (MME), “The Biodiesel Development and Utilization Strategy of Ethiopia [Report],” Addis Ababa : Ministry of Mines and Energy. 2007.

[5] A. Demirbas, and M.F. Demirbas, “Importance of algae oil as a source of biodiesel,” Energy Conversion and Management, 2011, 52, 163-170.

[6] P. Spoiler, C. Joannis-Cassan, E. Duran, A. Isambert, “Commercial applications of microalgae”, J of Bioscience and Bioengineering, 2006, 101 (2): 87–96.

[7] Y. Chisti, “Biodiesel from microalgae”, Biotechnol. Adv., 2007, 25: 294-306.

[8] P. Schenk, S. Thomas-Hall, E. Stephens, U. Marx, J. Mussgnug, C. Posten, et al., “Second generation biofuels: high-efficiency microalgae for biodiesel production”, Bioenergy Res., 2008, 1, 20-43.

[9] J. K. Heydarzadeh, G. Amini, M. A. Khalizadeh, M. Pazouki, A.A. Ghoreyshi, M. Rabeai and G.D. Najafpour, “Esterification of Free Fatty Acids by Heterogeneous-Alumina-Zirconia Catalysts for Biodiesel Synthesis”, World Appl. Sci. Journal, 2010, 9 (11): 1306-1312.

[10] K. Sudhakar, M. Rajesh and M. Premalatha, “A Mathematical Model to Assess the Potential of Algal Biofuels in India”, Energy Sources, Part A: Recovery, Utilization and Environmental Effects, 2012, 34 (12): 1-7.DOI: 10.1080/15567036.2011.645121.

[11] H. M. Amaro, Guedes, A. C. and F. X. Malcata, “Advances and perspectives in using microalgae to produce biodiesel”, Applied Energy, 2011, 88 (10): 3402–3410.

[12] S.A. Khan, Rashmi, M.Z. Hussain, S. Prasad and U.C. Banerjee, “Prospects of biodiesel production from microalgae in India”, Renew. Sust. Energy. Rev., 2009, 13(9): 2361-72.

[13] K. Hussain, K. Nawaz, A. Majeed and F. Lin, “Economically Effective Potential of Algae for Biofuel Production”, World Appl. SCI. J., 2010, 9(11): 1313-1323.

[14] A. Richmond, “Microalgal biotechnology at the turn of the millennium: a personal view”, J. Appl. Phycol., 2000, 12, 441-451.

[15] J. Benemann, “CO_2 mitigation with microalgae systems”, Energ. Convers. Manag., 1997, 38, 475-479.

[16] Q. Hu, M. Sommerfeld; E. Jarvis, M. Ghirardi, M. Posewitx, M. Seibert, and A. Darzins, “Microalgal Triacylglycerol as Feedstock for Biofuel Production: Perspectives and Advances,” The Plant Journal, 2008, 54 (4): 621-639.

[17] J. Sheehan, T. Dunahay, J. Benemann and P. Roessler, “Look back at the U.S. Department of Energy’s Aquatic Species Program: biodiesel from algae; Closeout Report”, NREL Report No. TP-580, 1998.

[18] D.W. Lawlor, “Photosynthesis: metabolism, control and physiology. Longman Scientific and Technical, Essex. 1987.

[19] J. Bolton, and D. Hall, “The maximum efficiency of photosynthesis”, Photochem. Photobiol, 1991, 53 (4): 545-548.

[20] J.F. Cornet, C.G. Dussap and J.B. Gros, “Conversion of radiant light energy in photobioreactors”, AIChE. J., 1994, 40(6): 1055-1066.

[21] J.A. Raven, “Limits to growth. In: M. Borowitzka and L. Borowitzka (eds) Micro-algal biotechnology.” Cambridge University Press, Cambridge, 1988.

[22] E.L. Maxwell, A.G. Folger and S.E. Hogg, Resource evaluation and site selection for microalgae production systems, SERI/TR-215-2484, 1985.

[23] M. R. Tredici, "Photobiology of microalgae mass cultures: understanding the tools for the next green revolution", Biofuels, 2010, 1 (1), 143–162.

[24] L. Barsanti, and P. Gualtieri, "Algae-Anatomy, Biochemistry and Biotechnology," CRC, Boca Raton, FL/Taylor and Francis, London, 2006.

[25] T. Lundquist, J. Benemann, A. Feffer, I. Woertz, "Presentation on Nutrient Removal and Biofuel Production through Microalgae-Based Wastewater Treatment", First Western Forum on Energy and Water Sustainability University of California Santa Barbara March 22-23, 2007.

[26] National Aeronautical and Space Administration (NASA), USA, 2008. NASA surface meteorology and solar energy: RET Screen, data, [Online], Accessed 10 February 2013. Available from http://eosweb.larc.nasa.gov.

[27] R. Hill, and F. Bendall, "Function of the Two Cytochrome Components in Chloroplasts-A Working Hypothesis", Nature (London), 1960, 186 (4719): 136-137.

[28] C. Gueymard, "Parameterized transmittance model for direct beam and circumsolar spectral irradiance", Sol Energy, 2001, 71 (5): 325-346.

[29] I. Karube, T. Takeuchi, and D. J. Bares, "Biotechnological Reduction of CO_2 Emissions." Advances in Biochemical Engineering/Biotechnology, 1992, 46, 63-79.

[30] A. Kumar, S. Ergas, Xin Yuan, Ashish Sahu, Quiong Zhang, Jo Dewulf, F. Xavier Malcata, and Herman van Langenhove, "Enhanced CO_2 fixation and biofuel production via microalgae: recent developments and future directions", Trends in Biotechnology, 2010, 28, 371–380.

[31] J.A. González, and J. Calbó, "Modelled and measured ratio of PAR of global radiation under cloudless skies", Agric. For Meteorol., 2002, 110, 319-325.

[32] C.P. Jacovides, F.S. Timvios, G. Papaioannou, D.N. Asimakopoulos and C.M. Theofilou, "Ratio of PAR to broadband solar radiation measured in Cyprus", Agric. For Meteorol., 2004, 121, 135-140

[33] M. W. Kristina, R. B. Daniel, D. Al and D. W. Bryan, "Theoretical Maximum Algal Oil Production", Bioenerg. Res.. 2010, 3:204–213, DOI 10.1007/s12155-009-9046-x.

[34] P.T. Vasudevan, and M. Briggs, "Biodiesel production–current state of the art and challenges." J Ind Microbiol Biotechnolgy, 2008. Doi10.1007/s10295-008-0312-2.: 10p.

[35] D.A. Walker, "Energy, plants and man." Packard Publishing Limited, East Sussex 1992.

[36] P.G. Falkowski, and J.A. Raven, Aquatic photosynthesis. Princeton University Press, Princeton, 2007.

[37] J. Goldman, "Outdoor algal mass cultures-II. Photosynthetic yield limitations", Water Res., 1979, 13, 119-136.

[38] J.H. Ryther, "Potential productivity of the sea", Science, 1959, 130, 602–608.

[39] Q. Hu, "Several fundamental biological aspects of algal biofuel application." In Jonathan Trent, editor, Wind Sea Algae Workshop Proceedings, pages 15–28, Maribo, Denmark, April 2009. Baltic Sea Solutions and STP Productions.

[40] M.M. Rebolloso-Fuentes, Navarro-Pèrez A, Garcìa-Camacho F., Ramos-Miras J.J., J.L. Guil-Guerrero, "Biomass nutrient profiles of the microalga Nannochloropsis", J Agric Food Chem., 2001,49, 2966–2972.

[41] A. E. Clarens, E. P. Resurreccion, M.A. White, and L. M. Colesi, "Environmental Life-cycle Comparison of Algae to other Bioenergy Feedstock", Environmental Science and Technology, 2010. 44, (5): 1813–9.

[42] L. Lardol, A. Helias, B. Sialve, J. P. Steyer, and O. Bernard, "Life-cycle Assessment of Biodiesel Production from Microlgae", Environmental Science and Technology, 2009, 43 (17): 6475–81.

[43] P.J.L. Williams, and L.M.L. Laurens, "Microalgae as biodiesel and biomass feedstocks: review and analysis of the biochemistry, energetics and economics", Energy Environ, Sci., 2010, 3, 554-590.

[44] K. Sudhakar, and M. Premalatha, "Theoretical Assessment of Algal Biomass Potential for Carbon Mitigation and Biofuel Production", Iranica Journal of Energy and Environment, 2012, 3 (3): 232-240.

[45] K. Miyamoto, Biological Energy Production, Renewable Biological Systems for Alternative Sustainable Energy Production, FAO Food and Agriculture Organization of the United Nations, Agricultural Consumer Protection, 2009.

[46] M. Kodama, H. Ikemoto, S. Miyachi, "A new species of highly CO_2-tolerant fast-growing marine microalga suitable for high-density culture", Journal of Marine Biotechnology, 1993, 1, 21-25.

[47] N. Hanagata, T. Takeuchi, Y. Fukuju, D. J. Barnes, I. Karube, "Tolerance of microalgae to high CO_2 and high temperature", Phytochemistry, 1992, 31 (10): 3345-3348.

[48] J. Seckbach, H. Gross, M.B. Nathan, "Growth and photosynthesis of *Cyanidium caldarium* cultured under pure CO_2", Israel journal of botany, 1971, 20, 84-90.

[49] L.E. Graham, and L.W. Wilcox, Algae. Prentice-Hall, Inc., Upper Saddle River, NJ., 640, 2000.

[50] K. Maeda, M. Owada, N. Kimura, K. Omata, I. Karube, "CO_2 fixation from the flue gas on coal fired

thermal power plant by microalgae", Energy convers. Mgmt., 1995, 36, 717-720.

[51] S.Y. Chiu, C.Y. Kao, M.T. Tsai, S.C. Ong, C.H. Chen and C.S. Lin, "Lipid accumulation and CO_2 utilization of *Nannochloropsis oculata* in response to CO_2 aeration", Bioresour. Technol., 2009, 100, 833-838.

[52] Y. Chisti, "Biodiesel from microalgae beats bioethanol", Trends Biotechnol., 2008, *26*, 126–131.

[53] L. Brennan, and P. Owende, "Biofuels from Microalgae–A Review of Technologies for Production, Processing, and Extractions of Biofuels and coproducts", Renewable and Sustainable Energy Reviews, 2010, 14 (1): 557–77.

[54] G. Torzillo, B. Pushparaj, J. Masojidek, and A. Vonshak, "Biological Constraints in Algal Biotechnology", Biotechnology and Bioprocess Engineering, 2003, 8 (6): 338–48.

[55] H. Xu, X.L. Miao and Q.Y. Wu, "High quality biodiesel production from a microalga Chlorella protothecoides by heterotrophic growth in fermenters", J. Biotechno., 2006, 126: 499-507.

[56] A. Converti, A.A. Casazza, E.Y. Ortiz, P. Perego, Del M. Borghi, "Effect of temperature and nitrogen concentration on the growth and lipid content of *Nannochloropsis oculata* and *Chlorella vulgaris* for biodiesel production", Chemical Engineering and Processing, 2000, 48, 1146–1151.

[57] P. Zemke, B. Wood, and D. Dye, Technoeconomic Analysis of Algal Photobioreactors for Oil Production, Workshop on Algal Oil for Jet Fuel Production, February 2008, the National Renewable Energy Laboratory (NREL).

[58] K. M. Weyer, D. R. Bush, A. Darzins, and B. D. Wilson, "Theoretical maximum algal oil production." Bioeng. Res., 2010, 3, 204–213, doi: 10.1007/ s12155-009-9046-x.

[59] S.J. Pirt, "The thermodynamic efficiency (quantum demand) and dynamics of photosynthetic growth." The New Phytologist, 1986. 102: p. 3-37.

[60] D. Al, P. Pienkos and L. Edye, "Current status and potential for algal biofuels production: A report to IEA Bioenergy task 39 commercializing liquid biofuels from biomass, 2010.

[61] N.H. Ravindranath, and P.R. Bhat, "Monitoring of carbon abatement in forestry projects-case study of western ghat project", Mitigation and adaptation strategies for Global change, 1997, 2, 217-230.

[62] A. BenAmotz, Algae Biomass Summit III. Algal Biomass Organization, San Diego, CA, October 6–9, 2009.

[63] V. Kovacevich, and J. Wesseler, "Cost-effective Analysis of Algae Energy Production in the EU", Energy Policy, 2010, 38 (10): 5749–57