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Theoretical Assessment of Algal Biomass Potential for Carbon Mitigation and Biofuel Production

[1]*K. Sudhakar* and [2]*M. Premalatha*

[1]Bioenergy Laboratory, Maulana Azad National Institute of Technology, Bhopal, India
[2]Biosequestration Laboratory, CEESAT, National Institute of Technology, Tiruchirapalli, India

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Abstract: In view of ever increasing global demand for energy, there has been substantial interest in developing renewable biologically produced fuel. Microalgae are one such emerging resource considered as an alternative for biodiesel production. However its realistic potential is often either over estimated or underestimated. In view of this, a rigorous assessment is carried out to evaluate the realistic potential of micro algal biodiesel based on photosynthesis, thermodynamics and physical assumptions. This paper identifies six best regions in each continent for algal biomass cultivation considering both sunlight and local climatic conditions. The mean hourly meteorological data, sunlight, ambient temperature and rainfall information for the identified potential site is combined to estimate annual biomass production, lipid production and carbon mitigation potential. Maximum possible algal biomass yield and oil productivity have been estimated for six global sites at three different scenarios of photosynthetic efficiency 11.42, 6 and 3%. The upper optimistic biomass, oil yield and carbon fixation potential was calculated to be 533 T/ha/yr, 1, 25, 333 L/ha/yr. and 95 Tons CO_2/ha/yr. This study provides a baseline data for theoretical maximum, minimum and best estimates of open pond microalgae production systems.

Key words: Microalgae; Biofuel; Carbon-fixation; Photosynthetic efficiency; Biomass productivity; Raceway pond

INTRODUCTION

Microalgae are one of the planet's most promising sources of renewable biomass [1]. Biomass derived from seaweed and algae are gaining significance for production of biodiesel [2]. Algae can grow in a wide variety of conditions from freshwater to extreme salinity [3-5]. They are more efficient converters of solar energy than terrestrial plants and take carbon dioxide out of the atmosphere as they grow [6]. 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 lack of viable technologies at large scale [7]. Macroalgae, on the other hand, such as seaweed, are less preferred than microalgae. The preference towards microalgae is due largely to its less complex structure, fast growth rate and for high oil content. There are many varieties of micro-algae; each species has a different proportion of lipids, carbohydrates and proteins. Very few species of microalgae namely *Spirulina*, *Dunaliella saliina*, *Chlorella vulgaris* and *Haematococcus pluvialis* have been invariably exploited commercially [8]. Some algae strains may contain up to 80 percent lipids making them very suitable for the production of liquid fuels [8, 9, 10]. Biodiesel derived from microalgae were found to have similar properties to that of a standard diesel [11].

The site selected for algae cultivation have to meet the following criteria.

- Availability of sunlight throughout the year.
- Favourable climatic conditions, temperature, relative humidity, precipitation and evaporation.
- Land topography.
- Assess to nutrients, carbon sources and water [12].

Corresponding Author: K. Sudhakar, Bioenergy Laboratory, Maulana Azad National Institute of Technology, Bhopal, India.
Tel: +91-755-2670327, Fax: +91-755-2670562, E-mail: sudha_k@sify.com

For the above reasons, microalgae production will not be possible in all regions of the world. Algae have the potential to play a big role in green revolution but it is essential to identify the true potential of algae. Suitable locations meeting all the above criteria need to be identified in each country. There are several studies on maximum theoretical efficiency of photosynthesis [13-15], but they have not been applied specifically to algal photosynthesis. Estimates of algal productivity based on small-scale experiments were also reported in literature [16, 17]. Maximum instantaneous efficiency and annual algae biomass production yield was calculated based on numerous assumptions without addressing lowest possible yield [18]. Calculations by Weyer, *et al*., [19] is the closest in methodology to this work, but they have primarily focussed on maximum yields on random sites and include complex terms and did not address minimum possible estimates and carbon fixation potential. None of the studies had done earlier have addressed the theoretical minimum and maximum algae biomass, oil productivity and carbon dioxide fixation potential. Hence, in present study a conceptual photosynthetic open pond microalgae system is proposed. The quantitatively estimated biomass, oil productivity and photosynthetic efficiency were 11.42, 6 and 3%, respectively. The objective of this paper is to determine the realistic productivity of oil yield using weather data for six global climates and in order to generate preliminary data under optimum growing conditions. The optimistic, pessimistic and most likely estimates of open pond microalgae production could be used in algae biodiesel project designing, planning and decision making. The study is also done to evaluate the carbon fixation potential of microalgae production systems. The results and literature data in terms of dry biomass productivity have been successfully compared; thus demonstrating the validity of the proposed analysis.

Methodology: Photosynthetic efficiency of microalgae was derived using fundamental equations. The algal biomass productivity, lipid productivity and carbon fixation potential are determined for the selected sites. The calculation was done for three different scenarios of photosynthetic efficiency which are described below.

Site Selection: About 1367 W/m^2 of light energy reaches the outer atmosphere of earth and on average only 240 W/m^2 reaches the earth surface [20]. Annual solar radiation with in the world generally varies between 700 and 2500 kWh/m^2. Site suitable for algal cultivation should have a basic requirement of abundant sunlight. This is undoubtedly an important consideration since insolation is directly linked to biomass yield. Tropical countries experiencing more intensive sunlight are ideally suited for microalgae cultivation. However, to identify the variation in productivity of each continent, the hypothetical algae biodiesel production facility for this study is considered to be located in six global climates as shown in Figure 1.

Weather Data: The sites selected for the study are based on availability of adequate sunlight, optimum air temperature, abundant rainfall and proximity to coastal area. The sites having annual average horizontal solar radiation greater than 1500 kWh/m^2 and temperature

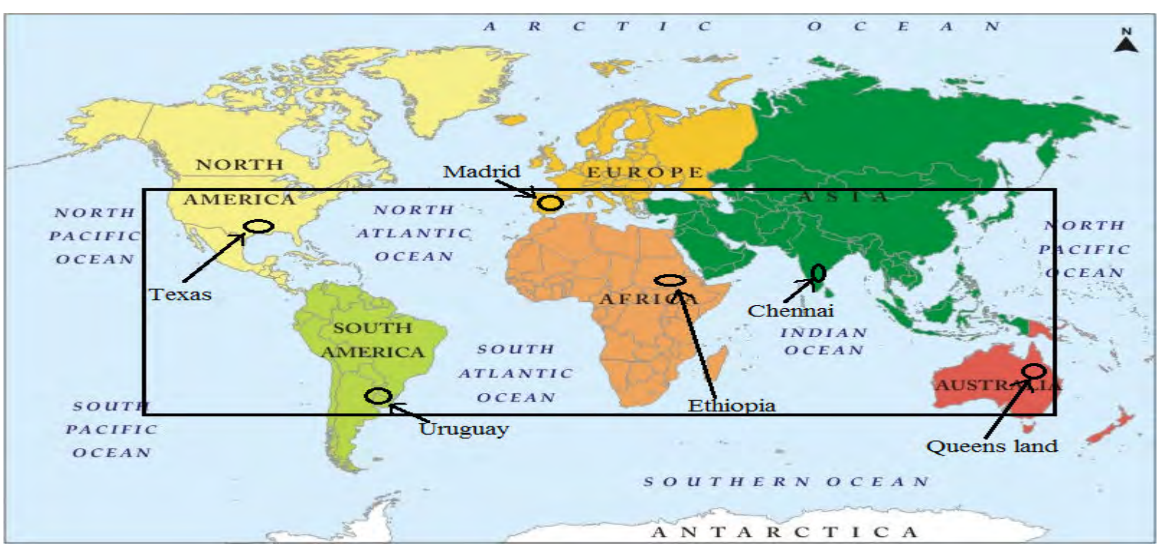

Fig. 1: Map showing the selected sites

greater than 15 °C are selected for this study. The metrological data such as solar radiation intensity and ambient temperature of potential sites are obtained from NASA maps/RETscreen software [21].

Photosynthetic Efficiency of Microalgae: Photosynthesis uses light energy and CO_2 to make sugars like glucose [22, 23]. A general equation for photosynthesis is given below: [24].

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

Algae convert solar energy into biomass by oxygenic photosynthesis in a natural condition at a photosynthetic efficiency of 4-6% [6]. Not all of the solar energy is suitable for photosynthesis. Algae absorb sunlight in the wavelength ranging from 400-700nm for photosynthesis which is only 47% of total energy from the sun [25, 26]. Photosynthetically Active Radiation (PAR) varies with latitude, seasonality and geographical factors. The two maintain limitations of converting sunlight into energy lies in the mechanism of photosynthesis and PAR.

Photosynthetic organisms use 8 photons to capture or fix one molecule of CO_2 into carbohydrate $(CH_2O)_n$ [27-31].

- Heating value of one mole of CH_2O= 468 kJ [32, 33].
- Mean energy of a mole of PAR photons= 217.4 kJ [34, 35].
- Maximum/ideal theoretical conversion efficiency of PAR energy into carbohydrates is = 468kJ/ (8x 217.4kJ) = 27%.

The energy in the form of biomass that can be obtained via photosynthesis thus depends on the level of PAR, photosynthetic efficiency and other transmission losses as given below:

$$PE_{Microalgae} = PAR \times \eta_{photosynthetic} \times \eta_{transmission} \quad (2)$$

Initially, out of total solar spectrum only 47% is available for photosynthetic applications [25, 26]. 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 [35]. 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% using equation (2) [36].

Table 1: Various losses in algal photosynthesis

Environmental factor	Reduction	Eficiency, %
Total solar irradiance	-	100
Absorption spectrum	53	47
Photo synthetic efficiency	73	12.69
Photon transmission (scattering and reflection properties of surface) light saturation	10	11.42

However, the magnitude of photosynthetic efficiency observed in the field, is further decreased by factors such as poor absorption, transmission, reflection, respiration and photo-inhibition [37]. The net result being an overall photosynthetic efficiency between 3-6% of total solar radiation. Thus, it is shown that algae should obey the law of thermodynamics. The various losses occurring in algal photosynthesis is shown in Table 1.

Annual Biomass and Lipid Productivity:

$$\text{Annual biomass productivity } BM_{annual} \text{ (T/ha/yr)} = BM_{daily} \text{ (g/m}^2\text{/day)} \times n \text{ (days)} \times 10^{-2} \quad (3)$$

$$\text{Annual lipid productivity } Lipid_{annual} \text{ (L/ha/yr)} = c \times BM_{annual} \text{ (T/ha/yr)} \times 10000 / \rho \text{ (kg/L)} \quad (4)$$

C = lipid fraction of algae biomass
$Lipid_{annual}$ = Annual average lipid productivity (L/ha/yr)
BM_{annual} = Annual average biomass productivity (T/ha/yr)
BM_{daily} = Daily average biomass productivity (g/m^2/day)
ρ = specific gravity (kg/L) [10]
n = Number of operating days of pond

Carbon Mitigation Potential: The microalgae have the ability to fix carbon dioxide efficiently [6, 7]. 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. The CO_2 fixation rate can be calculated by applying law of conservation of mass:

Biomass molecular formula: $CO_{0.48}H_{1.83}N_{0.11}P_{0.01}$ [38].

$M_{biomass}$ = 23.2 gram/mol: $M\ CO_2$ = 44 gram/mol

$$4CO_2 + \text{nutrients} + H_2O + h\nu \rightarrow 4CO_{0.48}H_{1.83}N_{0.11}P_{0.01} + 3.5\ O_2 \quad (5)$$

Rate constant $K = MCO_2/M_{biomass} = 44/23.2 = 1.89$.

$$\text{Total } CO_2 \text{ fixation} = K \times \text{biomass productivity} \times \text{fixation efficiency} \quad (6)$$

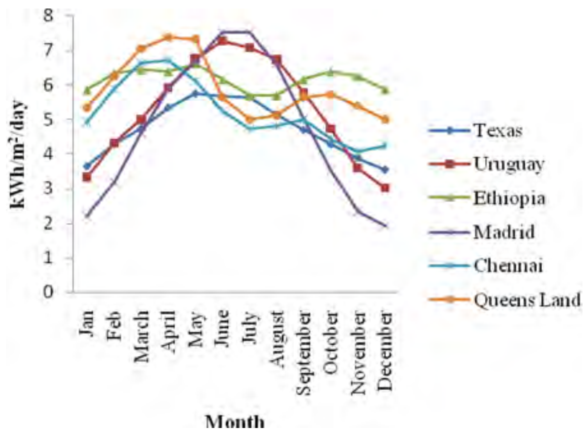

Fig. 2: Variation in solar insolation across six selected sites

The CO_2 fixation or removal efficiency varied from 16 to 58% for an experiment conducted in a semi continuous photobioreactor [39].

Sunlight Data: Monthly average hourly global radiations for the selected locations were obtained from RETScreen database. The average solar radiation received by all the sites is around 4.52 kWh/m^2/day. The maximum and minimum intensities of solar radiation for Ethiopia and Texas were 6.14 and 4.71 kWh/m^2/day, 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 insolations, providing an ideal combination for algae open pond cultivation. The variations in solar radiation for the selected sites are shown in Figure 2.

Weather Data: Monthly average hourly ambient temperatures for the selected locations were obtained from RET Screen database. The annual average air temperature for Texas, Uruguay, Ethiopia, Madrid, Chennai and Queens land were 21, 17.3, 22.3, 17.7, 27.7 and 26.7 °C, respectively. The temperature required for optimum growth of algae is around 20 to 35 °C [10]. The maximum and minimum annual average air temperatures for Texas were 29 and 12 °C, respectively. All the sites selected have ideal air temperature for the growth of microalgae. Artificial heating of the pond may be required in Texas and Uruguay during winter months when temperature goes beyond optimum conditions. Figure 3 compares the monthly average ambient temperatures for the six selected locations.

Assumptions: Annual average biomass productivity, oil yield and carbon fixation potential were calculated by using incoming solar radiation and photosynthetic efficiency of algae. The maximum possible energy production is estimated theoretically for the following scenarios. The average conversion efficiency of sunlight to organic biomass drops from the1oretical value of 11.42 to 3% [36].

***Scenario* I:** Optimistic /maximum yield (Theoretical efficiency of 11.42%) [36].

The scenario of perfectly efficient algae and all the efficiency components are close to maximum values.

***Scenario* II:** Most likely /probable yield (Theoretical efficiency of 6%) [40].

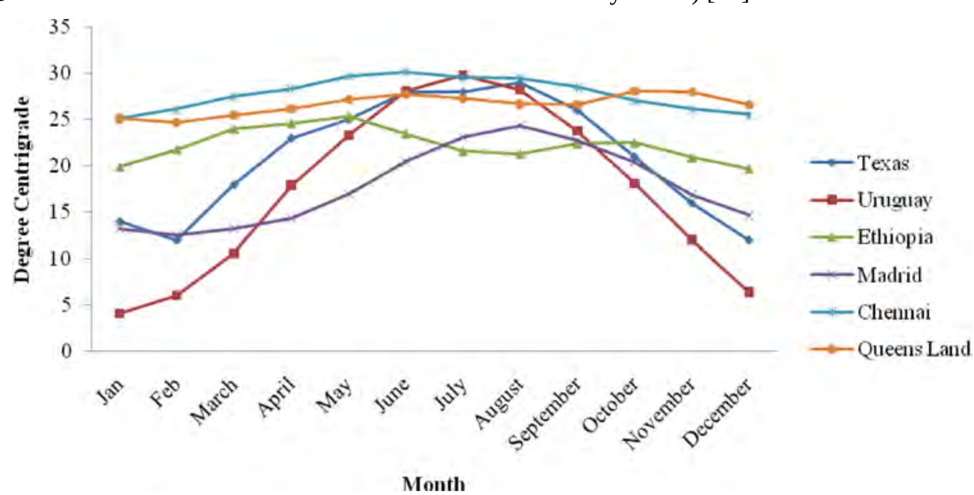

Fig. 3: Variation in air temperature across six selected sites

The scenario of moderately efficient algae and all the efficiency components are considered to be reasonable.

***Scenario* III:** Pessimistic /minimum yield (Theoretical efficiency of 3 %) [41].

The scenario of less efficient algae and all the efficiency components are close to minimum values.

The following conservative values are assumed based on literature data for all the above cases.

- Higher heating value of algal biomass =14.21 MJ/Kg [42].
- Specific gravity of algae oil = 0.85 kg/l [11]
- CO_2 fixation efficiency = 10% (lowest value based on reported data [39])
- Algae biomass lipid fraction = 20% (lowest value based on literatures [8, 9, 10])
- No. of operating days of pond = 300

RESULTS

Daily Average Biomass Productivity for Each Scenario: The optimistic maximum yield for the selected sites varies between 177 to 136 g/m^2/day which closely match with other reported calculations [20]. The optimistic maximum yield based on the solar energy available represents an unattainable maximum and cannot be realised practically. The most likely yields for Ethiopia and Texas ranged from 93 to 71 g/m^2/day respectively. The minimum pessimistic biomass productivity for the study areas varies between 35 to 46 g/m^2/day. Daily biomass yield achieved in practical conditions for the variety of location and those reported in the published literature ranged from 10 to 58 g/m^2/day [1, 35, 10]. Comparison of optimistic, most likely and pessimistic yield for six selected sites showed that productivity is directly dependent on solar radiation intensity. The values obtained confirm the linear relationship between the solar radiation and biomass productivity. The optimistic biomass yield cannot be exceeded thermodynamically in sunlight regardless of whether the algae are grown in open ponds or photo bioreactors. The estimates of daily average biomass productivity are summarized in Table 2.

Annual Average Biomass Productivity: The annual average biomass productivity for the study area is summarized in Figure 4. The calculation predicted the optimistic annual average biomass yield ranging from 530 to 408 tons/ha/yr. The most likely possible productivity of algal biomass is around 250 tons/ ha/yr. The minimum theoretical yield is 107 tons/ha/yr of microalgal biomass based on the solar insolation level at Texas. The estimated algal biomass productivity is eventually higher than other terrestrial energy crops. Algae link, photo bioreactor supplier claimed year round productivity of 365 tons/ha/yr and green fuel technologies corporation, based in Massachusetts, demonstrated dry weight productivities between 250 to 292 tons/ha/yr in their sunlight-powered algal bioreactors.

Annual Average Oil Productivity: The annual average oil productivity for the study area is summarized in Figure 5. The average potential oil yield for the three different scenarios ranges from 1,08,000 L/ha/yr to 28,000 L/ha/yr. Under all three scenarios, the oil productivity of algae could be significantly higher than other energy crops like jatropha, palm, sunflower and soya bean [43]. However, if algal lipid productivity approaches even a fraction of the calculated minimum, they will be extremely productive compared to first and second generation bio fuels.

Table 2: Daily average Biomass productivity for different scenario

		11.42% Efficiency		6% Efficiency		3% Efficiency	
Site	Energy from sun kwh/m^2/day	Output Energy kJ/m^2 /day	Biomass productivity g/m^2/day	Output Energy kJ /m^2 /day	Biomass productivity g/m^2/day	Output Energy kJ/m^2/day	Biomass productivity g/m^2/day
Texas, North America	4.71	1933	136.03	1015	71.42	508.68	35.79
Uruguay South America	5.29	2174	153.10	1141	80.29	571.32	40.20
EthiopiaAfrica	6.14	2523	177.55	1324	93.17	663.12	46.66
Madrid, Spain	4.75	1951	137.29	1026	72.20	513	36.10
Chennai India	5.23	2149	151.23	1126	79.23	564.84	39.74
Queens land Australia	5.90	2422	170.44	1274	89.65	637.2	44.84

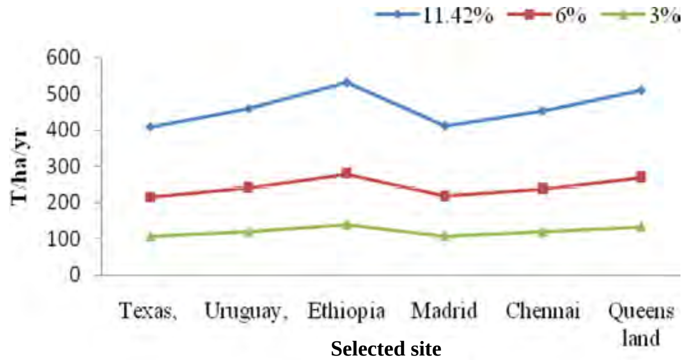

Fig. 4: Annual average Biomass productivity for different scenario

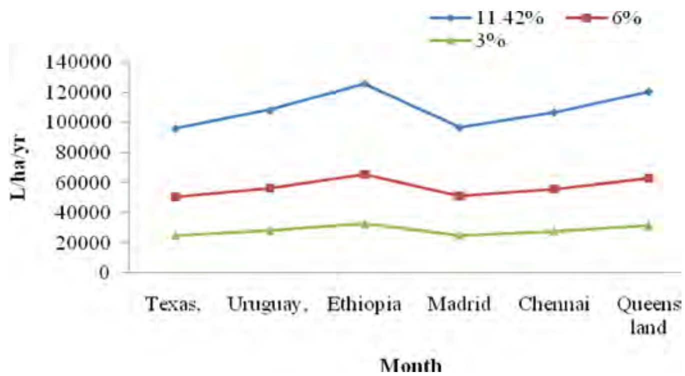

Fig. 5: Annual average Oil productivity for different scenario

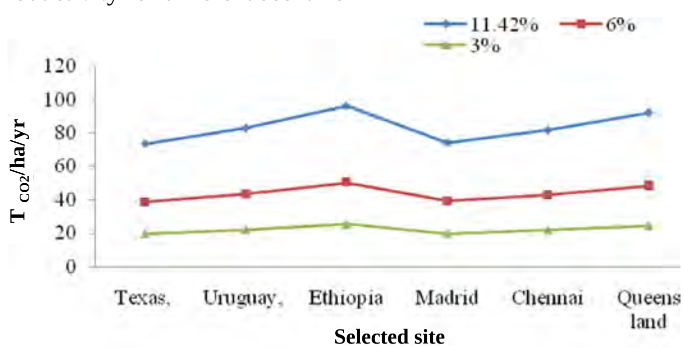

Fig. 6: Carbon fixation potential for different scenario

Carbon Fixation Potential: The annual average carbon fixation potential for the study area is summarized in Figure 6. The maximum optimistic CO_2 fixation capacity by algal biomass is 95Tons CO_2/ha/yr. The lowest projection in this paper was 19 Tons CO_2/ha/yr for Texas and Madrid. This estimate is drastically higher than carbon fixation capacity of terrestrial plants [44]. 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 fixation ability of microalgae, it would be ideal to locate algae production plants next to stationary emitters as a carbon capture and storage (CCS) option.

DISCUSSION

Algal biodiesel production is considered as an emerging source. In this study we used reasonable assumptions and tried to predict the potential based on thermodynamic limit. The use of photosynthetic microalgae for biomass can be expected to operate at an optimistic efficiency of at most 11%. The most likely practically achievable efficiency is very close to 6%. Photosynthetic efficiency of 3-6% is possible under field condition. This photosynthetic yield is comparatively higher than other traditional C_3 and C_4 plants whose yield is around 1-3%. Ninty percent of the inefficiencies is due to the biological limitations of sunlight utilisation. The theoretical optimistic productivity represents an unattainable limit despite improved cultivation techniques and efficient algal strains. The production yield results presented here confirms its realistic potential and it will assist the bio fuel 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 T/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 to 50,415 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 tonnes $C0_2$/ha/yr. Our optimistic, most likely and pessimistic estimate of open pond microalgae production provides baseline information to assess the realistic potential of microalgae in various climatic conditions of the world. 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 still in their infancy, significant improvements in algal cultivation technology is required to achieve the most likely estimates of biomass and oil productivity. Future long-term research should be focused on increasing biomass productivity and lipid content during colder months.

CONCLUSIONS

An attempt was made to estimate algal biomass productivity, lipid productivity and carbon fixation potential based on readily available input data. The assessment presented here based on photosynthetic light efficiency can assist researchers to know the realistic potential of algal biofuels. The use of microbial photosynthesis for biofuel production can be expected to operate with efficiencies of at most 6%. At very most, optimistic biomass yield of 530 T/ha/yr and 1, 25,000 L/ha/yr of oil can be expected from microalgae under optimum climatic conditions. The upper optimistic biomass and oil yield can never be improved upon very much in open pond cultivation system. Any production numbers higher than the upper optimistic yield in a particular region is definitely impossible and is often questionable. Higher biomass yield closed to optimum value can be achieved in closed photo-bioreactor. These values can be used to explore the importance of the design features of large scale open pond cultivation system. A systematic approach and strategy is required to enhance the sustainability and productivity of algal bioenergy. The study shows the realistic potential of algae biodiesel and agrees with other author's work that microalgae could contribute to meet a significant portion of the renewable fuel targets. 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. The analysis is for assessing the global algal biomass potential and not intended to disqualify any locations for microalgae cultivation.

REFERENCES

1. Sudhakar, K., M. Rajesh and M. Premalatha, 2012. A Mathematical Model to Assess the Potential of Algal Bio-fuels in India. Energy Sources, Part A: Recovery, Utilization and Environmental Effects, 34(12): 1-7.
2. Heydarzadeh, J.K., G. Amini, M.A. Khalizadeh, M. Pazouki, A.A. Ghoreyshi, M. Rabeai and G.D. Najafpour, 2010. Esterification of Free Fatty Acids by Heterogeneous ~-Alumina-Zirconia Catalysts for Biodiesel Synthesis. World Appl. Sci. Journal, 9(11): 1306-1312.
3. Khalid Hussain, Khalid Nawaz, Abdul Majeed and Feng Lin, 2010. Economically Effective Potential of Algae for Biofuel Production: World Appl. Sci. J., 9(11): 1313-1323.
4. Khan, S.A., Rashmi, M.Z. Hussain, S. Prasad and U.C. Banerjee, 2009. Prospects of biodiesel production from microalgae in India. Renew. Sust. Energy. Rev., 13(9): 2361-72.
5. Zilinskas Braun, G. and B. Zilinskas Braun, 1974. Light absorption, emission and photosynthesis. In: Stewart WDP, editor. Algal physiology and biochemistry. Oxford: Blackwell Scientific Publications.
6. Richmond, A., 2000. Microalgal biotechnology at the turn of the millennium: a personal view. J. Appl. Phycol., 12: 441-451.
7. Benemann, J., 1997. CO_2 mitigation with microalgae systems. Energ. Convers. Manag., 38: 475-479.
8. Spolaore, P., C.C. Joannis, E. Duran and A. Isambert, 2006. Commercial Applications of Microalgae, J. Biosci. Bioeng., 101(2): 87-96.
9. Metting, F.B., 1996. Biodiversity and Application of Microalgae, J. Ind. Microbiol., 17: 477-489.

10. Chisti, Y., 2007. Biodiesel from microalgae, Biotechnol. Adv., 25: 294-306.
11. Xu, H., X.L. Miao and Q.Y. Wu, 2006. High quality biodiesel production from a microalga Chlorella protothecoides by heterotrophic growth in fermenters, J. Biotechno., 126: 499-507.
12. Maxwell, E.L., A.G. Folger and S.E. Hogg, 1985. Resource evaluation and site selection for microalgae production systems, SERI/TR-215-2484.
13. Bolton, J. and D. Hall, 1991. The maximum efficiency of photosynthesis. Photochem. Photobiol., 53(4): 545-548.
14. Cornet, J.F., C.G. Dussap and J.B. Gros, 1994 Conversion of radiant light energy in photobioreactors. AIChE. J., 40(6): 1055-1066.
15. Lawlor, D.W., 1987. Photosynthesis: metabolism, control and physiology. Longman Scientific and Technical, Essex.
16. Schenk, P., S. Thomas-Hall, E. Stephens, U. Marx, J. Mussgnug, C. Posten, *et al.*, 2008. Second generation biofuels: high-efficiency microalgae for biodiesel production. Bioenergy Res., 1: 20-43.
17. Sheehan, J., T. Dunahay, J. Benemann and P. Roessler, 1998. Look back at the U.S. Department of Energy's Aquatic Species Program:biodiesel from algae; Close-Out Report. NREL Report No. TP-580-24190.
18. Raven, J.A., 1988. Limits to growth. In: M. Borowitzka and L. Borowitzka (eds) Micro-algal biotechnology. Cambridge University Press, Cambridge.
19. Weyer, K.M., D.R. Bush, A. Darzins and B.D. Wilson, 2010. Theoretical maximum algal oil production, Bioeng. Res., 3: 204-213.
20. Barsanti, L. and P. Gualtieri, 2006. Algae-Anatomy, Biochemistry and Biotechnology, CRC, Boca Raton, FL/Taylor and Francis, London.
21. National Aeronautical and Space Administration (NASA), USA 2008. NASA surface meteorology and solar energy: RET Screen, data, [Online], Available from http://eosweb.larc.nasa.gov.
22. Wikipedia, 2009. Photosynthesis, http://en.wikipedia.org/wiki/Photosynthesis.
23. Britannica, E., 2009. Photosynthesis, www.britannica.com.
24. Hill, R. and F. Bendall, 1960. Function of the Two Cytochrome Components in Chloroplasts-A Working Hypothesis, Nature (London), 186(4719): 136-137.
25. Gueymard, C., 1995. SMARTS, a simple model of the atmospheric radiative transfer of sunshine: algorithms and performance assessment. Professional Paper FSEC-PF-270-95. Florida Solar Energy Center.
26. Gueymard, C., 2001. Parameterized transmittance model for direct beam and circumsolar spectral irradiance. Sol Energy, 71(5): 325-346.
27. Falkowski, P.G. and J.A. Raven, 2007. Aquatic photosynthesis. Princeton University Press, Princeton.
28. Govindjee, R. and Rabinowitch E. Govindjee, 1968. Maximum quantum yield and action spectrum of photosynthesis and fluorescence in Chlorella. Biochim Biophys Acta, 162: 539-544.
29. Lawlor, D.W., 1987. Photosynthesis: metabolism, control and physiology. Longman Scientific and Technical, Essex.
30. Raven, J.A., 1974. Photosynthetic electron flow and photophosphorylation. In: W.D.P. Stewart (ed) Algal physiology and biochemistry. University of California Press, Berkeley.
31. Walker, D., 1992. Energy, plants and man. Packard Publishing Limited, East Sussex.
32. Ryther, J.H., 1959. Potential productivity of the sea. Science, 130: 602-608.
33. Goldman, J., 1979. Outdoor algal mass cultures-II. Photosynthetic yield limitations. Water Res., 13: 119-136.
34. González, J.A. and J. Calbó, 2002. Modelled and measured ratio of PAR to global radiation under cloudless skies. Agric. For Meteorol., 110: 319-325.
35. Jacovides, C.P., F.S. Timvios, G. Papaioannou, D.N. Asimakopoulos and C.M. Theofilou, 2004. Ratio of PAR to broadband solar radiation measured in Cyprus. Agric. For Meteorol., 121: 135-140.
36. Williams, P.J.L. and L.M.L. Laurens, 2010. Microalgae as biodiesel and biomass feedstocks: review and analysis of the biochemistry, energetics and economics, Energy Environ, Sci., 3: 554-590.
37. Miyamoto, K., ed., 2009. Biological Energy Production, Renewable Biological Systems for Alternative Sustainable Energy Production, FAO Food and Agriculture Organization of the United Nations, Agricultural Consumer Protection.
38. Chisti, Y., 2008. Biodiesel From Microalgae Beats Bioethanol, Trends Biotechnol., 26(3): 126-131.

39. Chiu, S.Y., C.Y. Kao, M.T. Tsai, S.C. Ong, C.H. Chen and C.S. Lin, 2009. Lipid accumulation and CO_2 utilization of *Nannochloropsis oculata* in response to CO_2 aeration. Bioresour. Technol., 100: 833-838.
40. Benemann, J.R., B.L. Koopman, D.C. Baker, R.P. Goebel and W.J. Oswald, 1978. The photosynthesis energy factor: Analysis, synthesis and demonstration. DOE contract number EX-76-C-01-2548: Intertechnology/Solar corporation.
41. Odum, H.T., 1971. Environment, power and society. Wiley-Interscience, pp: 331.
42. Mirón, A.S., M.C.C. García, A.C. Gómez, F.G. Camacho, E.M. Grima and Y. Chisti, 2003. Shear Stress Tolerance and Biochemical Characterization of Phaeodactylum Tricornutum in Quasi Steady-State Continuous Culture in Outdoor Photobioreactors, Biochem. Eng. J., 16(3): 287-297.
43. Darzins, Al, Philips Pienkos and Les Edye, 2010. Current status and potential for algal biofuels production: A report to IEA bioenergy task 39 commercializing liquid biofuels from biomass.
44. Ravindranath, N.H. and P.R. Bhat, 1997. monitoring of carbon abatement in forestry projects-case study of western ghat project, Mitigation and adaptation strategies for Global change, 2: 217-230.