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RESEARCH ARTICLE

SOLAR ENERGY A VALUABLE ASSERT FOR CARBON SEQUESTRATION IN INDIAN SUBCONTINENT (RENEWABLE ENERGY RESOURCE A BREAK-THROUGH IN POLLUTION CONTROL)

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ABSTRACT

Kyoto Protocol, after which the CO_2 Sequestration (one of the CDM methods) that has been identified as valid Necessity for all growing Nations. The GDP grows through Industrial/ Technological Exploitations. Here the evaluation Terrestrial methods of CO_2 sequestration by Solar Energy utilization in Bio-Algae growth, which in turn fixes the CO_2 in various form such as less Emissive Bio-fuels. And the Yield of Biomass that fixes the Carbon is varying by the variation of the light energy incident on the algal culture.

INTRODUCTION

The growing need of every developing nation is the fuel to feed their industrial pursuits to materialize the resources to economy. The traditional fuels such as Coal and natural gas are at the verge of vanish; therefore the recent need of hour is to hunt for a promising fuel which is also renewable in nature. The energy generated from the fossil fuels is not sustainable. As its clear by the environmental impacts that is created by the high emissions and effluents. These emissions could be controlled by western countries by costly and high energy intensive methods of carbon capture, and sequestration. Still the methods of Geological and oceanic CO_2 sequestration finds no good fit in the present scenario as the land pollution and oceanic pollution is rising at a deadly rates even in grown-up nations. In Kyoto Protocol held at 1997, the CO_2 Sequestration has been identified as a valid Necessity for all growing Nations. The earlier researches in renewable-fuels for replacing conventional ones didn't pick up momentum, due to lack of interest from stack holders and lack of sufficient policies from governments. But now the need is to have at best a reliable and renewable fuel, is very vitally felt by everyone unanimously, so micro-algae based bio-diesel is very promising one for now. We are assured to have better oil yield through micro-algae in comparison to any other biomass, and they have high carbon capture capacity than any other terrestrial biomass available. Therefore to meet the ends of the hour, we ought to accept Bio fuels by Microalgae which has a very high lipid content compared to the other oil crops such as Oil-palm, Rapeseed, Corn, etc. Therefore have better scope in Micro-algae as it can used in various forms after oil extractions, such as Biogas production by anaerobic respiration of residues of micro algae after oil yield or producer gas production by gasification through such dried residues, or bio-ethanol production through dry fermentation, or co-firing along with coal in power plants, and it serves to human kind as the single cell protein.

To grow microalgae require good sunlight levels and consistent temperatures for high productivity throughout the year. Producing Algal bio-fuels would require the discovery of Algal strains that can sustain at low temperatures and varying light levels. Our work here is to find the feasibility of growing micro-Algae for Carbon Sequestration in Indian Power Plants. There is not much results reported from Indian situations in account to the growth statistics. The growth is with respect to the sunlight which is a major criterion in growing algae, as they would get inhibited for lesser and heavier radiations. There is also a need for make-up water for growth, but could be managed with sewage/drainage effluent. The nutrients, CO_2 required is met by the artificial supplements which can be done by passing industrial emissions. At last by analyzing the availability of sunlight, water, nutrients and CO_2 and effects of

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all these parameters in Indian context, we have predicted the feasibility before investing tonnes of money for pilot plant.

MATERIALS AND METHODS

The solar radiation as evaluated by the modeling that is predicted in the earlier solar energy researches papers. And its taken as it is evaluated by that model which is the standard model used by major modeling software's at present. Also we assume that the solar radiation is same, without taking into account of the non-seasonal rainfall, sudden cyclones, unpredicted cloudy skies due to the smog and the other random changes in climate which affect the sunshine. We tend to have our photosynthetic efficiency of the algae which is specific to algae. The values of K_1 K_2 K_c are empirical constants that are taken from literature (David Michael Wogan, 2010).

The growth of algae is predicted with the assumption that the daily evaporation of water in pond is 0.06m/day in a good bright sunny day. And the loss of the water is equated to zero apart from yield time losses and evaporation. (David Michael Wogan, 2010) Here its taken as such the algae pond is protected from the external predators which invade the pond and make the cell death. Also the temperature is assumed as safer limits, for the specific algae, so that there is no possibility of cell decay apart from the yield period. The other possibility such as cell-decay due to the drought climate is neglected by assuming the pond is always maintained by the standard water availability as the cell concentration. The oxygen removal is not necessary in case of the open ponds. So we are neglecting such complexities in case of an open pond, because the O_2 removal is taken care of the ambient air flow. The pH is maintained as (8.2)pH. (David Michael Wogan, 2010)

The nutrient concentration required as taken as it is from pre-determined values. The concentration of the nutrients is maintained as such the C02 is also maintained in a standard value. By keeping the concentrations as constant we are effectively mapping the growth of the algae with respect to the standard normal conditions without abrupt changes that inhibits the algal growth. The land utilized for the algae culture are the standard website of the NREL, (National Renewable Energy Laboratory, 1991-2005) which are approved to be best suited for the algal growth in Indian sub-continent, with regard to the land, water, industrial CO_2, effluents water/fresh water/Rain-water, and with good sunshine.

I. Modeling of the "Solar Insolation Evaluation":

The following Equations are used in finding photosynthetically-active-irradiance at a given latitude and solar day (as per Julian calendar) (Liu and Jordan, 1960; Duffie and Beckman, 1980; Rudras *et al.,* 2010)

A. Declination angle

Seasonal variations in solar irradiance may be attributed to changes in the solar declination angle. The solar declination angle varies throughout the year and is a function of the day (Liu and Jordan, 1960) number of the year (*N*). *N* takes on values from 1(January 1) to 365. The solar declination angle (δ) is constant for all locations in the northern hemisphere (Liu and Jordan, 1960) and can be calculated for each day as follows:

$$\delta = 23.45 \text{ Sin}\left(\frac{360(284+\text{N})}{365}\right) \quad \text{.....................................(1)}$$

Note. 23.45° is the angle at which the axis of the earth is tilted and 360° and 284 are conversion factors from radians to degree. 365 denotes the number of days taken to complete one revolution by the earth around the sun.

B. Local solar time(L_{st}):

Twelve noon local solar time (LST) is defined as when the sun is highest in the sky. (Liu and Jordan, 1960) Local standard time (LT) usually varies from LST because of the eccentricity of the Earth's orbit, and because of human adjustments such as time zones and daylight saving The positive sign indicates the standard meridian of the country lying in the Westside of the hemisphere, and negative sign indicates the standard meridian of the country lying in the eastern side of the hemisphere

$$local\ Solar\ time = Standard\ time \pm \left[\frac{TCF}{60}\right]$$

C. Equation of time(E):

The equation of time (E) (in minutes) is an empirical equation that corrects for the eccentricity of the Earth's orbit and the Earth's axial tilt.

$$E = 9.87(Sin2B) - 7.53(CosB) - 1.5(SinB) \quad \text{....(2)}$$

$$B = \frac{360(N-81)}{364} \quad \text{...(3)}$$

D. Time Correction Factor(TCF)

The net Time Correction Factor (in minutes) accounts for the variation of the Local Solar Time within a given time zone due to the longitude variations within the time zone and also incorporates the E.

$$TCF = 4(L_{st} - L_{oc}) + E \quad \text{............... .....(4)}$$

E. Solar hour angle(W)

The solar hour angle (ω) (degrees) for a location on earth is zero when the sun is directly overhead and negative before noon and positive in the afternoon (E.Molina, 1999). Similarly, hourly changes in the solar irradiance depend upon solar hour angle (ω), which is a function of the solar hour (*h*). The solar hour *h* varies from24 to 1 (Liu and Jordan, 1960):

$$\omega = 15\ (\text{Local Solar time} - 12) \quad \text{..................... ...(5)}$$

F. Solar angle(ω_s)

The angle between sunrise and sunset is given by (2 ω_s.). The solar angle at sunrise (ω_s) incorporates seasonal variations in solar declination angle with the latitude (Φ) (degrees) of the area being considered (Liu and Jordan, 1960).

$$\omega_s = \cos^{-1}(-\tan\delta\ \tan(\emptyset - \beta)) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(6)$$

For (Jan 1 to ma 21, Sept 22 to dec31)

$$\omega_s = \cos^{-1}(-\tan\delta\ \tan(\emptyset)) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(7)$$

For (March 21 to Sept 21)

G. Angle of incidence(θ):

$$\theta = \cos^{-1}(\sin\emptyset \sin\delta \cos\beta - \sin\delta \sin\beta\ \cos\emptyset \cos\gamma + \cos\emptyset \cos\delta \cos\omega_s + \cos\emptyset \cos\delta \sin\beta\ \cos\omega \cos\gamma + \cos\delta \sin\beta \sin\delta \sin\omega) \quad \ldots..(8)$$

H. Zenith angle θ_z:

$$\theta_z = \cos^{-1}(\cos\emptyset \cos\delta\ \cos\omega - \sin\beta \sin\emptyset) \quad \ldots\ldots\ldots\ldots..(8)$$

I. Day length(t_d):

Total Sunshine hours for a particular day of the year at a given location is evaluated here. Since the 15deg of hour angle angle is equivalent to one-hour duration, the duration of sunshine hours, t_d or daylight hours is given by (Liu and Jordan, 1960)

$$t_S = (\tfrac{2}{15}) \cos^{-1}(-\tan\delta\ \tan(\emptyset)) \quad \ldots\ldots\ldots..(9)$$

$$Sunshine\ hours, N = \left(\frac{2\,\omega_s}{15}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots.....(10)$$

J. Empirical constants(a & b):

Empirical constants by regression parameters for a particular location, obtained by fitting data:(2)

$$a = 0.409 - (0.5016\ \sin(\omega_s - 60)) \quad \ldots\ldots\ldots\ldots\ldots\ldots(11)$$

$$b = 0.6609 - (0.4767\ \sin(\omega_s - 60)) \quad \ldots\ldots\ldots\ldots\ldots..(12)$$

K. Daily Solar Radiation(H_g)

Total Sunshine Radiation, of monthly average *daily Solar Radiation*, on a horizontal surface of the ground is evaluated as followed. (Duffie and Beckman, 1980) The total extraterrestrial irradiance incident on the earth (*Ho*) (kJ $m^{-2}d^{-1}$) varies seasonally. Some of the incoming solar irradiance is lost due to varying atmospheric transmissivity (n/N) associated with cloud cover. The atmospheric transmissivity, which is also known as the clearness index, is the ratio of the total daily radiation (*H*) (kJ $m^{-2}d^{-1}$) at ground level to the total daily extraterrestrial radiation (*Ho*) (kWhm^{-2}d^{-1}). The total irradiance incident that makes it to the earth surface (H) surface was calculated as the product of *Ho.* (K_h) associated with cloud cover and its a unitless parameter which varies by every month. (National Renewable Energy Laboratory, 1991–2005) I_{sc}=1.367(kJ $m^{-2}d^{-1}$), which is the solar constant energy received from sun for a unit time on a unit area perpendicular to sun rays.(1kJ/Sq.m = 3600kW/Sq.m)

$$H_o = \left(\frac{24\,I_{sc}}{\pi}\right)\left(1.0 + 1.033\cos\left(\frac{360\,N}{365}\right)\right)\left(\left(\cos\emptyset \cos\delta \sin\omega_s\ \right) + \left(\frac{2\pi\omega_s}{360}\ \sin\emptyset \sin\delta\right)\right) \ldots..(13)$$

$$H_g = H_o\left(a + b\left(n/N\right)\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(14)$$

$$H_d = H_g\left(1.354 - 1.570(k_f)\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots..(15)$$

$$H_b = H_t - H_d \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(16)$$

n is the measured number of sunshine hours data *N* is the number of sunshine hours calculated as shown in the page .

L. Hourly Solar Radiation(I_g)

Total Sunshine Radiation, of monthly average *hourly Solar Radiation*, on a horizontal surface of the ground: (Rudras *et al.*, 2010; E. Molina, 1999)

$$I_g = \left(\frac{3.142\,H_g}{24}\right)(a + b\cos\omega_s)\left|\frac{\cos\omega_s - \cos\omega}{\sin\omega_s - \omega_s\cos\omega_s}\right| \quad \ldots\ldots(17)$$

$$I_d = \left(\frac{3.142\,H_d}{24}\right)\left|\frac{\mathrm{Cos}\omega - \mathrm{Cos}\omega_s}{\sin\omega_s - \omega_s\cos\omega_s}\right| \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(18)$$

$$I_r = (I_b + I_d)\,(\rho)\,\left(\frac{1 - Cos\,\beta}{2}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots...(19)$$

$$I_b = I_g - I_d \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(20)$$

$$I_{bt} = I_b\left(\frac{Cos\,\theta}{Cos\,\theta_z}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(21)$$

$$I_{dt} = I_d\left(\frac{1 + Cos\,\beta}{2}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(22)$$

$$I_t = I_{bt} + I_{dt} + I_r \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(23)$$

(only for closed Photo-Bio-Reactor)

$$I_t = I_g \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(24)$$

(for open-ponds; since the (β=0), for horizontal surfaces therefore the (I_r =0))

M. Photo synthetically active irradiance (PAR)

The photosynthetically active irradiance (*I*) (μE$m^{-2}s^{-1}$)used in (2) is a function of various solar angles (ω,ω_s),total solar irradiance (*H*) (J$m^{-2}d^{-1}$), and photosynthetic efficiency (E_f) (μEJ−1). The total photosynthetically active irradiance (*I*) over a horizontal culture surface can be determined from the total solar irradiance (I_t) (kJ $m^{-2}d^{-1}$) directly by utilizing the following equation

$$I = (I_t) * (E_f) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(25)$$

The photosynthetic efficiency (E_f) is the ratio of the photosynthetically active radiation to the total incident radiation (H). E_f ($1.74 \pm 0.09 \times 10{-6}$ EJ^{-1}) (Rudras *et al.,* 2010; E. Molina, 1999). It is substituted as a normal distribution with mean 1.74 ×10−6 and standard deviation 0.09 ×10−6 for Monte Carlo simulations.(PAR), where, the standard deviation 0.09 is positive for the case of maximum photosynthetic efficiency and negative for the least photosynthetic activity.

II. Modelling of Carbon-dioxide intake

A. Calculating dissolved CO_2

The amount of photons in the photo-bioreactor decreases exponentially with increasing reactor depth. Algae growth varies with carbon dioxide concentration, from atmospheric concentrations (0.038 percent) to higher concentrations typical of flue gas (12-14 percent). (Berberoglu *et al.,* 2008; Benjamin, 2002). The literature suggests that optimal growth is possible at concentrations higher than atmospheric levels, (Benemann, 1997; David Michael Wogan, 2010) the optimal carbon dioxide concentration used is 0.05 mole fraction (5 percent). The total dissolved carbon in the liquid phase, C_{tot}, depends on the initial molar fraction of carbon dioxide provided to the algal culture and can be expressed as (David Michael Wogan, 2010):

$$C_{tot} = \left(10^{-1.5} X_{CO_2,g}\right) + \left[\left(\frac{10^{-7.8}}{10^{-pH}}\right) X_{CO_2,g}\right] + \left[\left(\frac{10^{-28.1}}{10^{-2pH}}\right) X_{CO_2,g}\right] \ldots \ldots\ldots\ldots (26)$$

where, the *pH* is the pH of medium and *xCO2,g* is the initial molar fraction of carbon dioxide. (Berberoglu *et al.,* 2008; Benjamin, 2002) The amount of dissolved carbon depends on the pH and initial molar carbon dioxide concentration of the air, or gas being bubbled in algal culture. This model takes that the liquid and gas phases are at quasi equilibrium (David Michael Wogan, 2010).

The mass transport on the liquid side of the bubble surface is analyzed because this is considered limiting and transport on the gas side is much faster. By setting the liquid flow rate high enough, the CO2 concentration is maintained at less than or equal to 10% of its saturation value at the liquid phase exit and the bulk liquid CO2 concentration (C) could be approximated as 0.

III. Modeling the Algae growth

A. Specific growth rate

Algae growth may be found by the Monod growth model, initially developed in 1949 by Claude Monod to model the growth of bacterial cultures. (Monod, 1949) It has been modified throughout the annals to consider the additional variables and environmental effects that affect Algae growth.

The environmental conditions considered in this model are available solar radiation, amount of dissolved carbon dioxide in the algae broth, and various other constants that deal with carbon uptake rates by the algae. This analysis handles the below found version of earlier Monod's model (Asenjo and Merchuk, 1995) :

$$\mu = \mu_{max} \left(\frac{I_t}{I_t + K_1}\right)\left(\frac{C_{tot}}{K_c + C_{tot} + \frac{C_{tot}^2}{K_1}}\right) \ldots\ldots\ldots\ldots (27)$$

μ is the Microalgae growth rate, or specific growth rate, with the units (1/s or 1/h). (Dunn *et al.,* 2003) A higher specific growth rate indicates a system that takes less time to reproduce and double its mass. The actual rate of growth would be the function of certain other parameters (temperature, stirring, etc.), still is assumed to that only a function of incident solar radiation and amount of carbon dioxide in this model. This assumption is embedded in the modified Monod model used by Berberoglu (Krause-Jensen and Sand-Jensen, 1998).

The maximum specific growth rate, μ_{max}, is determined experimentally and can be used to capture temperature effects of a culture; I_t is the available amount of light available within the reactor expressed in ($kJ\ m^{-2} d^{-1}$); K_G is the half-saturation constant of light ($kJ\ m^{-2} d^{-1}$) Ctot is the total amount of dissolved carbon (liquid phase) in the reactor ($kmol\ Cm^{-3}$); and K_C and K_I are the half-saturation and inhibition constants for carbon ($k\ mol\ Cm^3$). (Berberoglu *et al.,* 2008) The constants K_G, K_C, and K_I vary by species and have been determined. Here the species of Micro Algae that is considered is Chorella vulgaris and its resepective values are taken into Account for the modeling; this species is reported to have better oil content as well as better carbon fixing rates in its photosynthetic conversion (Mata *et al.,* 2010)

B. Growth Yield

In general, algae growth can be described by four phases: lag, exponential growth, linear growth and death. (Richmond, 2004) A reactor is typically initiated with a culture of algal cells and nutrient media. The alga cells do not immediately begin reproducing and instead take time to adapt to their new environment. This time period is referred to as the lag phase. Once the alga cells have adapted to their environment they begin growing at an exponential rate until they become limited by the lack of a given resource or nutrient. This behavior is called the exponential growth phase. The algae continue to grow until all of the resources and nutrients are consumed, which marks the beginning of the death phase. (Dunn *et al.,* 2003) Only the exponential growth phase is considered in this model. This model assumes that the algal culture has been inoculated and has had sufficient time to adapt to the growth conditions. It is assumed that the algae will be removed continually from the reactors before reaching the latter growth stages (linear growth and death). The exponential growth phase is represented as the time rate of change of the cell density in the culture,

$$\frac{dX}{dt} = \mu t \ldots\ldots\ldots\ldots (28)$$

where X is the cell concentration of the algae in g dry cell/m3 and μ is the specific growth rate of the algae in h-1. (Dunn *et al.,* 2003; Goldman, 1979) The biomass produced at a given time *t* is found by integrating Equation 5 for the final cell concentration *X(t)*:

$$X = X_o(e^{\mu t}) \ldots\ldots\ldots\ldots (29)$$

IV. Chemical Engineering design aspects of Carbon sequestration system

A. Gas –liquid mass transfer

The transport rate (R) of CO_2 from the bubble surface is followed from the equation given by (Pirt, 1975):

$$R = k_L(C_{s}\_C) \qquad \text{…….…………………………..(30)}$$

where kL is the liquid-phase mass transport coefficient (0.00016 m/sec from (Shah *et al.,* 1982) A is the bubble surface area, and Cs is the saturation concentration of CO_2. Using Henry's Law at 30 ºC the concentration of CO_2 is estimated as:

$$C = P_A \rho_m k_H \qquad \text{……………………………….(31)}$$

$$= 28P_A \qquad \text{……………………..……………..(32)}$$

where PA is the partial pressure of CO_2 in atm, qm is the molar density of water (56,000 mol/m^3) and kH is Henry's Law constant for CO_2 at 30 ºC (2000 atm/mol fraction obtained from (Emmert and Pigford, 1963). The Cs in-pond water at 30 ˚C was calculated s:

$$C_s = 28 \times P_1 \qquad \text{……………………………….…(34)}$$

And the liquid flow-rate at saturation is calculated to be as 1.37 L/min. By these calculations about 5 times higher flow-rate to the model value i.e., 7.0 L min^{-1} of pond water flow to the column was selected to avoid a significant approach to saturation.

B. Gas bubble content

The rate of CO_2 out of the bubble and in the liquid phase in terms of the time rate of change of CO_2 partial pressure in the gas bubble is:

$$= V\,Vm\frac{dP_A}{dt} \qquad \text{……………………………………(35)}$$

where V is the volume of the gas bubble, V_m is the molar volume of ideal gas at 30˚C (41 mol/m^3/atm). Equating the transport and time rate-of-change terms:

$$V\,Vm\frac{dP_A}{dt} = 0.00016 \times 28P_A \times \mathrm{A} \qquad \text{…………….(36)}$$

$$V\,Vm\frac{dP_A}{dt} = 41 \times V \times \frac{dP_A}{dt} \qquad \text{…………………….(37)}$$

$$41 \times V \times \frac{dP_A}{dt} = 0.00016 \times 28P_A \times \mathrm{A} \qquad \text{………..(38)}$$

For a 0.003 m diameter bubble, the value of A/V is 2000 m^{-1}, therefore :

$$\frac{dP_A}{dt} = 0.22dt \qquad \text{…………………..……………(39)}$$

C. Carbonation column design

For a 10-fold reduction in partial pressure of CO_2 (i.e. 90% transfer and PA1/PA2 = 10), it is found that t = 10.47 s. Since the bubble rise velocity was set at 0.3 m/s (Shah *et al.,* 1982), the minimum column height (H) should be 3.1 m.

D. Calculation of column diameter

The area of column cross-section (A_c) was designed as ten times of area of gas bubble (A_g = 0.52 cm^2), and was calculated as follows:

$$A_c = 10A_{\,g} \text{…………………………………….(40)}$$

$$A_c = 10\,\left({}^{Q}\!/_{v}\right)\text{=5.2cm2} \qquad \text{………………..……(41)}$$

where Q , gas flow rate (0.93 L min^{-1}); t, bubble rise velocity (30 cm/sec). Thus the minimum diameter of column should be 2.57 cm. A PVC pipe of 7.6 cm (diameter) is selected, the structural stability of the 3.1 m high column and also because of its availability off the shelf. (RonPutt *et al.,* 2011)

E. Actual CO_2 utilization

Biomass productivity, P_b (dry g L^{-1} day^{-1}) in batch mode was estimated from the following equation (Balachandran Ketheesan and Nagamany Nirmalakhandan, 2012)

$$P_b = \frac{1}{T}\left({}^{C_{f,b}}\!\Big/_{C_{i,b}} \right) \qquad \text{……………………………(42)}$$

where $C_{f,b}$ and $C_{i,b}$ are the final and initial dry biomass concentrations (g L^{-1}), respectively in the batch test period T (day). Biomass productivity, Pc (dry g L^{-1} day^{-1}) in continuous growth was estimated from the following equation:

$$P_c = \frac{W_h}{1000\,V_R} \qquad \text{……………………………………(43)}$$

where Wh is the average harvested dry biomass per day (dry g day^{-1}) and VR (m^3) is the total working volume of the reactor in a continuously operated algal reactor. Lipid productivity, $P_{C/L}$(g L^{-1} day^{-1}) in continuous growth was estimated from:

$$P{c}/_{L} = l\,P_c \qquad \text{……………………………………..(44)}$$

where l is the fraction of the lipid content in the dry biomass (g lipid (dry g biomass)_1).CO_2 fixation rate per unit culture volume, FCO_2 (g CO_2 L^{-1} day^{-1}) can be estimated as:

$$F_{CO_2} = aP_c \qquad \text{……………………………………(45)}$$

where a is the mass of CO_2 fixed by unit biomass, considering 50% of carbon in the dry biomass (Becker, 1994)

$$a = 0.5\left({}^{44}\!/_{12}\right) \qquad \text{………………………….…..(46)}$$

$a = 1.833$ ……………………………………...(47)

V. Power required for paddlewheel-driven raceway

In this section, expressions for estimating the power requirements for the traditional paddlewheel-driven raceways and the proposed airlift-driven raceways are developed from theoretical considerations. Power required in paddlewheel-driven systems should include the energy losses in the raceway and the energy required by the paddlewheel to maintain the circulation. The Manning formula has been used to analyze open channel flow and estimate head losses in open channel flow (Anderson, 2005). Theoretical mixing power requirement for paddle wheel driven raceway system has been estimated using mixing energy calculation (Hendricks, 2006).

A. Power required for maintaining flow in raceway (P_R)

Power required for maintaining flow in the raceway, P_R (W) is considered to be due to head loss in the raceways, which can be calculated from the Manning formula Velocity in the raceway (Ketheesan and Nirmalakhandan, 2011).

$$V_{raceway} = \frac{1}{n} R^{2/3} s^{1/2} \qquad \text{……………………….(48)}$$

Head loss per unit length of raceway

$$s = \frac{n^2 V^2{}_{raceway}}{R^{4/3}} \qquad \text{…………………….…….(49)}$$

Total head loss in raceway

$$H_R = \frac{n^2 L_R\, V^2{}_{raceway}}{R^{4/3}} \qquad \text{…………………….…..(50)}$$

Power required for maintaining flow in raceway

$$P_R = \frac{Q_L \rho_L g\, n^2 V^2{}_{raceway}}{R^{4/3}} \qquad \text{…………………..…(51)}$$

where QL is the volume flow rate of liquid in raceway (m3/s), g is gravitational acceleration (9.81 ms^{-2}), LR is length of raceway (m), R is hydraulic radius (m) for partial flow in the raceway (hydraulic elements graph for circular sewers) (Water pollution control federation and ASCE, 1970), n is Manning's coefficient (0.008) for PVC pipes) (Becker, 1994), and qL is the density of the water = 998.2 kg/m3.

B. Power required for mixing by the paddlewheel (P_p)

Power required, Pp (W) for mixing by the paddlewheel can be found from (Ketheesan and Nirmalakhandan, 2011):

$$P_P = F_p v_p \qquad \text{…………………………………..(52)}$$

Where F_P is the drag force on paddle wheel (N) and v_p is the velocity of paddle relative to water (m/s). The drag force can be estimated from

$$F_p = \frac{C_D \rho_L A_P v_P^2}{2} \text{……………………………(53)}$$

where CD is the drag coefficient for flat paddles and A_p is the area of the paddle in a plane perpendicular to the direction of the motion (m^2). Hence, the power required for mixing by the paddlewheel can be found.

$$P_P = \frac{C_D \rho_L A_P v_P^2}{2} v_p = \frac{C_D \rho_L A_P v_P^3}{2} \qquad \text{……………..(54)}$$

In this study, CD was taken as 1.8 (Rouse, 1946) and CD value of 1.16 and 1.2 were used for different paddle wheel configurations (Rouse, 1946). Slippage factor (ratio of velocity of water mass to velocity of the paddle wheel) was assumed as 0.3 as the whole water mass is transported by the paddle movement (Hendricks, 2006). Concentration of volatile CO2 in the pond, in moles per cubic meter.

VI. Modeling the Algal culture area

A. Mixable Length optimization

For a pond that has a depth of 30 cm (d), a mixing velocity (V) of 30 cm/s, a change in depth (Δd) of 7.5 cm, a channel length (w) of 6 m, Manning friction factor (n) of 0.01 the optimum length of the pond (L) can be calculated. (Yan *et al.,* 2006)

$$L = \left(\frac{\Delta d \left({}^{d\times w}/_{(w+2d)} \right)^{4/3}}{V^2 \times n^2} \right) \qquad \text{……………………(55)}$$

B. Mixable area

The mixable area can be calculated by using (30);

$$A = L\,B \qquad \text{……………………………………...(56)}$$

(this holds good for rectangular open raceway ponds)

C. Calculation of biomass productivity per unit power input (PB/P, $gW^{-1}day^{-1}$):

Light energy input per unit reactor volume, EL (kJ $m^{-2}d^{-1}$) was estimated from the measured PAR value, I_t (l mol m^{-2} s^{-1}) (as evaluated in earlier in Eqn.23 and 24)incident on the light receiving area, AR (m2) as follows: (Balachandran Ketheesan and Nagamany Nirmalakhandan, 2012)

$$E_L = \frac{0.22\, I_L\, A_R}{V_R} \qquad \text{………………………….……..(57)}$$

Mechanical energy input per unit reactor volume, EG (W m^{-3}) by gas spraying in airlift and bubble column reactors was estimated as follows.

$$E_G = \frac{Q_G \gamma\, h}{V_R} \qquad \text{……………………………………(58)}$$

where Q_G volumetric flow rate of gas (m^3 s^{-1}), γ is the specific weight of the broth (N m^{-3}), and h is the culture depth (m). In this study, specific weight of the broth is taken as that of water (= 9810 N m^3). Hence, biomass productivity per unit power input ($P_{B/P}$, g W^{-1} day^{-1}) can be estimated as:

$$P_{B/P} = \frac{1000P}{(E_G + E_L + P_P)} \qquad \text{…………………………(59)}$$

where P can be either P_b (batch) or P_c (continuous) depending on the mode of reactor operation.

VII. Resource Evaluvation

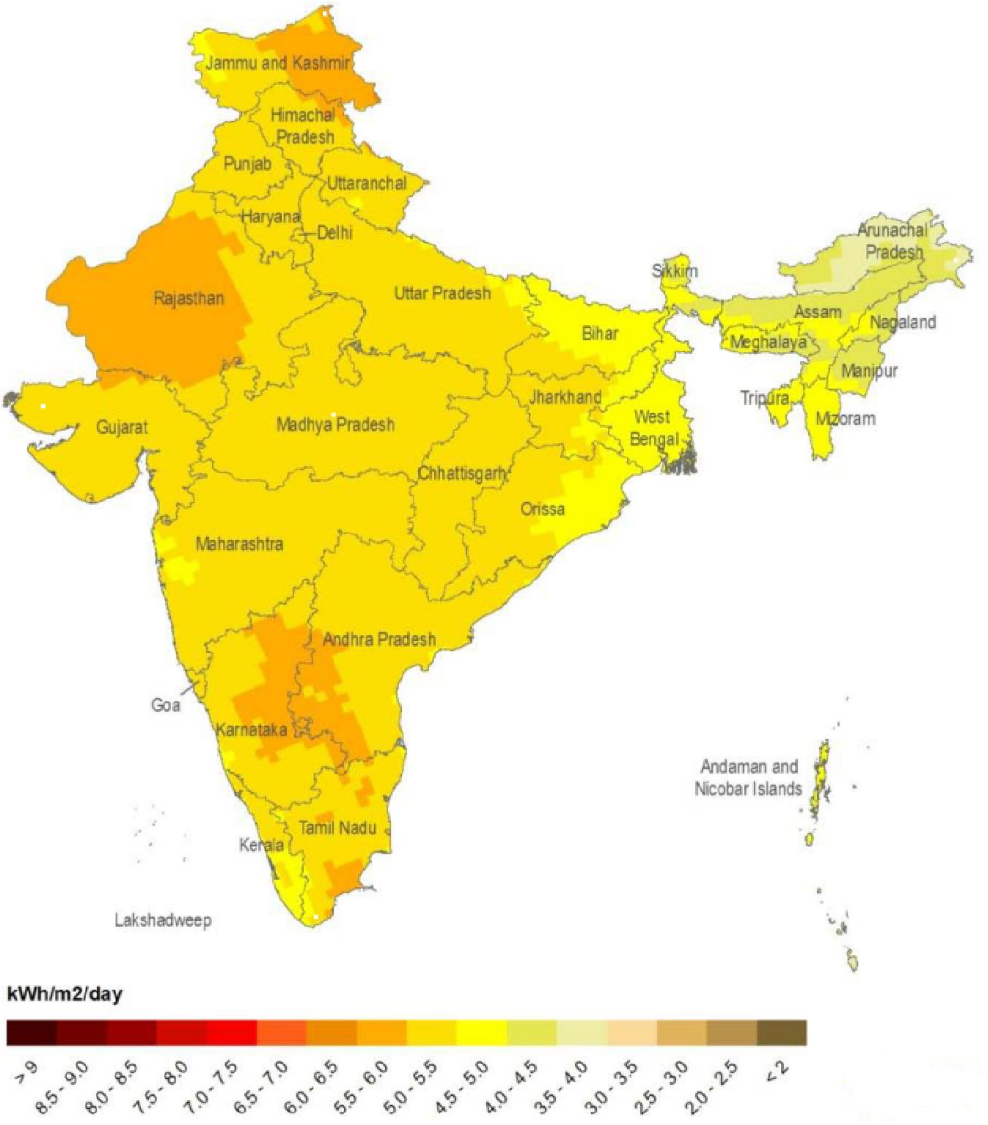
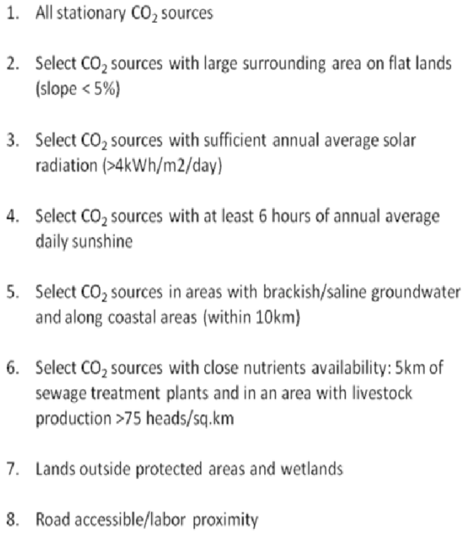


Fig.1. Solar Radiation in India (Solar Radiation Hand Book, 2008)



1. All stationary CO_2 sources
2. Select CO_2 sources with large surrounding area on flat lands (slope < 5%)
3. Select CO_2 sources with sufficient annual average solar radiation (>4kWh/m2/day)
4. Select CO_2 sources with at least 6 hours of annual average daily sunshine
5. Select CO_2 sources in areas with brackish/saline groundwater and along coastal areas (within 10km)
6. Select CO_2 sources with close nutrients availability: 5km of sewage treatment plants and in an area with livestock production >75 heads/sq.km
7. Lands outside protected areas and wetlands
8. Road accessible/labor proximity

Fig. 2. Flow chart of Algae Site Selection (Anelia Milbrandt and Eric Jarvis, 2010)

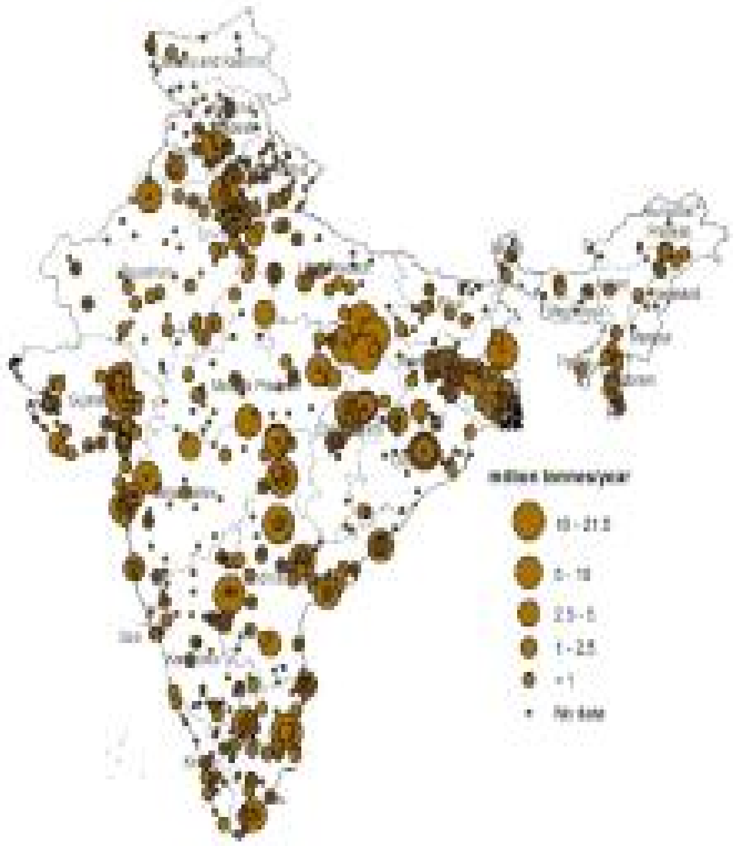


Fig. 3. Major Carbon sources in India (Anelia Milbrandt and Eric Jarvis, 2010)

Fig.4. Algae sites favorable for CO_2 Sequestration (Anelia Milbrandt and Eric Jarvis, 2010)

So based on the Fig.1and Fig.4 we choose to evaluvate the above mentioned parameters, in 6 sites which has abundent sunlight, good CO_2 supply, and large land area.

The sites chosen are., Cuddalore in Tamilnadu (TN Site), Nellore in Andhra Pradesh(AP Site), Bellary in Karnataka(KN Site), Sabarkantha in Gujarat(GJ Site), Gurgaon in Haryana(HR Site), Dewas region in Madhya Pradesh(MP Site).

VIII. Results

Now here evaluvate the PAR(Photosynthetically Active Radiation), the specific growth rate of Algae, the growth yield of Algae , total Solar power incident on the Algal culture, Requirement total water pumping power for the algae growth/culture mixing, Requirement of the CO2 gas pumping power, Requirement of total power for CSS(Carbon sequestration System)

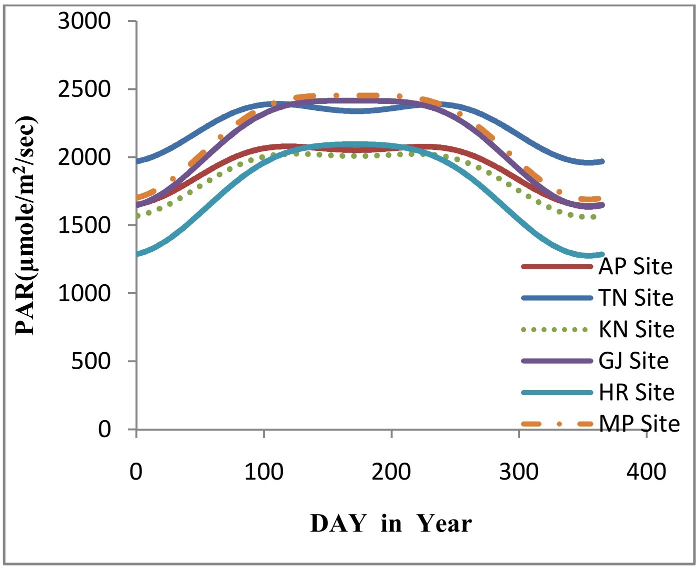


Fig. 5. PAR Variation in different Sites

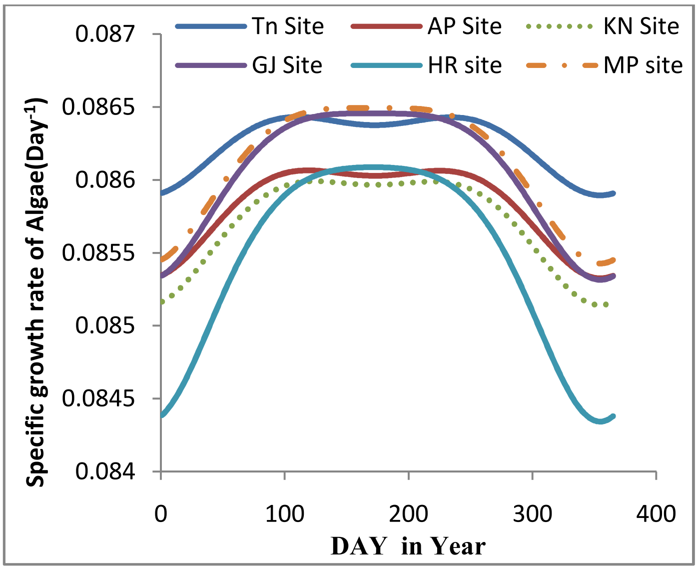


Fig. 6. Variation in Specific Growth of algae

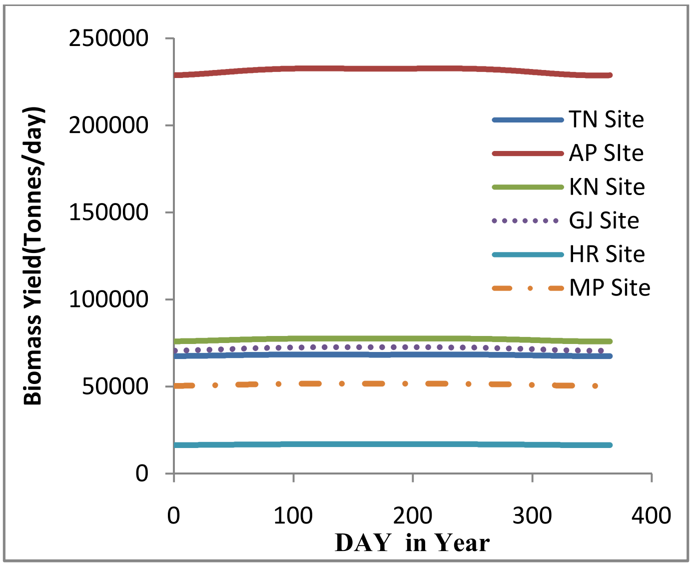


Fig.7. Variation in Biomass yield

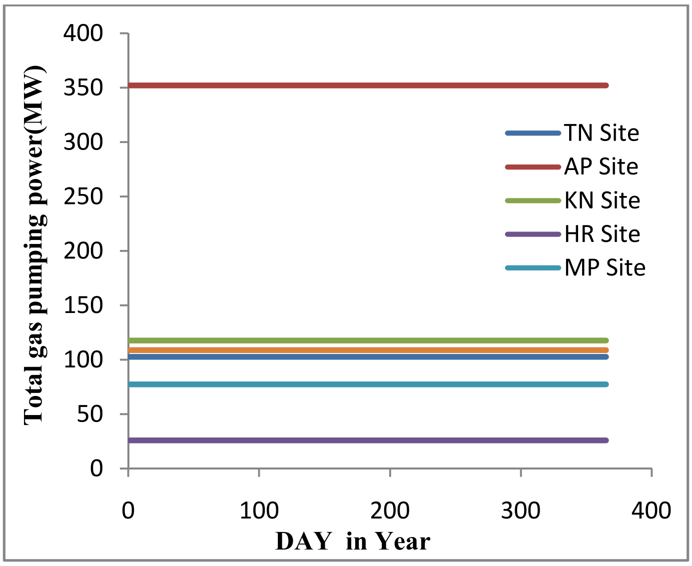


Fig.8. Variation in gas pumping Power

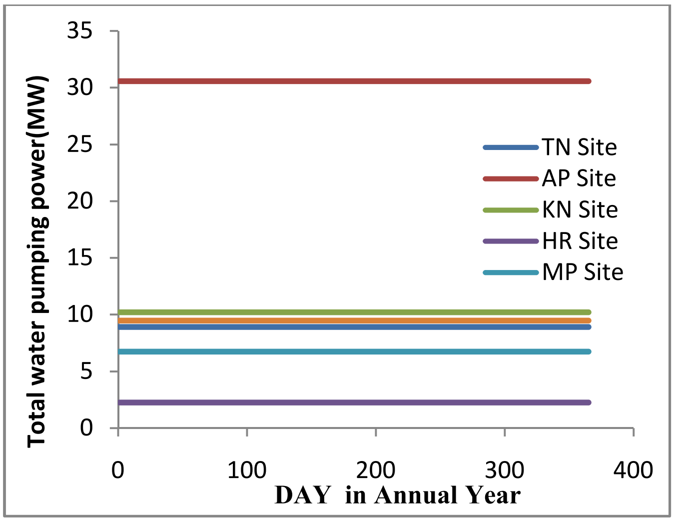


Fig.9. Variation in water pumping power

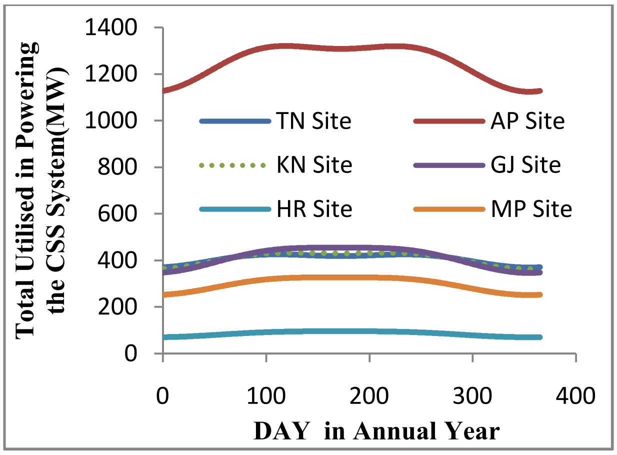


Fig.10. Variation in total required for CSS Unit

Conclusion

Thus the paper mainly identifies the Solar Resorce as the parameter that varies according to every place, and also the land available to construct the CSS Unit in the given location. This way the paper validates how the solar potential is very crucial to CO_2 sequestartion through cultivating Bio-Algae in open Raceway ponds. This Alage in turn gives low emmisive and a low cast Bio-fuel as the end product apart from the carbon mitigation. Although the Alage don't reduce carbon emmsion rate, but maintains the rate as fixed as of now, by fixing the carbon to the nature.

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