Effect of photoinhibition on microalgal growth in open ponds of NIT Rourkela, India

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Abstract

The aim of wastewater treatment should think beyond water purification to minimize the waste generation as well as the use of non-renewable resources to make the treatment process as sustainable. Currently, microalgae have been utilized in tertiary treatment methods to address water-energy nexus through biofuel production. The present paper focus on the mathematical modeling of microalgal lipid production along with carbon dioxide sequestration potential of open ponds of National Institute of Technology Rourkela (NITRKL). The model incorporates the site-specific data of solar radiation to derive the bioenergy content of microalgal biomass by photon energy balance. NITRKL has the average microalgal biomass production potential as 54.13 $g.m^{-2}.day^{-1}$ and the maximum growth has been predicted in the month of April. Scalability of microalgae and their introduction as wastewater treatment tools necessitate these modeling studies as a preliminary work for the better comprehension of the effect of climate on the microalgal growth rate.

Keywords: Bioenergy, Carbon dioxide, Mathematical modeling, Microalgae, Photoinhibition, Wastewater treatment

Introduction

Currently, the world faces critical challenges in both energy and environmental sectors due to the intensive industrial revolution progressed in the last two centuries. Energy crisis due to the depletion of fossil fuels and environmental pollution associated with the excessive use of petroleum fuels is the prime concern. However, the conventional energy sources represent the 80% of global energy utilized in the world (Christenson and Sims 2011; Shen 2014; Bhattacharjee and Siemann 2015). Secondly, the forest, land, air, and water pollution deteriorates the environmental quality and severely threats the sustainable livelihood of every organism in the ecosystem. The availability of water for human use is drastically decreasing, while on the other hand, the consumption rates were growing. Though conventional wastewater treatment (WWT) encourages the reuse of the treated wastewater; however, the treatment process are cost-intensive and often demands much energy.

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The concept of industrial symbiosis could be applied to WWT systems with algal growth to meet the escalating demand for renewable energy and high-quality water. This technique might solve the two biggest challenges that the today's world face (Zhou et al. 2013; Reda et al. 2014). The introduction of microalgae in the secondary treated effluent of conventional WWT might consume the nutrients such as nitrogen, phosphorus and eliminates the need for synthetic nutrients as well as enhance the reuse potential of treated wastewater for appropriate applications. Furthermore, the microalgae are the best solution for the bioenergy production while comparing with higher plants since they grow fast, survive in extreme conditions (non-arable place), high photosynthetic efficiency, and achieve higher yield for biomass and oil (Chisti 2007; Gouveia and Oliveira 2009; Park et al. 2011; Milano et al., 2016). Scalability and economics are the two most important challenges for biofuel production after the successful demonstration at laboratory scale. To minimize the risks associated with scalability and to influence the policy makers, the comprehensive knowledge on microalgal growth rate, lipid productivity and carbon dioxide (CO_2) captured from the atmosphere is essential.

Recently, several researchers have reported the different influencing factors of microalgal growth. However, mathematical studies with majority of data taken into consideration for predicting the production potential are very much lacking. The theoretical maximum of microalgal oil production with prime focus on the effect of latitude were studied by considering six various places in the world such as Kuala Lumpur of Malaysia (3°N); Honolulu of Hawaii (21°N); Tel Aviv of Israel (32°N); Phoenix of Arizona (33°N); Malaga of Spain (37°N) and Denver of Colorado (40°N) (Weyer et al. 2010). Similarly, Sudhakar and Premelatha, (2012) studied the theoretical estimation of microalgae in the six different countries of each continent such as Texas, Uruguay, Ethiopia, Madrid, Chennai, and Queensland. Further, similar procedures were utilized to estimate the microalgal production in the five different places of Ethiopia (Asmare et al. 2013).

Moreover, the utilization of sophisticated modern tools such as geographical information systems (GIS) and the concerned software tools could assist the researchers to predict the microalgal growth potential at much wider scale. For instance, Moodya et al. (2014) developed a mathematical model to predict the microalgal production potential by executing 4300 spatial data. However, extrapolation failed to predict the actual real-time possibilities for the prescribed site conditions due to the significant spatial and temporal variations. Though several research institutes focused on the exploration of microalgal applications in a wide array of sectors such as renewable energy, cosmetics, food and pharmaceuticals; however, none of the studies has been reported so far at an institutional level to couple WWT with microalgal growth aimed for biofuel production. The objective of the present study is to estimate the microalgal growth, lipid production, and carbon dioxide sequestration potential of the open ponds of NITRKL campus while exploring the technological feasibilities of coupling WWT with microalgae as a sustainable approach to addressing energy-water nexus.

Materials and Methods

Study location

NITRKL of India is located at 22.24°N and 82.91°E, at 219 m above the sea level. The climate is tropical in Rourkela, and the city has high rainfall during the southwest monsoon (June to September) and receding in northwest monsoon (December to January). The annual rainfall has a range between 1600 to 2000 mm. The institute is located in the city of Rourkela, Sundergarh district of Odisha, India. The study location with the open pond is shown in Figure 1.

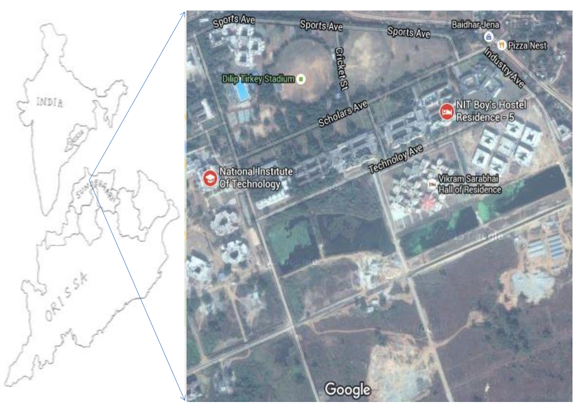

Figure 1: Localization of the open pond of the NITRKL in India

Parameters and equations used in the model

A mathematical model was used to estimate the microalgal biomass and algal oil productivity potential given the site-specific solar insolation data as the key input with other various parameters. The present study is based on photosynthetic limitations of microalgal growth that were formulated into several mathematical equations (Table 1) to calculate the microalgae and lipid production along with carbon dioxide sequestration potential. Metrological data such as the daily solar insolation in the horizontal of the site location and the air temperature at 10 m above the earth surface were obtained from National Aeronautical and Space Administration (NASA), USA databases and utilized as the model inputs. The model incorporates the realistic limits for light distribution, land use, photon transmission, photon utilization, photosynthetic efficiencies, and microalgal oil content based on literature data. The mean daily meteorological data, sunlight, ambient temperature and rainfall information for the identified potential site is combined to estimate the daily biomass production, lipid production, and carbon dioxide mitigation potential.

Table 1: List of the equation used in the study

Term	*Equation*
Photosynthetic active radiation	$\%PAR = \frac{\int_{\lambda=400}^{700\ nm} Esolar\ (\lambda)d\lambda}{\int_{\lambda=0}^{4000\ nm} Esolar\ (\lambda)d\lambda} * 100$
Photon energy	$Ephoton = h * \frac{c}{\lambda}$
Photon conversion efficiency	$PCE_{PAR} = \frac{HHV\ of\ CH_2O}{n_{photons}\ X\ Energy\ of\ PAR}$
Photon transmission efficiency	$\eta_{transmission} = \eta_{light} * \eta_{land\ use} * \alpha * \%PAR$
Energy capture efficiency	$\eta_{capture} = \eta_{photosynthesis} * \eta_{photoutilization} * (1-r)$
Photon utilization efficiency	$\eta_{photoutilization} = \frac{I_s}{I_1}\left[\ln\left(\frac{I_1}{I_s}\right) + 1\right]$
Biomass energy content	$E_{microalgae} = f_L * E_L + f_P * E_P + f_C * E_C$
Microalgae daily production	$MB_{(daily)} = \frac{\eta_{transmission} * \eta_{capture} * SI}{E_{microalgae}}$
Daily lipid production	$ML_{(daily)} = \frac{f_L * MB_{(daily)}}{\rho_L}$
Rate constant of CO_2 captured	$k = \frac{M_{CO_2}}{M_{biomass}}$
CO_2 captured efficiency	$Total\ CO_2 = k * MB * fixation\ efficiency$

Assumptions and limitations of the model

The developed mathematical model has taken the account of several most influencing parameters for autotrophic microalgae to grow in open pond systems. First of all, sunlight is the prime energy requirement through which the photosynthesis converts carbon dioxide to carbohydrate. Though the energy requirement is in the form of light energy, calculations were made based on the quantum of photons to have the thorough understanding of the biochemical effect of light. The energy balance equation also accounts all the losses of energy due to the atmospheric conditions, bioreactor geometry and the respiration of microalgae. The model included the

Table 2: List of the parameters utilized as the model input

Term	Optimum Value	References
Photosynthetically active radiation	0.43-0.47	Weyer et al. 2010; Zemke 2010
Photon energy	208-225.3 kJ.mol^{-1}	Weyer et al. 2010; Zemke 2010; Sudhakar and Premalatha, 2012
Photon conversion efficiency	0.267-0.274	Jacovides 2004; Brennan 2010
Photon transmission efficiency	0.43-0.44	Sudhakar and Premalatha 2012; Asmare et al. 2013
Energy capture efficiency	0.27	Sudhakar and Premalatha 2012; Asmare et al. 2013
Photon utilization efficiency	≤ 1	Zemke 2010
Biomass energy content	Specific to microalgae	Zemke 2010; Asmare et al. 2013
Microalgae daily production	Variable	Site specific
Daily lipid production	Variable	Site specific
Rate constant of CO_2 captured	1.89	Sudhakar and Premalatha 2012; Asmare et al. 2013
CO_2 captured efficiency	Variable	Site specific

consequences of the photoinhibition when the solar energy is higher than the normal required for microalgae. For the further improvement of the mathematical model, the role of water temperature and the nutrients present in the pond could also be included in the later stage. Since the growth of microalgae mostly depends on solar radiation, this model could able to estimate the theoretical maximum production along with real-time predictions. The biochemical composition (say Carbohydrates: Proteins: Lipids) of the microalgal biomass was presumed to be 35:35:30 respectively. Table 2 summarizes the parameters utilized in the model with the optimal values.

Results and Discussion

Solar insolation data

Solar radiation is the key primary energy input for the mathematical model that is affected by multiple variables such as cloud cover and concentration of few greenhouse gasses in the atmosphere. The calculation depends on several factors including full-spectrum energy, photosynthetically active radiation, photon transmission efficiency of sunlight to microalgae, capability of biomass to absorb carbon dioxide and light energy as well as the lipid content of the microalgae. The climatic condition data are retrieved from NASA databases in which the information depends exactly on latitude and longitude of the location with high accuracy (Stackhouse 2015). NIT Rourkela campus was considered for the present study due to the availability of the 7.7 hectare of open ponds in the Institute. The secondary treated effluent discharge from the Institute sewage treatment plant is allowed to mix in the open ponds. The organic nutrients availability in the treated effluent were minimal and sufficient for supporting the growth of microalgae. Hence, the treated wastewater from the sewage treatment plant was assumed to be a source of the water rather than nutrients, and the microalgae were assumed to be autotrophic in nature that need carbon dioxide as carbon sources. The open ponds were constructed into four various compartments and are directly exposed to the sunlight without any cover or filter.

The baseline information was taken on a monthly basis that starts from January 1985 to December 2005. The average of the 21 years of air temperature and solar radiation data was also analyzed. The main parameters related to the climatic conditions employed as inputs are represented in Figure 2. The lowest solar insolation that has been recorded out of the considered period is in the July month of 1994 with 2.97 kWh.m^{-2}.day^{-1}. Further, the highest solar insolation was observed in the month of April 1999 with 7.2 kWh.m^{-2}.day^{-1}. The solar insolation over the study period of 21 years was ranged in 4.9±0.96 kWh.m^{-2}. The net solar insolation based on a yearly basis were computed for the review period, and it was more than 1500 kWh.m^{-2}.yr^{-1} and the maximum were observed in the year 2004 around 1850 kWh.m^{-2}.yr^{-1}. The average of solar radiation in the world varies from 700 to 2500 kWh.m^{-2}.yr^{-1}. A small part of this energy only reach the outer atmosphere (1367 W.m^{-2}), and just 17.56% of the light energy reaching the atmosphere arrive at the earth surface. Microalgae needs an annual horizontal solar radiation more than 1500 kWh.m^{-2} equivalent to 4.1 kWh.m^{-2}.day^{-1}. The minimum requirement for microalgae are the availability of sunlight throughout the year; favorable climatic condition, precipitation and evaporation, humidity and of course temperature; land topography and finally access to nutrients, carbon sources, and water (Maxwell 1985). The calculation is based on the effect of the sunlight as a primary source of energy for algae to survive as well as for the lipid production and CO_2 sequestration. However, the others parameters are also equally significant for algae to grow faster and the necessary influencing parameters should be included in the mathematical model.

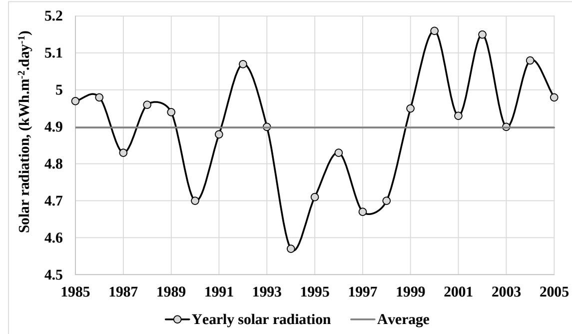

Figure 2 a: Solar radiation reaching the horizontal earth surface of open ponds of NIT Rourkela

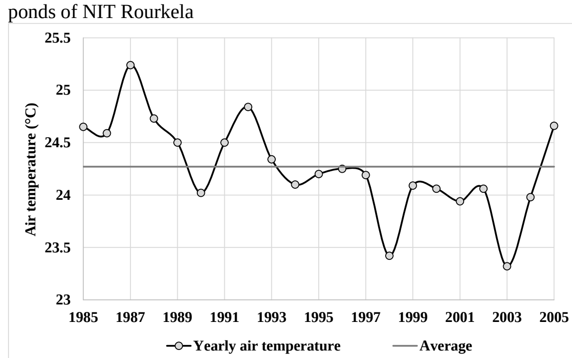

Figure 2 b: Air temperature at 10 m above the horizontal earth surface of open ponds of NIT Rourkela

The seasonal variation of the solar radiation was assessed for the study site for 21 years, and the following inferences were deduced. In the case of Rourkela, the peak summer season was witnessed in the months of March, April and May, while the lowest solar insolation was perceived in the month of July and August months of the year. It might be due to the variation in the number of daylight hours over the different seasons of the year. The average of the monthly data was computed and has been utilized as the input for the model to estimate the microalgal biomass production with a particular focus on algal oil through lipid productivity. Further, the model was extended to predict the carbon dioxide sequestration potential for the selected site. The baseline dataset was considered for 21 years because the solar radiation changes with respect to the position of the sun along with other atmospheric conditions like the cloud cover and the altitude of the locations.

Model output

The mathematical model to estimate the microalgal biomass production and carbon dioxide sequestration potential was developed based on the theoretical photosynthetic limitations on the corresponding equations mentioned in Table 1. The predicted seasonal variation of the microalgal biomass along with carbon dioxide sequestration potential was shown in Figure 3. It could be inferred from the results that the biomass productivity is directly dependent on solar radiation intensity data in case of theoretical predictions. The April month has the maximum biomass production, lipid production and CO_2 capture with 96.58 g.m^{-2}.day^{-1}; 33.53 ml.m^{-2}.day^{-1} and 27.47 g.m^{-2}.day^{-1} respectively. The reason is that in April, the pond gets the maximum of the solar radiation comparing to the other months of the year. Secondly, the lipid production depends on the percentage of the lipid, protein and carbohydrate concentration of the microalgae. Also, even the temperature in the April month is the maximum, but it is adequate for algae to grow because the optimum temperature for microalgae is between 20 °C to 30 °C; and 35 °C is the maximum water temperature at which the biomass could survive (Chisti 2007; Wigmosta et al. 2011).

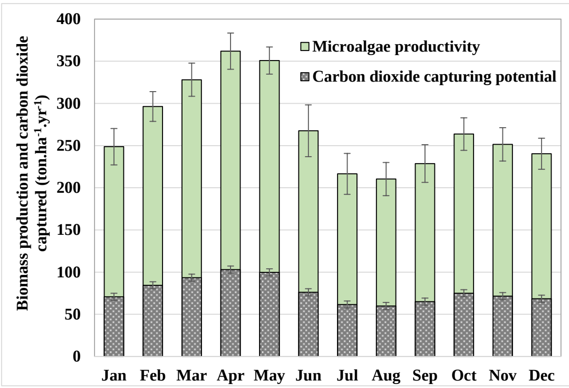

Figure 3: Theoretical maximum microalgae production and carbon dioxide sequestration potential

In case of theoretical maximum microalgal production without considering photoinhibition effect, the average microalgae and biomass production based on the 21 years of selected time frame is 72.58 g.m^{-2}.day^{-1}; 25.2 ml.m^{-2}.day^{-1} and 20.65 g.m^{-2}.day^{-1} for biomass, lipid and CO_2 mitigation respectively. The microalgal productivity in the April month is 1.7 fold higher than in August could explain the seasonal role in the prediction of overall growth. The capacity of microalgae to capture carbon dioxide is proportional to the concentration of the biomass available in the pond. So, there are several possibilities to calculate the trivial variation in the microalgal and subsequent lipid production with the increase in concentration by microkinetic model. However, in reality, the dissipation of excess absorbed energy is a prerequisite for microalgal survival. An excess of absorbed energy could photo-inhibited the overall photosynthetic productions, and it is highly essential to incorporate in the mathematical models for accurate predictions.

Effect of the photoinhibition

Photoinhibition mainly occurs in the electron transfer chain located at photosystem II (PSII) and photoadaptation is primarily attributed to change in the physiological and biochemical composition of microalgae at the photobioreactor. To comprehend the dynamic characteristics of photosynthetic capability of microalgae, one should recall the three different time scales associated with microalgal exposure to sunlight. It might be rapid photoresponse that occurring in minutes; photoinhibition in hours; and photoadaptation in days. Hence, the effect of the photoinhibition is very crucial for estimating the annual productivities due to the irrevocable damages on the microalgal cells by the consequences of the high solar radiation. The inhibition by the sunlight must be included in the mathematical models to estimate the real-time production scenarios. Further, it could assist the model practitioners to bridge the gap in theoretical estimation and real-time microalgal production. For instance, the annual average biomass production has dropped from 272.07 to 217.79 ton.ha^{-1}.yr^{-1} due to the photoinhibition effect on the growth of microalgal cells. Likewise, the carbon dioxide sequestration potential has been lessened from 77.4 to 62 ton.ha^{-1}.yr^{-1}. The lipid productivities were diminished from 87.5 to 68.65 m^3.ha^{-1}.yr^{-1}. Thus, the effect of photoinhibition on overall productivities are substantial, and almost 20% of the potential has been lost. The overall microalgal productivity pattern has been normalized on the monthly variation due to the influence of photoinhibition as shown in **Figure 4.**

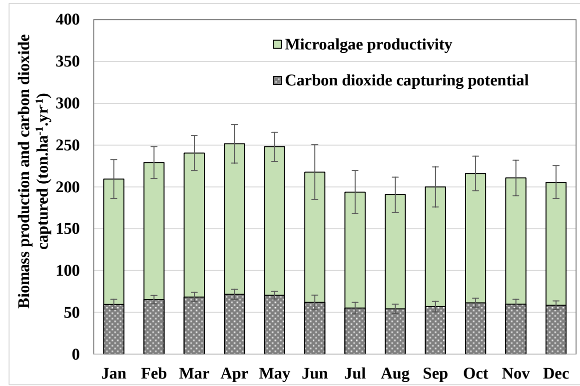

Figure 4: Effect of photoinhibition on the monthly average of microalgae production and carbon dioxide capturing potential

The normalized effect of the photoinhibition on the overall microalgal productivities was more profound on the peak summer seasons of April and May months rather than the winter peak seasons of November and December months. It is well evident that the summer seasons are getting more solar insolation, and almost 30% of the microalgal productivities has been lessened in these summer months. It is due to the severe consequences occurring to the photosystem II of the microalgal cell because of the high incoming solar radiation, and the influence is very minimal when it comes to the lesser solar insolation. However, the highest microalgal production was predominant in the summer seasons where the duration of the sunlight hours is quite significant comparing to the winter seasons. Further, the lowest microalgal production potential was estimated in the month of August due to the minimal availability of sunlight because of significant cloud cover in most of the days as in rainy seasons. The variation in microalgal lipid productivities due to the effect of photoinhibition was shown in **Figure 5.** The average daily variation of the microalgae and lipids productivity along with carbon dioxide capturing potential are tabulated in **Table 3.**

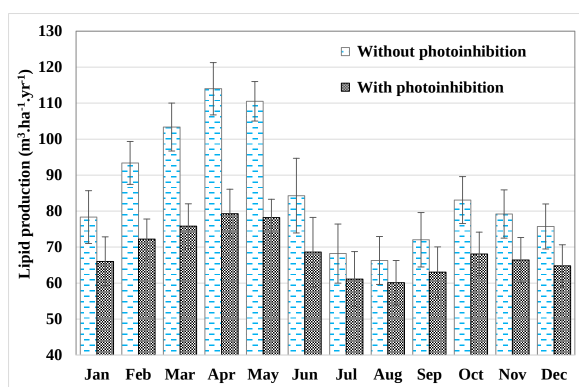

Figure 5: Effect of photoinhibition on the microalgal lipid productivity

Table 3: Average daily variation of the microalgae and lipids productivity along with carbon dioxide capturing potential

	Without photoinhibition			*With photoinhibition*		
	Biomass ($g/m^2/d$)	Lipid ($ml/m^2/d$)	CO_2 ($g/m^2/d$)	Biomass ($g/m^2/d$)	Lipid ($ml/m^2/d$)	CO_2 ($g/m^2/d$)
Jan	66.36	23.04	18.88	52.06	18.08	14.81
Feb	79.10	27.46	22.50	56.96	19.78	16.20
Mar	87.54	30.40	24.90	59.78	20.76	17.01
Apr	96.58	33.53	27.47	62.52	21.71	17.79
May	93.61	32.51	26.63	61.65	21.41	17.54
Jun	71.40	24.79	20.31	54.10	18.78	15.39
Jul	57.77	20.06	16.43	48.19	16.73	13.71
Aug	56.14	19.49	15.97	47.40	16.46	13.48
Sep	61.03	21.19	17.36	49.72	17.27	14.15
Oct	70.36	24.43	20.02	53.69	18.64	15.27
Nov	67.10	23.30	19.09	52.37	18.18	14.90
Dec	64.14	22.27	18.25	51.11	17.75	14.54
Avg.	**72.59**	**25.21**	**20.65**	**54.13**	**18.80**	**15.40**

Conclusion

The site selection based on the geographical location plays a significant role in assisting the policy makers for implementation at the field scale since the microalgae-derived biofuel is one of the most promising resource of renewable energy for the present generation. The mathematical model was developed to estimate the maximum microalgal growth along with carbon dioxide sequestration potential in the particular location based on solar insolation data obtained from NASA databases. Based on the model output, the open ponds of NITRKL is one of the promising sites to grow microalgae at large scale. NITRKL has the theoretical maximum microalgal biomass production potential as 72.59 $g.m^{-2}.day^{-1}$ and due to the photoinhibition effect, the productivity has been dropped to 54.13 $g.m^{-2}.day^{-1}$. The maximum growth has been predicted in the month of April, and the outcomes of the study could assist to evaluate approximately the microalgal biomass production system by prediction rather than time-consuming experiments on expensive large-scale outdoor pond facilities.

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Nomenclature

- *Full spectrum* known as also the solar radiation is the total amount of the insolation reaching the earth surface
- *PAR* is the Photosynthetically Active Radiation
- *h* is the Planck's constant (6.63e-34 $J.s^{-1}$)
- *c* is the velocity of the light (2.998e8 $m.s^{-1}$)
- λ is the wavelength of the light (400 to 700 nm)
- *Ephoton* is the energy photon
- *HHV* is the Higher heating value expressed in $kJ.mol^{-1}$ of photon

- *ηphoton* is the number of the photon required to convert one mole of the carbon dioxide to biomass (moles)
- *Energy of the PAR* is the total amount of energies falling in the PAR regions (kJ.mol^{-1} of photon)
- *ηtransmission* is the amount of the sunlight falling on the surface of the microalgae
- *α* is the coefficient absorption of the microalgae
- *ηcapture* is the percentage of the energy transform into the biomass in the form carbohydrates
- *ηphotosynthesis* is another term of the Photon conversion efficiency is the maximum conversion of the light energy to biomass, and it is common for all the microalgae
- *r* is the respiration efficiency of the microalgae
- *ηphoto-utilization* is the capacity of the microalgae to the used light available
- *Is* is the saturation of the light and *Il* is the incident light available on the surface of the microalgae
- *fP*, *fC*, and *fL* are the fractions of the Protein, Carbohydrate and Lipid in the microalgae respectively
- $E_{microalgae}$ is the energy stored in the microalgae (MJ.kg^{-1})
- E_P, E_c, and E_L are the energy content of each chemical composition
- *MB(daily)* and *ML(daily)* are the daily biomass and lipid productivities in (g.m^{-2}.day^{-1}) and (ml.m^{-2}.day^{-1}) respectively
- *k* is the rate constant of the microalgae
- *ρL* is the density of the lipid (kg.l^{-1})