J. Inst. Eng. India Ser. A (September 2020) 101(3):503–512
https://doi.org/10.1007/s40030-020-00450-8

ORIGINAL CONTRIBUTION

Theoretical Modeling of Algal Productivity and Carbon Capture Potential in Selected Places of Odisha, India

Bunushree Behera[1] · **Nazimdhine Aly**[1] · **Balasubramanian Paramasivan**[1]

Received: 2 August 2018 / Accepted: 17 May 2020 / Published online: 27 May 2020

Abstract Microalgae hold a promising potential for generating third-generation biofuel as well as for biological carbon sequestration. However, translation of algal technology to field scale is often hindered by a lack of appropriate data and economic challenges. Pertaining to these issues, a pre-estimate of the site-specific productivity of microalgae at realistic scenario is necessary. Five potential sites (Rourkela, Sambalpur, Bhubaneswar, Gopalpur and Balasore) in the Odisha state of India were chosen for predicting the average biomass, lipid productivity and carbon dioxide (CO_2) capture capacity of microalgae. Meteorological data averaged over 21 years (Jan' 1985–Dec' 2005) were fed into the biophysical empirical equations for estimating the biomass and lipid productivity of microalgae along with the CO_2 sequestration capacity. Maximum average biomass and lipid productivity was projected for Sambalpur, corresponding to an aerial value of 63.03 g/m^2/day and 21.89 ml/m^2/day, respectively, in the month of April with CO_2 sequestration potential of 17.87 g/m^2/day. Such preliminary site-specific theoretical estimates would facilitate policy making for realizing the potential of large-scale algal cultivation.

Keywords Biomass productivity · Carbon sequestration · Mathematical modeling · Microalgae · Lipid productivity · Solar radiation

✉ Balasubramanian Paramasivan
biobala@nitrkl.ac.in

[1] National Institute of Technology Rourkela, Rourkela, India

List of Symbols

E_{Solar}	Full-spectrum solar energy that accounts to the total amount of incident solar insolation
PAR	Photosynthetically active radiation, which relates to the amount of solar radiation (400–700 nm) used for photosynthesis
c	Velocity of light (2.998e8 m/s)
h	Plank's constant (6.63$e-$34 J/s)
λ	Wavelength of light (nm)
E_{Photons}	Energy of photons (kJ/mol)
HHV	Higher heating value of microalgae (36.6 kJ/mol of photon)
n_{photon}	Number of photons required to convert 1 mol of CO_2 to biomass
Energy of PAR	Amount of energy (kJ/mol of photon) corresponding to PAR (400–700 nm)
$\eta_{\text{Transmission}}$	Amount of light transmitted onto the surface of microalgae
α	Coefficient of light absorption by microalgae
η_{Capture}	Amount of incident solar energy captured by microalgae and converted into biomass
$\eta_{\text{Photosynthesis}}$	Photon conversion efficiency, which denotes the maximum amount of light energy that can be converted into biomass and is constant for all microalgal species
$\eta_{\text{Photon utilisation}}$	Capacity of utilization of the available photon energy by microalgae
r	Fraction of energy used by microalgae for respiration

I_S	Light saturation in the process of photosynthesis (μmoles/m^2 s)
I_I	Incident light used in photosynthesis (μmoles/m^2 s)
f_L	Fraction of lipids
f_P	Fraction of proteins
f_C	Fraction of carbohydrates
E_L	Energy content of lipids (kJ/g)
E_P	Energy content of proteins (kJ/g)
E_C	Energy content of carbohydrates (kJ/g)
$E_{Microalgae}$	Total energy stored in microalgae (MJ/kg)
$MB_{(daily)}$	Daily microalgal biomass productivity (g/m^2/day)
$ML_{(daily)}$	Daily microalgal lipid productivity (ml/m^2/day)
ρ_L	Density of lipids (0.85 kg/l)
M_{CO_2}	Molecular mass of CO_2 (44 g/mol)
$M_{Biomass}$	Molecular mass of microalgae (g)
K	Rate constant of CO_2 captured (1.89)
Total CO_2	Total amount of CO_2 sequestered (g/m^2/day)

Introduction

Microalgae are a promising future source of biofuel due to their ease of cultivation, faster growth rate and excellent carbon sequestration potential compared to other energy crops [1, 2]. Owing to the demands to mitigate climate change, numerous studies have been done on carbon sequestration by microalgae and thereby their conversion into bioenergy. 20–40% CO_2 from the coke oven power plant of China Steel Corporation, Southern Taiwan, has been reported to be sequestered using *Chlorella* sp. MTF15 [3]. Microalgae have been reported to be successfully cultivated using 11.24% CO_2 from flue gas of 4 MW coal fired boilers in Queensland, Australia [4]. Pradhan et al. [5] demonstrated that in Indian Scenario using E and F grade coals could result in algal productivity of 20 tons/acre/year resulting in carbon sequestration of 32 tons/acre/year. CO_2 from ambient air was reported to be stored as bicarbonate pool (100–500 mMol/L) with a pH of 10–12.5 resulting in algal biomass productivity of 1 g/L/day and carbon capture at the rate of 0.81 g/L/day [6].

Microalgal CO_2 sequestration is considered a popular sustainable development option in several countries. However, economic challenges related to the bioprocess principles of cultivation often hinder the large-scale application of algal technology [2, 7]. Despite the emerging studies focused on the reduction of energy and costs related to the upstream and downstream processing of algal biomass, the technology failed to be scaled up in real-time scenario due to inappropriate data for extrapolating the biomass and lipid production capacity at the field scale. In lieu of the above context, site-specific studies accounting for the local climatic conditions for predicting the potential of algal productivity could provide better insight into the practical problems witnessed at field levels [7]. Such studies could be used to appraise the potential sites for establishing a microalgal culturing facility that meets the requirements of sufficient availability of sunlight, along with favorable meteorological conditions [8].

Several theoretical studies at different locations have conveyed the role of site-specific meteorological variables on microalgal productivity and CO_2 capture capacity [9, 10]. Sudhakar and Premalatha [11] predicted the biomass, oil productivity, and CO_2 sequestration capacity of algae at six global sites based on the amount of sunlight received per day as well as local climatic conditions. A similar study was done by Asmare et al. [12] to estimate the algal productivity and CO_2 sequestration potential for five different regions in Ethiopia. Aly and Balasubramanian [13] have studied the effects of different geographical coordinates on CO_2 sequestration potential of microalgae. Ketife et al. [14] used theoretical modeling with algal specific characteristics, geographical location and climatic conditions of Arabian Gulf predicting an algal productivity of 133 tons/ha/year in a combined flue gas and wastewater treatment, with a forecast of 0.544 $ the break selling price for 1 kg of algal biomass. Many laboratory scale experiments predicting the maximum microalgal biomass and lipid productivity has also been reported in the literature [15, 16]. However, none of the studies have reported the biomass productivity, lipid productivity and CO_2 sequestration capacity of microalgae in various locations of Odisha, except a few previous studies by the authors. Aly and Balasubramanian [17] evaluated the effects of photoinhibition on microalgal growth in open ponds of NIT Rourkela, India, using the solar irradiance data. Aly et al. [18] studied the effect of photoinhibition on microalgal productivity and CO_2 sequestration potential using fixed and trackable photobioreactors for the entire state of Odisha in India. Behera et al. [7] used the site-specific biophysical model for open algal ponds considering the climatological conditions, water temperature, pond geometry and thereby predicted a biomass productivity of 170.28 kg/ha/day with a carbon capture of 224.77 kg/ha/day at National Institute of Technology (NIT) Rourkela. Algal productivity of 111.39 kg/ha/day with maximum CO_2 capture of 147.03 kg/ha/day was predicted using the geo-specific mathematical and techno-economic model at the thermal power plant at Jharsuguda, Odisha, with a potential carbon credits of 52 M$ per annum [19].

Fig. 1 Locations selected in the Odisha state of India, for predicting the microalgal productivity and CO_2 sequestration potential

The present study utilized the 21-year meteorological data (solar irradiance and air temperature) of five selected sites (Bhubaneswar, Balasore, Gopalpur, Rourkela, and Sambalpur) in Odisha, to theoretically estimate the biomass and lipid productivity as well as the CO_2 sequestration capacity of microalgae. Mathematical modeling using biophysical empirical equations relating to photosynthetic limitations was used to analyze the feasibility of algal technology at the selected sites. Validation with the comprehensive set of previously published literature data showed a good relation with the predicted estimates. These data can act as a baseline information for policymakers seeking to implement the large-scale cultivation of algae at realistic proportions.

Methodology

Site Selection and Meteorological Data Collection

Five different sites in the state of Odisha, namely Bhubaneswar (20.29° N, 85.82° E), Balasore (21.35° N, 86.66° E), Gopalpur (19.32° N, 84.79° E), Rourkela (22.26° N, 84.85° E) and Sambalpur (21.47° N, 83.98° E) were selected for studying the biomass productivity of microalgae in hypothetical open ponds. The sites (Fig. 1) were chosen as potential locations for evaluating algal productivity based on the availability of abundant sunlight and optimum air temperature as well as their proximity to either coastal areas or industries. The selected sites have horizontal solar radiation ranging from about (4.6–5.3) $kWh/m^2/day$ and air temperature ranging from 23 to 28 °C. The site-specific climatological datasets such as the solar insolation at horizontal position and air temperature at 10 m above the earth surface were retrieved from NASA (National Aeronautical and Space Administration) databases [20]. The entire set of data were collected on daily basis for the timeframe of 21 years (1st Jan 1985–31st Dec 2005) and averaged to utilize as the baseline information for future predictions of algal productivity and CO_2 sequestration potential. Due to the lack of availability of long-term solar irradiance and surface air temperature data, the dataset was restricted over 21 years. Lawin et al. [21] have also proposed the utilization of 21–30 years' meteorological data especially the solar insolation and air temperature is essential to understand the variation in climatic conditions and the projected trends would assist the policy makers in making decisions related to the environment. Therefore, the hourly datasets from NASA have been retrieved on daily basis, and the data for 21 years were further averaged to 365 daily data, which was then utilized as input on the framework of biophysical model through a set of empirical equations to predict the algal biomass and lipid productivity as well as carbon sequestration potential of microalgae.

Table 1 List of equations used for predicting the site-specific microalgal biomass and lipid productivity, and CO_2 sequestration potential

Terms	Equations
Photosynthetically active radiation	$\%PAR = \left(\frac{\int_{\lambda=400}^{700\,nm} E_{solar}(\lambda)d\lambda}{\int_{\lambda=0}^{4000\,nm} E_{solar}(\lambda)d\lambda} * 100\right)$
Photon energy	$E_{photon} = h * \frac{c}{\lambda}$
Photon transmission efficiency	$\eta_{transmission} = (\eta_{light\ distribution} * \eta_{land\ use} * \alpha * \%PAR)$
Photon conversion efficiency	$PCE_{PAR} = \frac{HV\ of\ CH_2O}{n_{photons} X\ Energy\ of\ PAR}$
Energy capture efficiency	$\eta_{capture} = \eta_{photosynthesis} * \eta_{photo-utilization} * (1 - r)$
Photon utilization efficiency	$\eta_{photo-utilization} = \frac{I_s}{I_I}\left[\ln\left(\frac{I_s}{I_I}\right) + 1\right]$
Biomass energy content	$E_{microalgae} = f_L * E_L + f_P * E_P + f_C * E_C$
Daily biomass 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 capture efficiency	$Total\ CO_2 = K * MB_{(daily)} * fixation\ efficiency$

Model Definition and Formulation

The mathematical model was formulated taking into account the effects of site-specific influencing parameter (mainly solar insolation) on the autotrophic growth of microalgae. The incident solar radiation plays an essential role in influencing the viability and growth rate of microalgae via the means of oxygenic photosynthesis. The biomass and lipid productivity as well as CO_2 sequestration capacity depends on the photosynthetic rate which is dependent on multiple factors including full-spectrum solar energy, photosynthetically active radiation, photon transmission and utilization efficiency, and biochemical content of microalgae [7]. To further improvise the model and provide a more realistic estimation of the productivity potential, the current study integrated photosynthetic limitations on microalgal growth via the inclusion of photoinhibition effects as the incident light crosses the threshold limit. The mathematical model used a set of empirical equations as shown in Table 1 to evaluate the average microalgal biomass and lipid productivity along with CO_2 mitigation potential.

Assumptions and Limitations of the Model

In order to understand the biochemical effect of light on microalgal growth, all calculations were done taking into

Table 2 List of parameters used in the model equations for estimating the site-specific microalgal biomass and lipid productivity, and CO_2 sequestration potential

Terms	Values
Full spectrum solar energy [9] (E_{solar}) (MJ/m^2 year)	5623–7349
Photon transmission efficiency [11] ($\eta_{Transmission}$)	0.43–0.44
Photosynthetically active radiation [23] (PAR)	0.45–0.47
Energy of photons (E_{photon}) (kJ/mol)	225.3
Photon conversion efficiency [11] ($PCE_{PAR}/\eta_{Photosynthesis}$)	0.26–0.27
Light distribution efficiency [11] ($\eta_{light\ distribution}$)	0.96
Photon-utilization efficiency [11] ($\eta_{Photon-utilisation}$)	1
Land use efficiency [11] ($\eta_{land\ use}$)	0.96
Fraction of energy used in respiration [11] (r)	0.2
Light absorption efficiency of algae [11] (α)	1
Saturation light used in photosynthesis [24] (I_S) ($\mu moles/m^2$ s)	200
Incident light used in photosynthesis [24] (I_I) ($\mu moles/m^2$ s)	200
CO_2 fixation efficiency [Assumptions]	0.15
Density of lipids in microalgae (ρ) (kg/l) [26]	0.85
Mean energy of 1 mol PAR [23] (Energy of PAR) (kJ/mol)	217.4
Energy content of protein [12] (E_p) (kJ/g)	16.7
Energy content of carbohydrate [12] (E_C) (kJ/g)	15.7
Energy content of lipid [12] (E_L) (kJ/g)	37.6

consideration the quantum of photons. Energy balance equation accounts for the losses in energy due to the metabolism of algae and atmospheric conditions. The model has been simulated based on the climatological site-specific data and could be broadly applied to any autotropic microalgae grown in open pond systems. The capacity of algae to absorb carbon dioxide and the molecular formula for algae has been taken from the literature based on the studies related to minimal nutrients required for the growth of autotrophic microalgae [22]. Molecular formula for

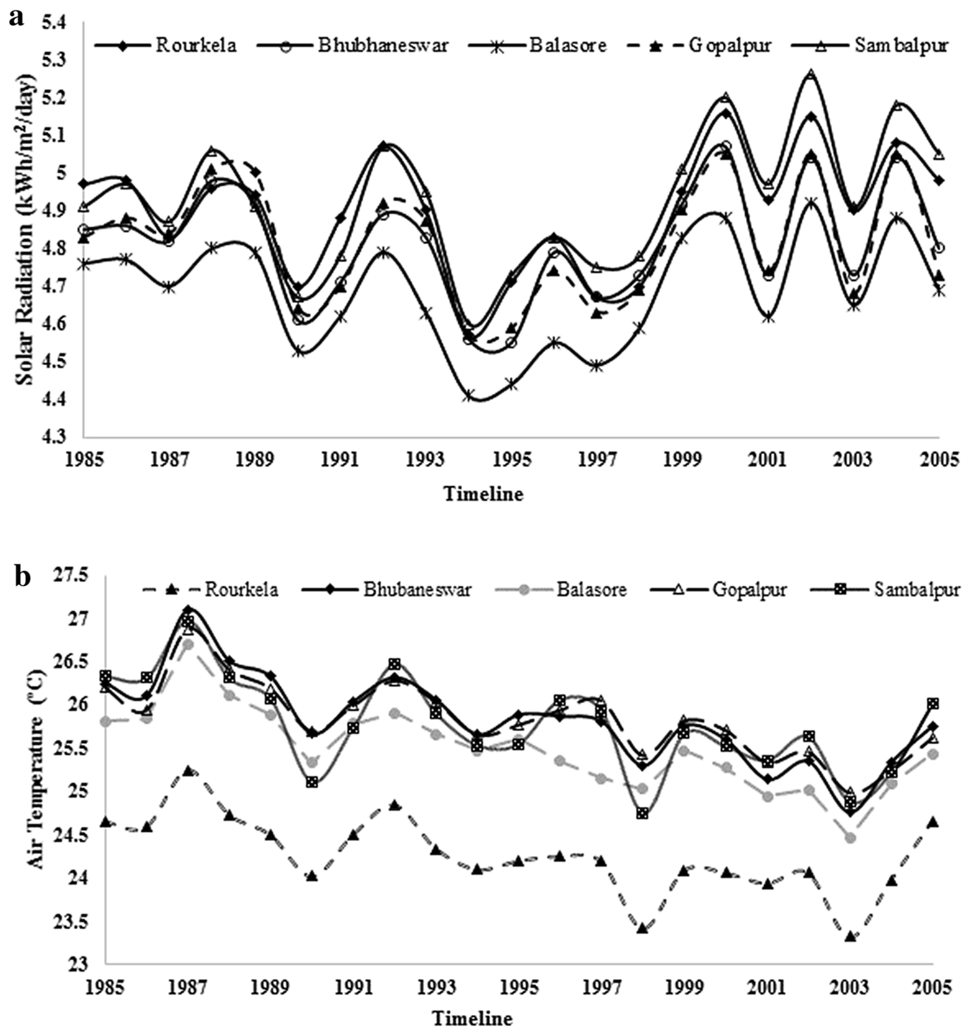


Fig. 2 **a** Daily solar insolation data of the selected sites of Odisha averaged over Jan' 1985–Dec' 2005. **b** Variations in daily air temperature of the selected locations of Odisha averaged over Jan' 1985–Dec' 2005

microalgal biomass has been assumed as $CO_{0.48}H_{1.83}N_{0.11}P_{0.01}$ which corresponds to a molecular mass of 23.2 g/mol. Biochemical composition of microalgae (Carbohydrates: Protein: Lipids) was assumed to be 35:35:30. Other assumptions, as well as values of different parameters used in modeling equations as cited in various literature, have been given in Table 2. Though the model considers the effects of photoinhibition to provide realistic estimates, the influence of water temperature, reactor specific characteristics and algal nutrient uptake rate could be included in future to further improvise the mathematical model.

Results and Discussion

Solar Insolation and Air Temperature Data

An appropriate light intensity (sunlight in case of large-scale outdoor ponds) is one of the key requirements for microalgal growth and viability. Average annual solar insolation of 1500 kWh/m^2/year (4.1 kWh/m^2/day) is essential for survival of microalgae [25]. Annual average solar radiation for five of the selected cities of Odisha was collected from US NASA Stackhouse [20] and was analyzed as shown in Fig. 2a. Out of the selected locations, Sambalpur received the maximum daily average horizontal solar insolation of 6.64 kWh/m^2/day in the month of April. The annual average solar radiation in the selected sites of Odisha ranged from about (4.6–5.3) kWh/m^2/day. However, these regions experience peak temperature during the summer season in the months of March, April and May. Aly et al. [18] also reported that the western Odisha receives higher amount of solar insolation compared to the other regions. India being a tropical region receives an average annual radiation varying from 3.25 to 6.08 kWh/m^2/day, with the eastern states receiving 4.25 kWh/m^2/day to 5.52 kWh/m^2/day [8]. Sudhakar et al. [26] reported an average solar irradiance of 4–7 kWh/m^2/day being received by most parts of India, which are considered suitable for algal cultivation. Thus, all the chosen locations could potentially be used for large-scale culturing of microalgae.

Apart from solar radiation, a nominal value of ambient air temperature also influences the algal productivity. The plotted curve of the air temperature represents the variation in air temperature of the selected cities of Odisha state (Fig. 2b). Maximum and minimum average air temperature was recorded as 27.10 °C and 23.32 °C in Bhubaneswar and Rourkela, respectively. The selected cities showed a similar profile of air temperature except for Rourkela that showed lowest air temperature pattern. Air temperature does not bear a linear correlation with that of the solar radiation as it is being influenced by several dynamic phenomena of conduction and convection [27]. Hence even though Rourkela has the lowest average annual air temperature, it still receives a good amount of sunlight. Annual average air temperature in each of the five selected cities varied from 23 to 27 °C. As the optimum temperature for most of the microalgae ranges between 20 and 30 °C, all the selected places could be considered suitable for large-scale production of microalgae [10, 28].

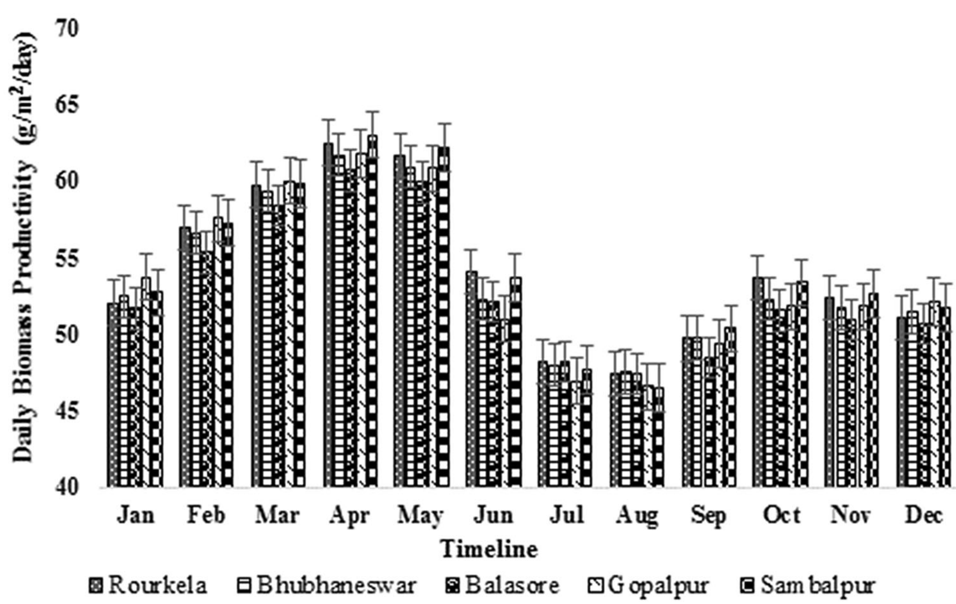
Theoretical Estimation of the Biomass Productivity of Microalgae

The predicted profile of average biomass productivity was observed to increase from the months of January till April after which it was found to decline gradually (Fig. 3). The daily average biomass productivity of all the selected places was observed to be maximum in the month of April which also received the maximum solar radiation. Thus, it can be inferred that in case of theoretical predictions, the biomass productivity bears a directly proportional relationship with the intensity of solar irradiation. Out of the chosen sites, maximum average biomass productivity of 63.03 g/m^2/day in the month of April was predicted in the city of Sambalpur. A minimal variation has been seen in case of monthly average biomass productivity of the selected sites, which ranged from around 47–63 g/m^2/day. Average biomass productivity reported in this study is in agreement with those cited in the literature [11, 29, 30], and thus this study unravels the potential of the selected sites for large-scale cultivation of algae. Sudhakar et al. [26] reported an average microalgal biomass productivity of 75 g/m^2/day in most parts of India. Average microalgal biomass productivity of 80.7 g/m^2/day was also reported by Asmare et al. [12] in various regions of Ethiopia. Relatively lower biomass productivity as reported in the current study compared to the previous studies might be attributed to the inclusion of photoinhibition effects. Photoinhibition due to increased intensity of solar irradiance and temperature beyond the sub-optimal range causes a decline in biomass productivity via decrease in photon utilization efficiency [7]. Incorporation of such photosynthetic limitations due to photoinhibition and dissipation of excess absorbed energy is a pre-requisite for precise and realistic theoretical pre-estimation of algal productivity.

Theoretical Estimation of the Lipid Productivity Potential of Microalgae

Lipid productivity of microalgae depends on the biomass concentration as well as the biochemical content of microalgae. Average lipid productivity showed a similar trend to that of the biomass productivity (Fig. 4). The

Fig. 3 Predicted daily microalgal biomass productivity in the selected places of Odisha



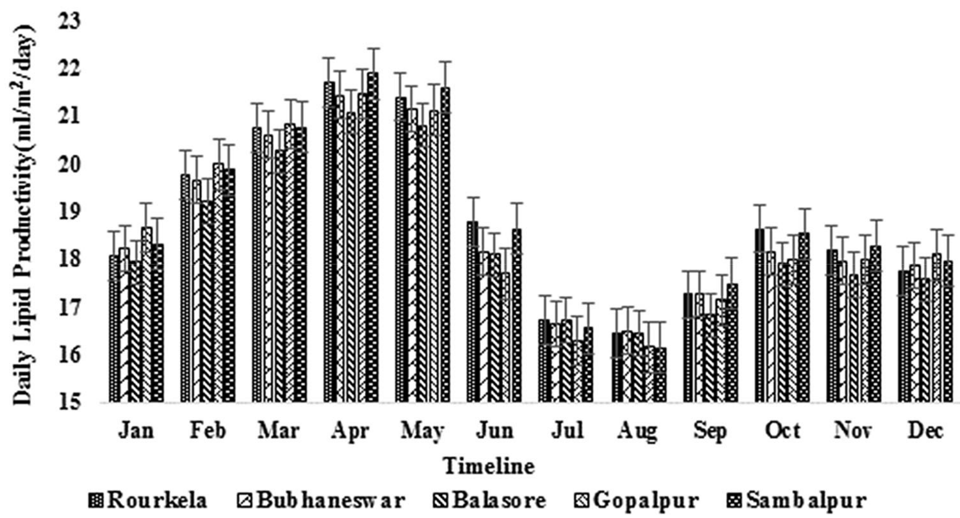


Fig. 4 Predicted theoretical daily microalgal lipid productivity in the selected places of Odisha

average lipid productivity of all the selected places was found to be maximum in the month of April, which also showed the highest biomass productivity. Maximum average lipid productivity of 21.89 ml/m^2/day was projected for the month of April in Sambalpur city. For the selected cities, average monthly lipid productivity was projected to range from 16 to 22 ml/m^2/day which is comparatively higher than other energy crops [12]. Weyer et al. [9] reported lipid productivity of 11.14 ml/m^2/day to 14.56 ml/m^2/day in different regions of USA, Israel, and Spain. Lipid productivity of 16.61 ml/m^2/day with a corresponding biomass productivity of 76.45 g/m^2/day for Rayong, Thailand, receiving 4.8 kWh/m^2/day was predicted by Das, [31]. The essentiality of site-specific climatic effects over the algal lipid productivity was also projected by the Das [31] which reported 60% higher lipid productivity due to greater microalgal biomass grown by higher average annual solar radiation received in Australia compared to Thailand. Thus, the present study establishes the suitability of the selected sites for the large-scale algal culturing facility, which in turn could act as a sustainable potential source of third-generation biofuel.

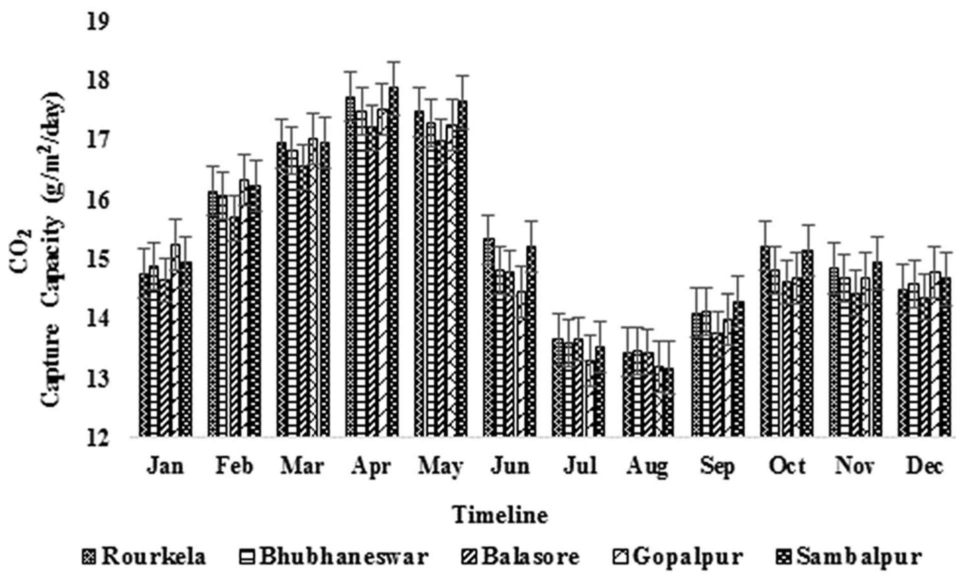
Carbon Dioxide Sequestration Potential of Microalgae in the Selected Sites

Monthly average CO_2 sequestration capacity of microalgae for the selected sites has been summarized in Fig. 5. The ability of microalgae to capture CO_2 is directly proportional to the biomass available in the pond [1, 7]. Thus, it is quite evident that higher the biomass productivity, better the sequestration potential. For the chosen locations, the extremities of biological CO_2 mitigation ability were projected to range from around 13–18 g/m^2/day. The estimated maximum CO_2 sequestration potential corresponds to a value of 17.87 g/m^2/day in the month of April for Sambalpur city. All the estimates indicated the excellent sequestration potential of algae over terrestrial plants which could potentially be used to reduce the carbon footprints [5]. Asmare et al. [12] reported algal carbon sequestration capacity varying from 20.95 g/m^2/day to 25.57 g/m^2/day for 5 different sites in Ethiopia. Behera et al. [19] predicted 14.70 g/m^2/day carbon capture using the biophysical growth kinetic model in the premises of a coal powered power plant in Jharsuguda district of Odisha. Algal carbon capture potential varying from 13.69 to 23.64 g/m^2/day has been projected for the Indian subcontinent using the GHI data of India [8]. Thus, the selected regions of Odisha hold a promising potential for establishing large-scale algal cultivation strategy for carbon sequestration and greenhouse gas emission reduction.

Model Output Comparison and Validation

The formulated mathematical model accounting to the biophysical laws governing the rate of photon utilization and thereby the process of photosynthesis was incorporated to analyze the biomass, lipid productivity as well as CO_2 sequestration potential of microalgae in the selected sites of Odisha. Minimal variation was seen in case of the biomass productivity of the chosen locations since these places received a nearly equivalent annual average solar radiation ranging from around 4.6–5.3 kWh/m^2/day. Since the lipid productivity and CO_2 sequestration potential of microalgae have a directly proportional relationship with that of the available biomass concentration, the projected estimates of these showed a trend similar to the biomass productivity. Since the predictive accuracy of model depends on the validation of the data obtained with that of the values reported by researchers, the data obtained were compared comprehensively with the data available in literature. Previous study by authors for 1195 spatial coordinates of

Fig. 5 Predicted microalgal CO_2 sequestration in the selected sites of Odisha



Odisha using the local climatic conditions predicted microalgal productivity utilizing the photon energy balance for photobioreactors. With the average solar insolation, varying from 5.86 to 7.80 kWh/m^2/day, maximum biomass and lipid productivity of 59.50–67.05 g/m^2/day, and 20.67–23.45 ml/m^2/day, respectively, with carbon capture of 16.94–19.21 g/m^2/day was predicted over the state of Odisha [18]. The estimates of the present study were well comparable and consistent with the previously cited literature, specifically in case of Indian scenarios, for validation of the proposed model as shown in Table 3. Deviations in the reported outputs are due to the differences in parameters taken into consideration. For instance, Sudhakar et al. [26, 32] have reported a significantly higher biomass and oil productivity compared to the present case study, without considering the effects of photoinhibition. The present study predicted a relatively lower yield compared to previous one, considering the effects of photoinhibition which causes an irreversible damage to the photosystem II. Consistent with the present study, Aly and Balasubramanian [13] have also reported a decline in biomass productivity from 76.20 to 55.90 g/m^2/day due to photoinhibition

Table 3 Validation of the predicted biomass productivity (Biomass prod.), lipid productivity (Lipid Prod.) and CO_2 capture capacity with the values reported in the literature

Locations	Annual Average Solar irradiance (kWh/m^2/day)	Average Biomass Prod. (g/m^2/day)	Average Lipid Prod. (ml/m^2/day)	Average CO_2 Capture capacity (g/m^2/day)	References
Sambalpur	5.30	63.03	21.89	17.87	This study
Rourkela	5.27	62.52	21.71	17.72	This study
Gopalpur	4.82	61.83	21.47	17.52	This study
Bhubaneswar	4.81	61.74	21.44	17.50	This study
Balasore	4.68	60.71	21.08	17.21	This study
Parts of India	4.50	80.00	18.82	–	[26]
Parts of India	5.50	97.00	22.82	–	[26]
Parts of India	6.50	115.00	27.05	–	[26]
Una, Himachal Pradesh	5.32	75.68	35.61	–	[32]
Chennai, Tamil Nadu	5.16	75.35	34.51	–	[32]
Indore, Madhya Pradesh	5.14	55.90	–	15.29	[13]
Southern Peninsular Parts of India	6.00	90.10	31.30	23.60	[8]

at National Institute of Technology, Rourkela, using simple empirical solar radiation based mathematical model. A subsequent drop in CO_2 sequestration potential from 21.69 to 15.92 g/m^2/day was also projected, since the carbon capture potential is directly proportional to the algal biomass productivity. Behera et al. [7] reported a 19% decline in microalgal productivity due to the photoinhibitory effects. It signifies the requisite of including photoinhibition effects for obtaining more realistic estimates.

Conclusion

The present study utilized the mathematical model based on biophysical empirical equations to estimate the biomass, lipid productivity and CO_2 sequestration capacity of the selected sites of Odisha. The study revealed that algal technology holds the diverse potential of large-scale applications in future. Among the selected locations, the highest average biomass and lipid productivity was predicted for Sambalpur in the month of April corresponding to values of 63.03 g/m^2/day and 21.89 ml/m^2/day, respectively. The maximal CO_2 sequestration of 17.87 g/m^2/day in the month of April was also predicted in the same city. Very minimal variations in algal productivity were reported for the selected locations as these areas receive nearly equivalent range of average solar irradiance ranging from around 4–5 kWh/m^2/day. However, the results predicted are limited to the effects of solar irradiance only. Annexation of the combinatorial effects of several other meteorological parameters like dew point, relative humidity, hydrodynamic water temperature and reactor geometry can provide a more accurate estimation. Such site-specific studies taking into account the basic physical laws and conservative assumptions therefore act as an effective technique to pre-estimate the growth and sequestration potential of algae at field scale. Such predictive analysis could facilitate the decision-making process of policymakers and industrialists on minimization of the greenhouse gas emissions.

References

1. B. Behera, A. Acharya, I.A. Gargey, N. Aly, P. Balasubramanian, Bioprocess engineering principles of microalgal cultivation for sustainable biofuel production. Bioresour. Technol. Rep. **5**, 297–316 (2019)
2. S. Rangabhashiyam, B. Behera, N. Aly, P. Balasubramanian, Biodiesel from microalgae as a promising strategy for renewable bioenergy production—a review. J. Env. Biotech. Res. **6**(4), 260–269 (2017)
3. C.Y. Kao, T.Y. Chen, Y.B. Chang, T.W. Chiu, L.H. Lin, C.D. Chen, J.S. Chang, C.S. Lin, Utilization of carbon dioxide in industrial flue gases for the cultivation of microalga *Chlorella* sp. Bioresour. Technol. **166**, 485–493 (2014)
4. A. Aslam, S.R. Thomas-Hall, T.A. Mughal, P.M. Schenk, Selection and adaptation of microalgae to growth in 100% unfiltered coal-fired flue gas. Bioresour. Technol. **233**, 271–283 (2017)
5. R.R. Pradhan, R.R. Pradhan, S. Das, B. Dubey, A. Dutta, Bioenergy combined with carbon capture potential by microalgae at flue gas-based carbon sequestration plant of NALCO as accelerated carbon sink, *Carbon Utilization* (Springer, Singapore, 2017), pp. 231–244
6. C. Zhu, X. Zhai, Y. Xi, J. Wang, F. Kong, Y. Zhao, Z. Chi, Efficient CO_2 capture from the air for high microalgal biomass production by a bicarbonate pool. J. CO2 Util. **37**, 320–327 (2019)
7. B. Behera, N. Aly, P. Balasubramanian, Biophysical modeling of microalgal cultivation in open ponds. Ecol. Modell. **388**, 61–71 (2018)
8. B. Behera, N. Aly, M.A. Rajkumar, P. Balasubramanian, Theoretical estimation of the microalgal potential for biofuel production and carbon dioxide sequestration in India, *Soft Computing for Problem Solving* (Springer, Singapore, 2019), pp. 775–790
9. K.M. Weyer, D.R. Bush, A. Darzins, B.D. Willson, Theoretical maximum algal oil production. Bioenergy Res. **3**, 204–213 (2010)
10. M.S. Wigmosta, A.M. Coleman, R.J. Skaggs, M.H. Huesemann, L.J. Lane, National microalgae biofuel production potential and resource demand. Water Resour. Res. **47**, 1–13 (2011)
11. K. Sudhakar, M. Premalatha, Theoretical assessment of algal biomass potential for carbon mitigation and biofuel production. Iran. J. Energy Env. **3**, 232–240 (2012)
12. A.M. Asmare, B.A. Demessie, G.S. Murthy, Theoretical estimation the potential of algal biomass for biofuel production and carbon sequestration in Ethiopia. Int. J. Renew Energy Res. **3**, 560–570 (2013)
13. N. Aly, P. Balasubramanian, Effect of geographical coordinates on carbon dioxide sequestration potential by microalgae. Int. J. Environ. Sci. Dev. **8**, 147–152 (2017)
14. A.M. Al Ketife, F. Almomani, E.N. Muftah, S. Judd, A technoeconomic assessment of microalgal culture technology implementation for combined wastewater treatment and CO_2 mitigation in the Arabian Gulf. Process. Saf. Environ. **127**, 90–102 (2019)
15. J. Moreno, M.A. Vargas, M.G. Guerrero, Outdoor cultivation of a nitrogen-fixing marine cyanobacterium, *Anabaena* sp. ATCC 33047. Biomol. Eng. **20**, 191–197 (2003)
16. G. De Bhowmick, G. Subramanian, S. Mishra, R. Sen, Raceway pond cultivation of a marine microalga of Indian origin for biomass and lipid production: a case study. Algal Res. **6**, 201–209 (2014)
17. N. Aly, P. Balasubramanian, Effect of photoinhibition on microalgal growth in open ponds of NIT Rourkela, India. J. Biochem. Technol. **6**, 1034–1039 (2016)
18. N. Aly, R.K. Tarai, P.G. Kale, P. Balasubramanian, Modelling the effect of photoinhibition on microalgal production potential in fixed and trackable photobioreactors in Odisha, India. Curr. Sci. **113**, 272–283 (2017)
19. B. Behera, N. Aly, P. Balasubramanian, Biophysical model and techno-economic assessment of carbon sequestration by microalgal ponds in Indian coal based power plants. J. Clean. Prod. **221**, 587–597 (2019)
20. P.W. Stackhouse, 2015 NASA Surface meteorology and Solar Energy: Interannual Variability. [Online] Available at: https://eosweb.larc.nasa.gov/cgi-bin/sse/interann.cgi?email=skip@larc.nasa.gov

21. A.E. Lawin, M. Niyongendako, C. Manirakiza, Solar irradiance and temperature variability and projected trends analysis in Burundi. Climate **7**, 83 (2019)
22. Y. Chisti, Biodiesel from microalgae. Biotechnol. Adv. **25**(3), 294–306 (2007)
23. J.A. Gonzalez, J. Calbo, Modelled and measured ratio of PAR to global radiation under cloudless skies. Agric. For. Meteorol. **110**, 319–325 (2002)
24. G. Torzillo, B. Pushparaj, J. Masojidek, A. Vonshak, Biological constraints in algal biotechnology. Biotechnol. Bioprocess. Eng. **8**, 338–348 (2003)
25. T.J. Lundquist, I.C. Woertz, N.W.T. Quinn, J.R. Benemann, *A Realistic Technology and Engineering Assessment of Algae Biofuel Production* (Energy Biosciences Institute, San Luis Obispo, 2010)
26. K. Sudhakar, M. Rajesh, M.A. Premalatha, A mathematical model to assess the potential of algal biofuels in India. Energy Source A Recov. Util. Environ. Effects **34**, 1114–1120 (2012)
27. S. Hindersin, M. Leupold, M. Kerner, D. Hanelt, Irradiance optimization of outdoor microalgal cultures using solar tracked photobioreactors. Bioprocess. Biosyst. Eng. **36**, 345–355 (2013)
28. S.H. Baek, S.W. Jung, K. Shin, Effects of temperature and salinity on growth of *Thalassiosira pseudonana* (Bacillariophyceae) isolated from ballast water. J. Freshw. Ecol. **26**, 547–552 (2011)
29. M.A. Borowitzka, Commercial production of microalgae: ponds, tanks, tubes, and fermenters. J. Biotechnol. **70**, 313–321 (1999)
30. S. Chinnasamy, A. Bhatnagar, R.W. Hunt, K.C. Das, Microalgae cultivation in a wastewater dominated by carpet mill effluents for biofuel applications. Bioresour. Technol. **101**, 3097–3105 (2010)
31. K. Das, A generic methodology for geographical assessment of microalgae potential, Master's thesis, Asian Institute of Technology, Thailand, 2013
32. K. Sudhakar, M.A. Premalatha, M. Rajesh, Large-scale open pond algae biomass yield analysis in India: a case study. Int. J. Sustain. Energy **33**, 304–315 (2014)