Modelling the Effect of Photoinhibition on Microalgal Production Potential in Fixed and Trackable Photobioreactors in Odisha, India

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Modelling the effect of photoinhibition on microalgal production potential in fixed and trackable photobioreactors in Odisha, India

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Microalgae have received a great deal of attention among researchers in recent decades in the production of sustainable bioenergy due to the limitations of second-generation biofuels. However, scalability and economics are the two key challenges that need to be overcome for sustainable biofuel production at field level, and mathematical modelling can be utilized as an effective tool to evaluate the influencing factors. This article focuses on the mathematical modelling of microalgal growth and carbon dioxide sequestration potential of a fixed photobioreactor (PBR) at 25° inclination facing south and a two-axis trackable PBR in Odisha, India. The total geographic area of Odisha has been represented in 1195 spatial sites, each site representing around 130 sq. km of the real scale dimensions approximately. The model incorporates site-specific data of solar radiation, climatic conditions and PBR configurations to derive the bioenergy content of microalgal biomass by photon energy balance. The effect of photoinhibition was also studied, and the outputs from the mathematical modelling, such as daily microalgal lipid production and carbon dioxide sequestration potential were plotted for the whole of Odisha using QGIS software. The net microalgal biomass production rate drastically reduced to around 30% and 40% due to the effect of photoinhibition in the case of fixed and trackable PBR systems respectively. The outcome of the present study could influence the policy-makers for selecting suitable sites for the implementation of microalgal-based biofuel production facility.

Keywords: Biofuel, mathematical modelling, microalgal photobioreactors, photoinhibition effect, production.

CURRENTLY, there is an enormous global need for clean and renewable energy sources due to the escalation in energy demand, depletion of finite fossil fuels and the negative consequences of conventional fossil fuels such as environmental pollution, global warming, climate change, human health and other related health impacts[1,2]. However, still around 80% of the energy used in the world is generated by fossil fuels and the demand is increasing everyday[3–5]. This critical situation warrants the necessity of searching for alternative sources of sustainable energy which is more eco-friendly and cost-effective with feasible production at a large scale. Biofuels are recognized as one of the most promising sources of renewables for the future generation. However, lignocellulose-based higher plants are not a viable source for biodiesel generation at a large scale due to the low lipid content, slow growth, intensive energy breakdown of the cell wall and massive requirements of arable land[6]. This situation has directed significant attention towards microalgae as a potential feedstock for producing biofuels due to their ease of scalability and techno-economic capabilities.

Weyer *et al.*[7] studied the effect of latitude on the theoretical maximum of microalgal oil production in six places of the world – Kuala Lumpur, Malaysia (3°N); Honolulu, Hawaii, USA (21°N); Tel Aviv, Israel (32°N); Phoenix, Arizona, USA (33°N); Malaga, Spain (37°N) and Denver, Colorado, USA (40°N). Sudhakar and Premelatha[8] made a theoretical estimation of microalgal biomass production potential in six countries of each continent – Texas, Uruguay, Ethiopia, Madrid, Chennai and Queensland. Zemke *et al.*[9] estimated the microalgal production along with carbon dioxide capturing potential based on the biochemical requirement of microalgae for photosynthetic conversion of photons to carbohydrate formation at the molecular level. Similar procedures were utilized by Asmare *et al.*[10] to estimate microalgal production in five different places of Ethiopia. The findings of these studies suggest that the microalgal biomass production potential is greatly influenced by the geographical location and climatic condition of a place. However, these models do not take into account water temperature and composition of nutrients, which are crucial for estimating the actual biofuel production potential. Malek *et al.*[11] incorporated the effect of nutrients, recycling process and harvesting techniques in mathematical models for the evaluation of outdoor, open-pond systems.

The utilization of sophisticated modern tools such as geographical information systems (GIS) and relevant

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software tools could assist researchers to predict the microalgal growth potential at a much wider scale. For instance, Moody *et al.*[12] developed a mathematical model to predict the microalgal production potential by executing 4388 spatial data and provided sufficient explanation related to the nonlinearity of biomass and lipid productions. Slegers *et al.*[13,14] proposed a mathematical model to evaluate temporal and spatial changes in an open pond and photobioreactor (PBR) for the growth of *Phaeodactylum tricornutum* and *Thalassiosira pseudomonas* in the Netherlands, France and Algeria. The constraining criteria for setting up microalgae cultivation facility and potential production vary according to geographic and socio-economic conditions. It constitutes a combination of factors and constraints for land, climate, CO_2, water and nutrients and infrastructure availability.

The present work is aimed towards the estimation of microalgal growth, lipid production and carbon dioxide sequestration potential of a PBR in Odisha, India. The key primary factors affecting microalgal growth rate, such as climatic condition, were incorporated into the model through solar irradiation and air temperature. Numerous parameters like full-spectrum energy, photon energy, photon transmission efficiency of sunlight to microalgae, capacity of biomass to capture energy from sunlight and the efficiency of conversion of light energy into biomass, lipid content and capacity to sequester carbon dioxide were also included in the model. The findings of the study could act as the baseline data for comprehending the seasonal variations of microalgal biomass production and scalability assessments for policy making as these evaluations require a site-specific calculation that incorporates geographically realized biological growth modelling to improve the validity and accuracy of the results.

Methodology

Study location

The site selected for this study is Odisha, which is among the 29 states in India. The state in the eastern part of the country is located in between 17.49–22.34°N and 81.27–87.29°E. It has a surface area of 155,707 sq. km (Figure 1) and is divided into 30 districts, 58 sub-divisions, 314 blocks and 103 urban local bodies with an average population density of 269/sq. km (ref. 15).

Coordinates of the selected site and map plotting

The coordinates have been fixed by preparing 50 × 50 square boxes over the selected study site. The new coordinates for each square box were estimated by computing eqs (1)–(4) below using MATLAB.

$$(\text{New latitude})_{\max} = \frac{(\text{Latitude})_{\max} - (\text{increment in latitude})}{2}, \quad (1)$$

$$(\text{New latitude})_{\min} = \frac{(\text{Latitude})_{\min} + (\text{increment in latitude})}{2}, \quad (2)$$

$$(\text{New longitude})_{\max} = \frac{(\text{Longitude})_{\max} - (\text{increment in longitude})}{2}, \quad (3)$$

$$(\text{New longitude})_{\min} = \frac{(\text{Longitude})_{\min} + (\text{increment in longitude})}{2}. \quad (4)$$

The delimiting of the selected study site resulted in 1195 spatial sites, each representing around 11.4 × 11.4 km of the real scale dimensions based on the surface area of Odisha. The coordinates representing latitudes and longitudes of all those 1195 spatial sites were stored in Excel in a comma delimited (.csv) format and imported to QGIS software for plotting. The colouring pattern and group of the selected coordinates have been represented as an icon that depends on the range of data available in the imported Excel file. Thus, the base map of Odisha was prepared (Figure 1) and the same procedure was followed for the other corresponding parameters.

Development of the mathematical model

A mathematical model was developed using MATLAB to estimate the microalgal biomass and algal oil productivity potential providing the site-specific solar insolation data as the key input along with various other parameters. The present study is based on photosynthetic limitations of microalgal growth that were formulated into several mathematical equations to calculate the microalgae and lipid production along with carbon dioxide sequestration potential (Table 1). The change in irradiance due to global environment as cloud cover, snow, micropollutants and gases in the atmosphere was already taken care while retrieving the solar radiation data from databases. The irradiance available is the precise net amount reaching the earth's surface, and microalgae could utilize photosynthetically active radiation (PAR) only. The reflection of sunlight due to the geometry of the reactor (land use and light distribution) was also included in the models. Meteorological data such as air temperature at 2 m above the earth's surface, and elevation were obtained from

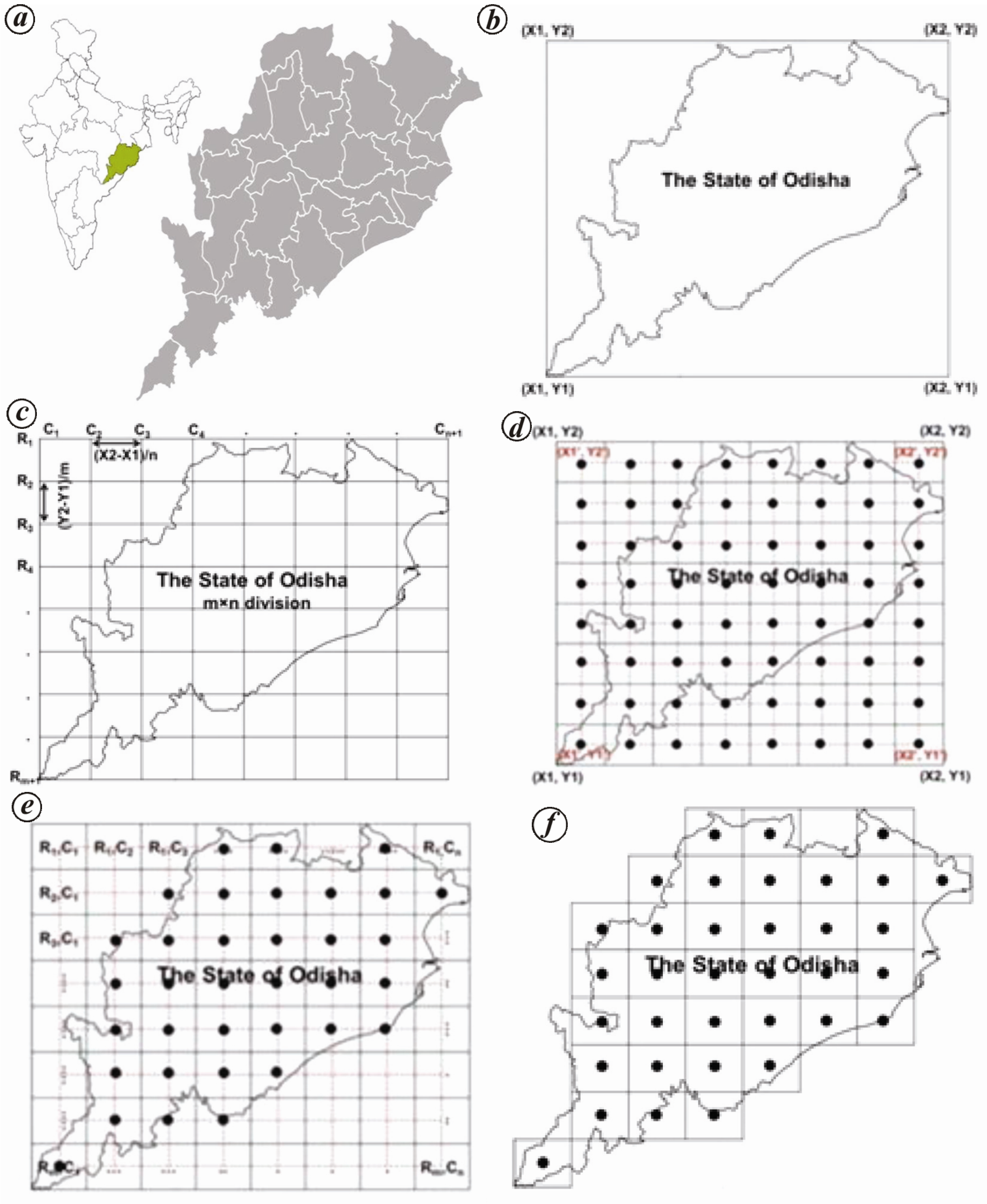

Figure 1. Procedure for creating the rasterized map for Odisha. ***a***, Localization of Odisha in India; ***b***, Indicating the coordinates of the total area of Odisha; ***c***, Division of Odisha into $m \times n$ square grids; ***d***, Defining the centre points of corner grid area; ***e***, Defining each grid into rows and columns; ***f***, Exclusion of regions that fall outside Odisha.

Solar-GIS database and utilized as model inputs[16]. The baseline information of solar insolation data collected through geostationary meteorological satellites and ground stations of the European Commission was retrieved on a monthly basis starting from January 2003 to December 2014 from PVGIS (Photovoltaic Geographical Information System) database[17]. The mean 12 years data of air temperature and solar radiation were also analysed. The developed mathematical model incorporates the representative limits for light energy distribution, land use, photon transmission, photon utilization, photosynthetic efficiency and microalgal oil content based on the literature data. Factors such as light energy distribution, photon transmission, photon utilization and photosynthetic efficiency control the overall photochemical fixation efficiency of light energy by the microalgae. The mean daily meteorological data, sunlight, ambient temperature and rainfall information for the identified potential site were combined to estimate the daily microalgal biomass production, lipid production and carbon dioxide mitigation potential. The daily solar insolation for south-facing photovoltaic at 25° inclination and two-axis solar

Table 1. Parameters and equations used in the present study

Term	Equation	Optimum value	References
Photosynthetic active radiation	$\%\text{PAR} = \frac{\int_{\lambda=400}^{700\text{ nm}} E_{\text{solar}}(\lambda)\mathrm{d}\lambda}{\int_{\lambda=0}^{4000\text{ nm}} E_{\text{solar}}(\lambda)\mathrm{d}\lambda} * 100$	0.43–0.47	7, 9, 32
Photon energy	$E_{\text{photon}} = h * \frac{c}{\lambda}$	208–225.3 kJ mol^{-1}	7–9
Photon conversion efficiency	$\text{PCE}_{\text{PAR}} = \frac{\text{HHV of CH}_2\text{O}}{n_{\text{photons}} \times \text{Energy PAR}}$	0.267–0.274	7, 33, 34
Photon transmission efficiency	$\eta_{\text{transmission}} = \eta_{\text{light}} * \eta_{\text{land use}} * \alpha * \%\text{PAR}$	0.43–0.44	8, 10
Energy capture efficiency	$\eta_{\text{capture}} = \eta_{\text{photosynthesis}} * \eta_{\text{photo-utilization}}$	0.27	8, 10
Photon utilization efficiency	$\eta_{\text{photo-utilization}} = \frac{I_S}{I_1}\left[\ln\left(\frac{I_1}{I_S}\right)+1\right]$	≤1	9
Biomass energy content	$E_{\text{microalgae}} = f_{\text{L}} * E_{\text{L}} + f_{\text{P}} * E_{\text{P}} + f_{\text{C}} * E_{\text{C}}$	Specific to microalgae	9, 10
Microalgae daily production	$MB_{(\text{daily})} = \frac{\eta_{\text{transmission}} * \eta_{\text{capture}} * SI}{E_{\text{microalgae}}}$	Variable	Site-specific
Daily lipid production	$ML_{(\text{daily})} = \frac{f_{\text{L}} * MB_{(\text{daily})}}{\rho_{\text{L}}}$	Variable	Site-specific
Rate constant of CO_2 captured	$K = \frac{M_{\text{CO}_2}}{M_{\text{biomass}}}$	1.89	8, 10
CO_2 captured efficiency	Total $CO_2 = K * MB *$ fixation efficiency	Variable	Site-specific

SI, Solar insolation.

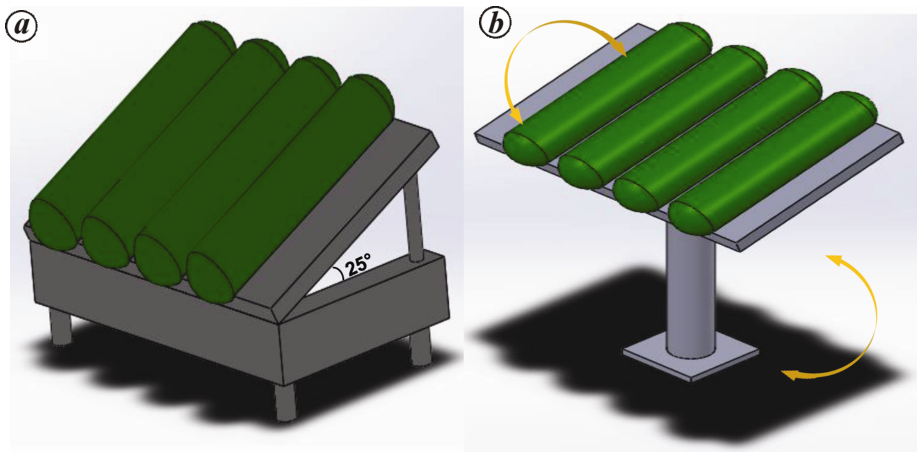

Figure 2. Schematic diagram of (***a***) 25° south-facing photobioreactor (PBR) and (***b***) two-axis solar-tracking PBR system.

tracking photovoltaic system was retrieved from PVGIS database and utilized for the hypothetical PBRs (Figure 2).

Assumptions and limitations of the mathematical model

The developed mathematical model takes into account several important influencing parameters for autotrophic microalgae to grow in PBR systems. First, sunlight is the prime energy requirement for photosynthesis, to convert carbon dioxide to carbohydrate. Though the energy requirement is in the form of light energy, calculations were made based on the quantum of photons for a thorough understanding of the biochemical effect of light. This was done on the basis that microalgae could utilize only energy in the PAR region for growth. Hence photon conversion efficiency, photon transmission efficiency, energy capturing efficiency and photon utilization efficiency were taken into account. The equations used in the study, also account for all the energy loss due to atmospheric conditions, bioreactor geometry and the respiration of microalgae. Further, the consequences of photoinhibition were also incorporated in the model when the solar energy was more than that required by the microalgae. As the growth of microalgae mostly depends on sunlight, this model was able to estimate the theoretical maximum production along with photoinhibition effect for real-time predictions. As models were developed for the prediction of microalgal growth in PBR systems under both fixed and tracking position, the solar insolation data were obtained from PVGIS database for both the cases. For fixed PBR, the solar insolation data at 25° inclination facing south were obtained and for the tracking PBR systems, two-axis tracking was utilized to collect the solar insolation data. Each of the 1195 spatial sites represents the surface area of 11.4 km × 11.4 km of Odisha on the map. The biochemical composition of microalgae was presumed to be protein, carbohydrate and lipid concentration as 35%, 35% and 30% respectively. The water temperature and nutrients present in the wastewater were assumed to be at an optimum level and also not affect the net growth of microalgae. The predicted results of the net microalgal biofuel production and carbon dioxide sequestration were plotted on maps using QGIS software for efficient interpretation of the results. For further improvement of the mathematical model, the role of water temperature and nutrients present in the wastewater could also be included in the later stage.

Effect of photoinhibition on microalgal growth rate

Photon energy is essential for its ability to absorb CO_2 and for the growth of microalgae. A microalgal cell under optimal conditions will absorb and use nearly all the incident photons. According to the assumptions for case 1 of the present study (fixed PBR at 25° inclination facing south), the environmental conditions are at the optimal range and so the theoretical maximum production could be estimated. Several countries in the northern part of the world suffer from lower solar radiation due to high cloud cover and/or snow formation that influences the net microalgae production. Hence, tracking of reactor systems towards sunlight path has been proposed to achieve higher photon capture efficiency. However, the microalgae could not assimilate the available sunlight for growth. It could be better comprehended with the 'photon utilization efficiency' that accounts for the reduction in photon absorption due to suboptimal conditions such as high levels of incident light or non-optimal temperature of the algal culture. Under these circumstances, photoinhibition occurs and part of the absorbed photons might be re-emitted as heat or cause damage to the cells. The photoinhibition effects could also be considered in routine part of the tropical regions and/or deserts. It is noteworthy to mention here that PAR will always be expressed in units of the photon, and photon energy in the PAR region was clearly explained using term 'photosynthetically photon flux density' (PPFD)[7]. Hence the solar radiation (or) saturated incident light needs to be represented in μmol m^{-2} s^{-1} as given in eq. (5)

$$\mathrm{PPFD}\left(\frac{\mathrm{mol}}{\mathrm{m^2 s}}\right)=\frac{E_{\text{Full-spectrum}}\left(\frac{\mathrm{MJ}}{\mathrm{m^2 s}}\right)\times\frac{\%\mathrm{PAR}}{100}}{E_{\text{photon}}\left(\frac{\mathrm{MJ}}{\mathrm{mol}}\right)}. \tag{5}$$

However, the net amount of light received by the microalgae could be estimated by multiplying the fractions of PPFD with the pond geometry configurations such as land-use efficiency and light distribution efficiency.

Results and discussion

Site selection and climatic conditions

Solar insolation data based on the availability of sunlight are the key for estimating microalgal bioenergy potential. Based on the geographical site location, cloud cover, presence of gases in the atmosphere and extent of daytime, the solar insolation data may vary. The appropriate location for establishing microalgal culturing facility should have requirements such as availability of appropriate solar radiation throughout the year, favourable climatic conditions, precipitation, evaporation, humidity, temperature, land topography and finally access to nutrients, carbon sources and water[18]. However, in this study, the entire Odisha region is represented as 1195 spatial sites, each representing 130 sq. km surface area. Almost 37% of the surface area of Odisha is covered by forests and water bodies, which are not suitable for establishing microalgae biomass culturing facility. The excessive forest shadow could limit the amount of the sunlight radiation reaching the earth surface. However, the presence of wetland is the most suitable requirement for the biomass growth due to the high water requirements for microalgae culturing facility. Therefore, while choosing an appropriate place for establishing microalgae culturing facility, the availability of water bodies nearby could minimize the production cost. Only 3% area of Odisha is covered with waterbodies. As availability of land is one of the key factors for establishment of the microalgae culturing facility, the distribution of wetlands, forests, and land of the entire state also needs to be analysed to find out the source of water for growing microalgae. Earlier studies have shown that microalgae are able to utilize nutrients present in the industrial, agricultural and municipal wastewater[19–21]. Integration of freshwater microalgae cultivation for biodiesel production has also been reported. Establishing microalgae culturing facilities outwards of the municipalities[22,23] for the efficient utilization of secondary treated municipal wastewater for microalgal cultivation also offers numerous

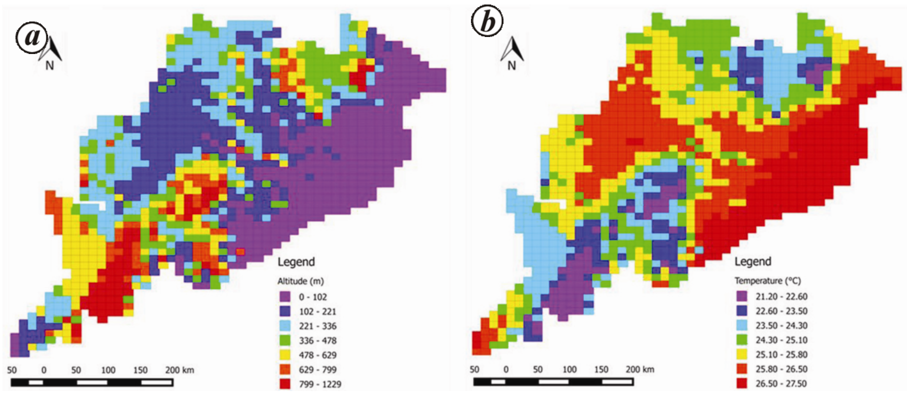

Figure 3. (***a***) Elevation map and (***b***) average annual temperature of Odisha.

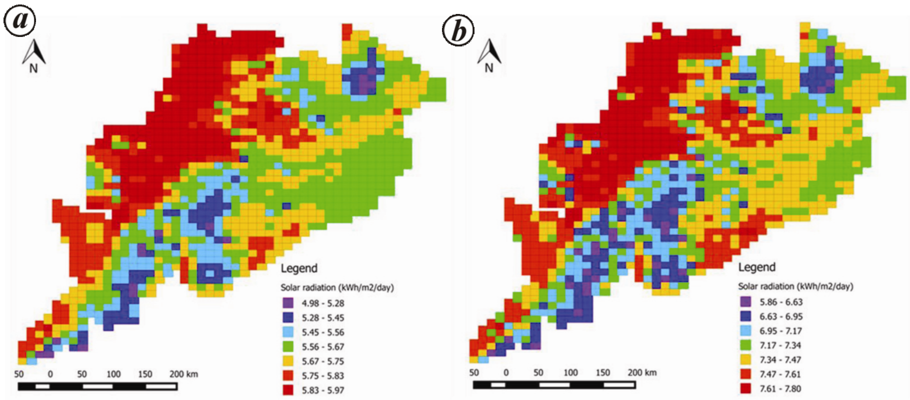

Figure 4. Daily average solar radiation in Odisha from 1985 to 2005 for (***a***) 25° south-facing PBR and (***b***) two-axis solar-tracking PBR systems.

advantages for biodiesel production[22,23]. As Odisha has around 480 km of coastal zone, it offers a great opportunity for bioprospecting the marine-based microalgae for biodiesel production, as several marine microalgae have been reported so far.

Odisha has the land base and climate necessary to produce a great variety of microalgae that could be processed, as well as the water required to operate the processing plants. The state experiences three meteorological seasons: summer (March–June), rainy season (July–September) and winter (October–February). However, traditionally seasons have been classified as spring, summer, rainy, autumn, winter and cool. In summer, the maximum temperature ranges between 35°C and 40°C and minimum between 12°C and 14°C. The coastal areas have a higher temperature range with severe humidity and precipitation compared to the high-altitude locations. The rainy season is from July to September, and maximum rainfall is in July. Long-term average annual rainfall of the state is 1482 mm. The annual rainfall, though substantial in quantity, is unevenly distributed in space and time. Around 80% of the annual rainfall is received from June to September and the remaining during the other eight months. The monthly average rainfall is 150 cm, with a range 120–170 cm. Water availability for microalgae growth will depend mainly on rainfall, precipitation and evaporation balance, as these are the main sources of water and land distribution.

Figure 3 represents the variation in altitude and annual average temperature of entire Odisha. However, the state is broadly divided into four physiographic zones, namely coastal plains, central table-land, northern plateau and the Eastern Ghats. The average annual temperature for the entire state varies between 21.2°C and 27.5°C. The western part of Odisha has normal temperature, while the southern part has the lowest temperatures as it is located at a high altitude of 1229 m amsl. As the eastern part of Odisha, i.e. the coastal regions are predominantly lesser than 100 m in altitude, the temperature is high. However, it is noteworthy to mention that the average annual temperature lies in the favourable range for supporting microalgae growth; it varies from 7°C in peak winter to 47°C in peak summer.

Figure 4 shows the solar radiation data for both fixed and solar tracking PBR systems. The average solar insolation for both systems ranged between 4.98 and 5.97 and 5.86 and 7.8 kWh m^{-2} day^{-1} respectively. Also, by integrating the tracking system, one could receive 1.5-fold greater solar insolation. The western part of Odisha has maximum solar insolation, while the eastern part has

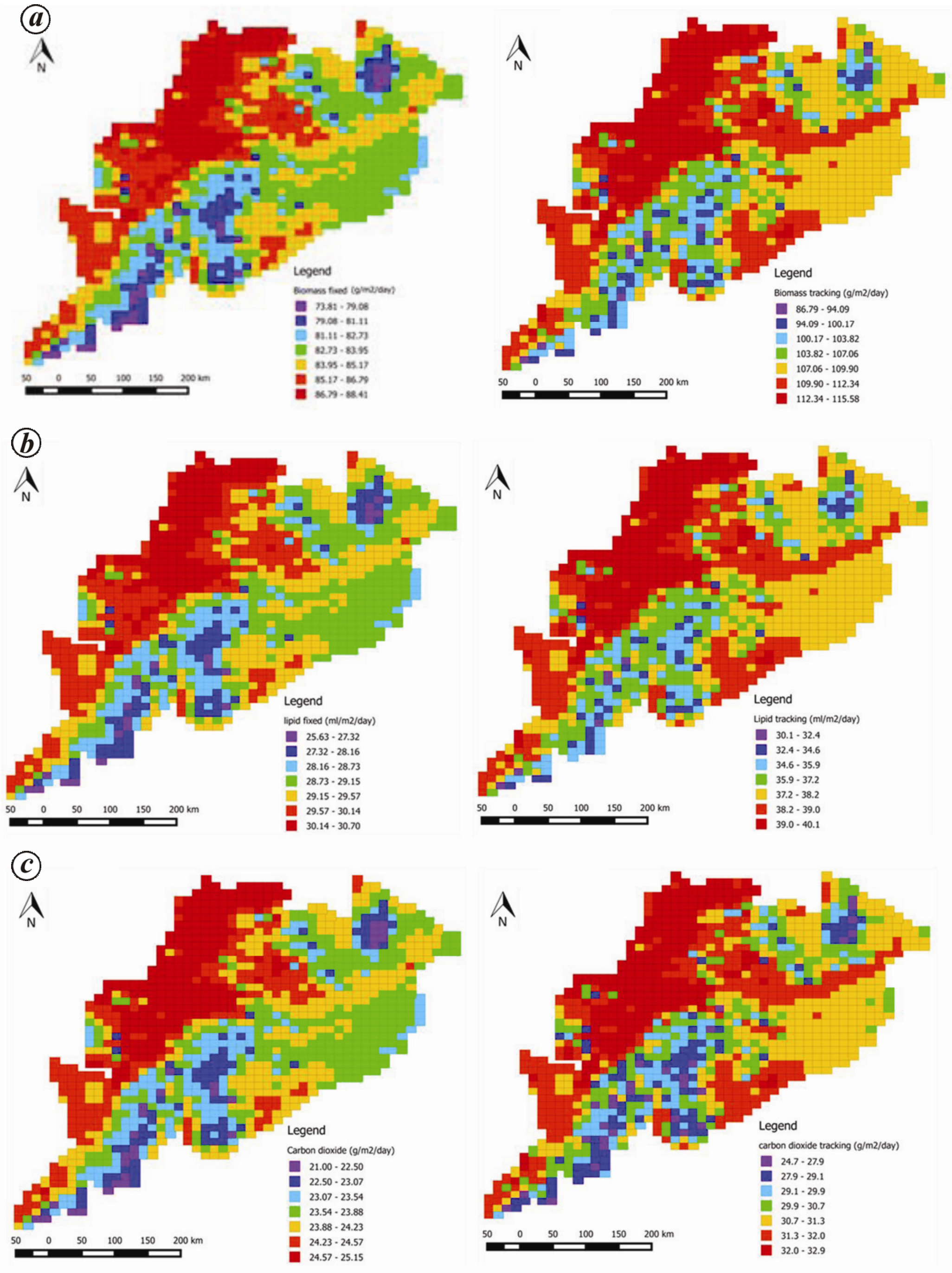

Figure 5. Theoretical maximum daily average microalgal biomass production (***a***) microalgal lipid production (***b***) and CO_2 captured by microalgae (***c***) in Odisha for (left column) 25° south-facing PBR and (right column) two-axis solar-tracking PBR systems.

average insolation. However, annual solar radiation over the world varies based on the geographical location and ranges between 700 and 2500 kWh m^{-2} $year^{-1}$ (3199 and 11,425 μmol m^{-2} s^{-1} respectively)[24,25]. This disparity in solar energy availability is due to several factors such as variation in geographic locations, cloud cover at that specific location, length of the clear sky day and associated seasonal changes at that site specific conditions.

Theoretical maximum microalgal production rate

The increment in latitude and longitude of 0.09514 N and 0.12128 E was used to compute the coordinates for the 1195 spatial sites in Odisha (17.8586–22.5204 N, and 81.4916–87.4343 E). The coordinates that lie inside the boundaries of the Odisha state were designed as exact square while the boundary coordinates were designed as such to mimic the actual geographical boundaries of Odisha state. In enhances the exactitude of mapping as mimic to the geographical images of the state. The daily biomass production for the fixed PBR system varied from 73.81 to 88.41 g m^{-2} day^{-1}. Moreover, the amount of CO_2 absorbed by the microalgae was around 28% of the equivalent mass of the biomass. The microalgal lipid production depends on the concentration of the biomass, and sites having higher biomass content show higher lipid production. The reason is that the lipid content of microalgae is assumed to be 30% of the total biomass according to the literature and this value remains constant for the overall calculation in the state. Moreover, lipid production at all the locations varied from 25.63 to 30.7 ml m^{-2} day^{-1} for the fixed systems. In the case of tracking PBR, the microalgal biomass potential of all the location ranged from 86.79 to 115.58 41 g m^{-2} day^{-1}. The trackable PBR always had higher microalgal biomass production compared to the fixed reactors. The lipid production of the tracking reactor system was between 30.14 and 40.13 ml m^{-2} day^{-1}, which is quite high compared to fixed PBRs. Similarly, the carbon dioxide sequestration potential in case of the tracking PBR ranged between 24.7 and 32.9 g m^{-2} day^{-1}. The overall microalgal biomass production, lipid production and carbon dioxide sequestration potential were estimated and plotted using QGIS (Figure 5). It is noteworthy to mention the reasons behind choosing two different positions for placing the PBR. First, these two positions are able to capture maximum sunlight effectively as well proved in the case of placing conventional solar panels. Secondly, the optimal inclination angle to get maximum sunlight energy in entire Odisha ranges between 22° and 27°, and the average of 25° has been chosen for the state for receiving maximum solar energy. Thirdly, novelty and emergence of solar-tracked PBR systems for optimization of solar irradiance at outdoor microalgal cultivation units could be future trends in microalgae culturing facilities[26].

Effect of photoinhibition on microalgal production rate

Only a few studies have been made on the effect of photoinhibition on microalgal growth and biofuel production potential. As the highest irradiance could damage the electron transport chain at the oxygenic photosystem II (PSII) of the microalgae by exposure to high light intensity, the growth of microalgae might be severely affected. Further, the regeneration of microalgal could be delayed/hindered due to rapid damage occurring in PSII. Thus, the overall photoadaptation is primarily attributed to change in the physiological and biochemical composition of microalgae in the PBR. The photosynthetic capability of microalgae is quite complex as it follows the dynamic characteristics such as fast photoresponse occurring in minutes, photoinhibition in hours and photoadaptation in days. The effect of photoinhibition could be comprehended based on the potential of carbon dioxide incorporation and/or oxygen evolution during the growth of microalgae[27,28].

In the case of hindered regeneration of microalgal growth, the photoinhibition effects were assumed to be irrevocable. The theoretical daily areal microalgal production without considering the effects of photoinhibition ranged from 55.03 to 60.06 g m^{-2} day^{-1} for fixed PBR and from 59.50 to 67.5 g m^{-2} day^{-1} for tracking PBR systems respectively. The variation in microalgal production rates among the fixed and tracking systems was insignificant because the study locations are in the tropical region of the world. As the irradiance of solar energy is inversely proportional to the photon utilization efficiency of microalgae beyond the nominal value, photoinhibition also plays a significant role in the growth of microalgae. The inclusion of tracking systems could be useful for a limited number of places in the world where low solar irradiance and high snow cover prevail. However, the operation and maintenance of trackable systems is complex and demands sophisticated tools, which might incur additional expenses that could escalate the capital cost multifold. The net microalgal biomass production rate has been drastically reduced to 30% due to the effect of photoinhibition in the case of fixed PBR systems in Odisha. However, in the event of tracking systems, the effect of photoinhibition was severe compared to the fixed systems and almost 40% of the microalgal production was reduced. This is due to the fact that the tracking systems are to capture more irradiance and so the damage to PS II of microalgae might be severe.

Though there is not much significant variation in capture efficiency of light by microalgae, their photon utilization capacity varies depending on the incoming solar radiation. It is presumed that there is no molecular damage to the microalgal cell, and that could be able to utilize the total solar irradiance in the case of non-inclusion of photoinhibition effect on net microalgal production. However, in reality, photoinhibition will influence the photon utilization efficiency. While comparing with the theoretical case without the inclusion of photoinhibition, the photon utilization efficiency dropped to 67.9% and 58.4% respectively in case of fixed and trackable PBR systems. This could be justified with earlier observations that the microalgae could utilize light energy around 50–90%, when they are exposed to low light and only 10–30% in case of high photon energy[29]. It envisages that the loss and inhibition effect is strong when the microalgae are exposed to the high light intensity. Thus, the effect of photoinhibition on overall microalgal biomass production, lipid production and carbon dioxide sequestration potential was estimated (Figure 6).

Almost 11% of the net microalgal lipid production could be achieved in the case of tracking systems rather than the fixed PBR systems. For instance, the net microalgal lipid production ranged from 20.67 to 23.45 ml m^{-2} day^{-1}

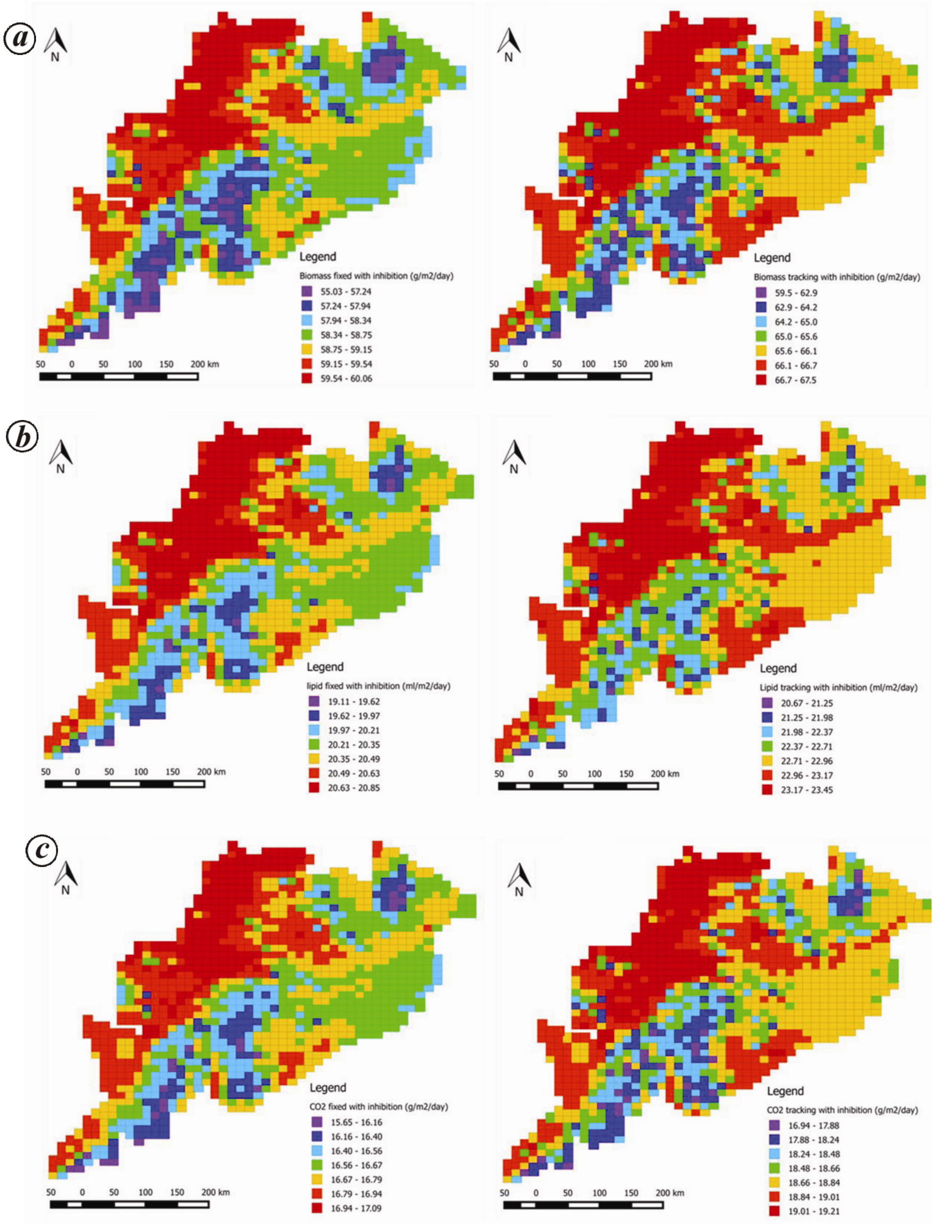

Figure 6. Effect of photoinhibition on daily average microalgal biomass production; (***a***) microalgal lipid production (***b***) and CO_2 captured by microalgae (***c***) in Odisha for (left column) 25° south-facing PBR and (right column) two-axis solar-tracking PBR systems.

in case of the tracking system, while it was around 19.11–20.85 ml m^{-2} day^{-1} in case of fixed PBR systems. Finally, the average of the carbon dioxide sequestration potential for the fixed and tracking PBR systems with photoinhibition effects were 16.37 and 18.08 g m^{-2} day^{-1} respectively for Odisha. Though the CO_2 sequestration capability seems to be less, it is quite high in view of field scale production compared to the areal higher plants using the same surface area to volume ratio. However, the inclusion of photoinhibition effects in the assessment could provide the real-time production potential of microalgae and CO_2 capture efficiency in all the study locations. In the case of fixed PBR system, maximum microalgal biomass production of 88.41 g m^{-2} day^{-1} was achieved in the northwestern districts of Odisha, such as Sundergarh, Jharsuguda and Sambalpur. Fortunately, mines and other related industrial complexes are situated in these districts, and thus the implementation of microalgae culturing facility might be feasible as well as technically viable. However, in the case of trackable systems, maximum microalgal biomass production was enhanced by 28% in the northwestern districts.

The theoretical prediction of microalgal biomass production in Odisha is around 73.81 to 88.41 g m^{-2} day^{-1}. However, the decline of photon utilization efficiency beyond the optimal point exhibits photoinhibition effect.

Table 2. Microalgae production capabilities reported in several places in the world

Location	Solar radiation (kWh m^{-2} day^{-1})	Microalgae production (g m^{-2} day^{-1})	Lipid production (ml m^{-2} day^{-1})	CO_2 captured (g m^{-2} day^{-1})	Reference
Addis Ababa, Ethiopia	4.99	73.91	25.66	20.95	10
Awassa, Ethiopia	5.83	86.36	29.98	24.48	10
Bahir Dar, Ethiopia	5.99	88.73	30.81	25.15	10
Mekele, Ethiopia	6.09	90.21	31.32	25.57	10
Nazret, Ethiopia	6.05	89.62	31.12	25.41	10
Kuala Lumpur, Malayasia			11.14		7
Denver, Colorado, USA			12.05		7
Malaga, Spain			12.59		7
Tel Aviv, Israel			13.36		7
Honolulu, Hawai, USA			14.15		7
Phoenix, Arizona, USA			14.56		7
Texas North, USA	4.71	71.42			8
Uruguay, South America	5.29	80.29			8
Ethiopia, Africa	6.14	93.17			8
Madrid, Spain	4.75	72.2			8
Chennai, India	5.23	79.23			8
Queensland, Australia	5.9	89.65			8
Rayong, Thailand	4.8	76.45	16.61	14.44	35
Karratha, Australia	6.4	99.07	26.59	18.72	35
Chennai, India	5.16	73.35	34.51		36
Una, India	5.32	75.68	35.61		36
Utah, Southwest USA	5.78	68.76	43.29		9
4388 locations in the world		0–54.04	0–7.62		12
2600 locations in USA		50.30	27.06–44.62		37
Rourkela, India	4.9	54.13	18.80	15.40	38, 39
1195 locations in Odisha for fixed reactor	4.98–5.97	55.03–60.06	11.19–20.85	15.65–17.09	Present study
1195 locations in Odisha for trackable reactor	5.86–7.80	59.5–67.05	20.67–23.45	16.94–19.21	Present study

Hence, the inclusion of photoinhibition effect in the overall prediction is mandatory to realize the actual possible microalgal production scenarios. Table 2 summarizes the theoretical prediction of microalgal biomass production in various places of the world. As the theoretical prediction of microalgal production in PBR is limited, we compare with the available production scenarios from open pond systems. Zemke *et al.*[9] proposed a methodology to predict the production in both PBR and open pond systems[9]. However, microalgal production in PBR with the inclusion of photoinhibition effect is comparable with other reported values from open pond systems. The variation in lipid production is quite high due to the assumption that lipid content varies from 15% to 50%.

Yearly areal microalgal production and carbon dioxide sequestration potential

Recent recognition of microalgal potential in greenhouse gas mitigation, promotion of carbon neutral biofuel source and biofixation of carbon dioxide released by power plants and industrial emissions are the motives behind the yearly prediction of microalgal production rates. Regional patterns of biofuel production and carbon dioxide sequestration using microalgae were developed utilizing the local solar insolation data along with the other key environmental and climatic conditions. Though annual microalgal production rates directly depend on the average daily biomass production, the yearly predictions were made after taking into consideration bioprocess engineering principles such as the number of days PBR could function effectively. Hence, the annual patterns at the regional scale were evaluated for four different cases as of pessimistic, realistic, optimistic and theoretic with 9, 10, 11 and 12 months respectively. The variation in the number of functional days of PBR per year was deliberated after taking in to consideration the problems associated with operation and maintenance followed by shutdown period for four different cases as discussed earlier. However, previous studies have considered only 25 days in the year for maintenance of the reactors at field scale[10,30,31]. Table 3 shows results related to the microalgal biomass and lipid production along with carbon dioxide mitigation potential for all the four cases. The theoretic potential of PBR showed a higher value compared to the other cses. Also, the solar tracked PBR had maximum potential than the fixed PBR. However, the effect of photoinhibition should be considered for real-time predictions, around 190 tonnes of microalgal biomass/ha could be produced annually. Additionally, it could biomitigate around 54 tonnes of carbon dioxide/ha and generate 60 m^3 of microalgal oil production per year. However, techno-economic feasibility studies of biofuel

Table 3. Yearly annual biomass and lipid production along with carbon dioxide sequestration potential in Odisha

Production scenario		Without photoinhibition		With photoinhibition	
		Fixed	Tracking	Fixed	Tracking
Areal microalgal biomass production (tonne ha^{-1} $year^{-1}$)	Pessimistic	219.6–261.6	258.3–344.0	168.3–178.7	177.2–201.0
	Realistic	244.0–290.7	287.0–382.2	182.0–198.6	196.9–223.3
	Optimistic	268.4–319.8	315.7–420.4	200.2–218.4	216.6–245.6
	Theoretic	296.9–353.7	349.2–465.0	221.4–241.6	239.6–271.7
Lipid production (m^3 ha^{-1} $year^{-1}$)	Pessimistic	69.2–82.9	81.4–108.4	51.6–56.4	55.8–63.3
	Realistic	76.9–92.1	90.5–120.5	57.4–62.6	62.1–70.4
	Optimistic	84.6–101.4	99.5–132.5	63.1–68.9	68.3–77.4
	Theoretic	93.6–112.1	110.1–146.6	69.8–76.2	75.5–85.6
CO_2 sequestration (tonnes ha^{-1} $year^{-1}$)	Pessimistic	62.5–74.9	73.5–97.9	46.6–50.9	50.4–57.2
	Realistic	83.3–81.7	81.7–108.8	51.8–56.5	56.1–63.5
	Optimistic	76.4–91.6	89.9–119.7	57.0–62.2	61.7–69.9
	Theoretic	84.5–101.3	99.4–132.4	63.0–68.8	68.2–77.3

production should be done in detail before establishing any microalgal biofuel production facility.

Conclusion

The site selection for establishing microalgal biofuel production facility plays an essential role in assisting policy-makers for implementation at field scale that demands the prediction of microalgal growth rate based on geographical locations. Hence, the present study was directed towards the development of a mathematical model for estimating the microalgal growth rate, biofuel production and carbon dioxide sequestration potential on 1195 spatial sites of Odisha. The microalgal bioenergy potential of Odisha is huge, as it receives a daily average solar radiation of 5.5 kWh/m^2 with around 300 clear sunny days/year. On an average, the theoretical microalgal biomass production rate in case of fixed PBR system was 85 g/m^2/day. By integrating the tracking systems of PBR in Odisha, 30% enhancement in the overall microalgal production rate could be achieved. The western part of the state showed maximal microalgal production rate and the southern part exhibited the lowest. The prevailing highest temperature at eastern part of Odisha leveraged the microalgal biomass production rates in spite of its presence at the coastal zone. The outcomes of the present study could assist policy-makers regarding site selection for establishing microalgal biofuel production facility based on geographical locations.

Nomenclature

- Full spectrum, also known as solar radiation, is the total amount of insolation reaching the earth's 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 ($2.998e^8$ m s^{-1}).
- λ is the wavelength of light (400–700 nm).
- E_{photon} is the energy of the photon.
- HHV is the higher heating value (expressed in kJ mol^{-1} of photon).
- η_{photon} is the number of the photons required to convert one mole of carbon dioxide to biomass (mol).
- Energy of the PAR is the total amount of energy falling in the PAR regions (kJ mol^{-1} of photon).
- $\eta_{transmission}$ is the amount of sunlight falling on the surface of the microalgae.
- α is the coefficient absorption of the microalgae.
- $\eta_{capture}$ is the percentage of energy transformed into biomass in the form carbohydrates.
- $\eta_{photosynthesis}$ is another term for the photon conversion efficiency. It is the maximum conversion of light energy to biomass and is common for all microalgae.
- r is the respiration efficiency of the microalgae.
- $\eta_{photon\ utilization}$ is the capacity of the microalgae for utilizing the available light.
- I_s is the saturation of light and I_l is the incident light available on the surface of the microalgae.
- f_P, f_C and f_L are the fractions of protein, carbohydrate and lipid respectively in the microalgae.
- $E_{microalgae}$ is the energy stored in the microalgae (MJ kg^{-1}).
- E_P, E_c and E_L are the energy content of protein, carbohydrate and lipid respectively in the microalgae.
- $MB_{(daily)}$ and $ML_{(daily)}$ are the daily biomass (g m^{-2} day^{-1}) and lipid (ml m^{-2} day^{-1}) productivities.
- k is the rate constant of the microalgae.
- ρL is the density of lipid (kg l^{-1}).

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