Theoretical Estimation of the Microalgal Potential for Biofuel Production and Carbon Dioxide Sequestration in India

Bunushree Behera, Nazimdhine Aly, M. Asok Rajkumar and P. Balasubramanian

Abstract The unprecedented decline in petroleum reserves along with the rising concerns of global warming and environmental pollution has resulted in the search for alternative energy. India receives an abundant amount of solar insolation that can be easily transformed into other bioenergy sources. In current years, microalgal biofuels have gained attention owing to the presence of substantial amount of lipids and ease of cultivation in the presence of light energy, wastewater, and carbon dioxide (CO_2). In spite of the theoretical knowledge, the lack of convincing technical data and economic hindrances limit their field-scale application. The current study utilizes the global horizontal solar irradiance data (from the year 2002 to 2008) of India as input into the photon energy balance equations, which were solved in MATLAB to predict the theoretical microalgal biomass, lipid productivity, and CO_2 sequestration potential. The maximum biomass productivity was predicted as 90.1 g m^{-2} d^{-1}, corresponding to the lipid productivity of 31.3 ml m^{-2} d^{-1} and CO_2 sequestration potential of 23.6 g m^{-2} d^{-1} in the southern peninsular regions and Western Ghats. Since the solar irradiance varies from 3.25 to 6.08 kWh m^{-2} d^{-1} for the entire Indian subcontinent, most parts of India were projected to be suitable for growing microalgae. Decline in biomass productivity by 32.5% was evident accounting for photoinhibition effects such preliminary estimates would help in assessing the real-time potential of microalgae before going for cost-intensive field-scale analysis.

Keywords Microalgae · Solar insolation · Photoinhibition · Biomass productivity · Lipid productivity · CO_2 sequestration

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1 Introduction

The substantial utilization of fossil fuels in the present era is the major contributor to environmental pollution and global warming. Further, the depletion of these reserves is highly alarming and demanded the search for alternative fuels [9]. Indian subcontinent holds vast reserves of renewable resources that harbor tremendous potential for replacing the conventional fossil fuels. However, most of these resources are unharnessed due to the lack of appropriate technical knowledge and economic hindrances [8, 9]. In recent years, microalgae have attracted lots of attention as the most promising source of bioenergy since they contain up to 60% lipids along with substantial amount of carbohydrates and proteins [5]. Further, their ease of cultivation compared to the first- and second-generation energy crops as the microalgae could be cultivated in either marine or brackish water in the presence of light energy increases their desirability in terms of energy requirements and cost economics [5, 10, 11]. The integrated symbiotic approach combining wastewater treatment with biofuel production utilizing the flue gas from industries is acknowledged as the strategy for curbing environmental pollution and global climate change [19]. In spite of the very well-known advantages of microalgae, still their real-time, large-scale application is highly restricted, especially in developing countries. Lack of convincing data on the productivity and economics limits their scale-up. As microalgae are autotrophic microorganisms that use the light energy to convert CO_2 into biomass, the algal productivity is a direct function of the horizontally received solar insolation [16]. Hence, site-specific studies via mathematical modeling approaches are essential to select the desired locations with appropriate solar insolation and climatic condition to facilitate easy decision making by policy makers and stakeholders.

Various researchers around the globe have theoretically predicted the microalgal productivity. **Slegers et al. (2011, 2013)** developed a mathematical model to estimate the biomass productivity of microalgae using the open pond and flat panel photobioreactors considering the influence of climatic conditions in Algeria, Netherlands, and France [12, 13]. **Sudhakar et al. (2012)** had predicted the biomass productivity and CO_2 sequestration potential of different regions of India taking into account the horizontal solar insolation data from RETScreen database [16]. **Asmare et al. (2013)** studied the biomass and oil productivity of microalgae for five different regions of Ethiopia concerning the variation in spatiotemporal conditions [4]. **Aly and Balasubramanian (2017)** evaluated the effects of various global geographical coordinates on microalgal growth rate and biomass productivity [1]. **Aly et al. (2017)** evaluated the growth of microalgae in a trackable solar photobioreactor for the state of Odisha, India [3]. Most of the earlier studies have taken into account the influence of solar insolation directly without considering the photoinhibition effects which cause irreparable damage to the photosynthetic system, thus declining the algal productivity. Another study by **Aly and Balasubramanian (2016)** calculated the microalgal productivity in hypothetical open ponds of National Institute of Technology (NIT) Rourkela, Odisha, including the effects of photoinhibition [2].

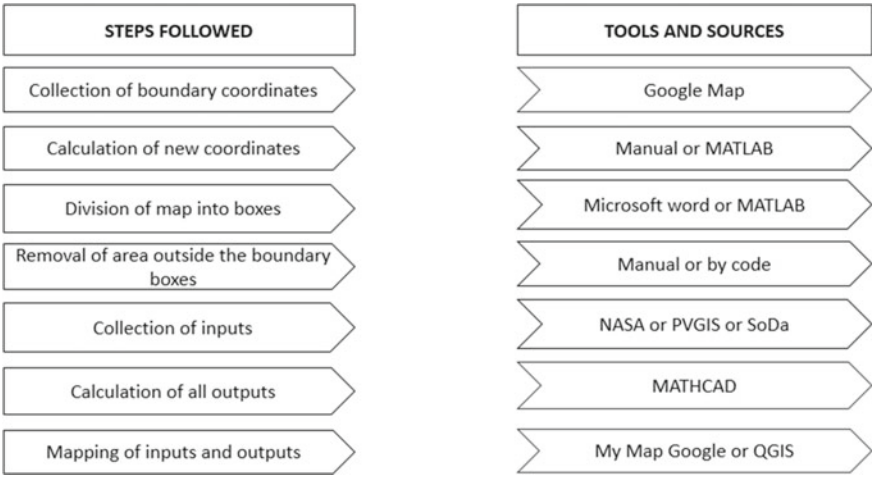


Fig. 1 Flowchart of the detailed methodology for map generation

The current study evaluated the potential of microalgal and lipid productivity along with the CO_2 sequestration potential for the entire Indian subcontinent based on global horizontal solar irradiance (GHI). The solar insolation received from different regions of India for the year 2002–2008 was collected, averaged, and fed as input into the photon energy balance equations to obtain the desired theoretical yields. Such kind of studies acts as a benchmark for the stakeholders and decision makers working in the area of large-scale microalgal cultivation to facilitate decision making, thus making algal biofuels a commercial reality.

2 Methodology

2.1 Data Collection and GHI Map Generation

Indian subcontinent lies toward the north of the equator between 6°44′ and 37°30′ north latitude and 68°7′ and 97°25′ east longitude. The entire Indian country was divided into 30,243 spatial coordinates based on the available GHI data from the Ministry of New and Renewable Energy (MNRE), Solar Energy Center database, Government of India. Latitude and longitude of all these spatial coordinates were considered for the study. The available GHI data were retrieved from MNRE databases for the year 2002–2008 and utilized further for calculations. The flowchart starting from the collection of the data until map generation has been detailed as presented in Fig. 1. The coordinates of the selected site and the map plotting were done as outlined in detail by the earlier studies of the authors **Aly et al**. **(2017)** [3].

2.2 *Modeling Equations for Estimating the Microalgal Productivity*

Solar radiation is the primary factor affecting the photosynthesis and metabolic growth rate of microalgae. However, the solar radiation incident over the raceway pond or the total energy available for microalgal growth is much less than that of the full spectrum solar energy. The biomass and lipid productivity along with carbon dioxide sequestration capacity of autotrophic microalgae depend on the photosynthetically active radiation (PAR). PAR is the amount of solar insolation in the visible range from 400 to 700 nm available to the algae for photosynthesis as given in Eq. (1).

$$\%\mathrm{PAR} = \frac{\text{PAR energy}}{\text{Full spectrum energy}} * 100 = \frac{\int_{\lambda=400}^{700\,\mathrm{nm}} \mathrm{Esolar}\,(\lambda)\mathrm{d}\lambda}{\int_{\lambda=0}^{4000\,\mathrm{nm}} \mathrm{Esolar}\,(\lambda)\mathrm{d}\lambda} * 100 \tag{1}$$

The daily biomass productivity of microalgae is dependent on the photon transmission efficiency, photon conversion efficiency, and photon utilization efficiency of microalgae. Photon transmission efficiency of microalgae takes into account the absorption efficiency of algal cells which is dependent on the light distribution efficiency of the microalgae $\left(\eta_{\text{light distribution}}\right)$ considering them as particulates distributed in the media, land use efficiency ($\eta_{\text{land use}}$), and %PAR. Equation (2) has been used to calculate the photon transmission efficiency.

$$\eta_{\text{transmission}} = \eta_{\text{light distribution}} * \eta_{\text{land use}} * \alpha * \%\mathrm{PAR} \tag{2}$$

Photon conversion efficiency ($\mathrm{PCE_{PAR}}$) as given by Eq. (3) denotes the number of photons converted into useful energy by algae.

$$\mathrm{PCE_{PAR}} = \frac{\mathrm{HV\ of\ CH_2O}\left(\frac{\mathrm{KJ}}{\mathrm{mol\ CH_2O}}\right)}{\mathrm{n_{photons}}\left(\frac{\mathrm{mol\ photons}}{\mathrm{mol\ of\ CH_2O}}\right)\mathrm{X\ ME\ of\ PAR}\left(\frac{\mathrm{KJ}}{\mathrm{mol\ photon}}\right)} \tag{3}$$

The capture efficiency of solar insolation by microalgae depends on the metabolic process efficiency of photosynthesis, absorption, and respiration, and thus can be represented by Eq. (4).

$$\eta_{\text{capture}} = \eta_{\text{photosynthesis}} * \eta_{\text{photo-utilization}} * (1 - \mathrm{r}) \tag{4}$$

To have a more realistic estimation of the photosynthetic ability, the photon utilization efficiency ($\eta_{\text{photo-utilization}}$) of microalgae as given in Eq. (5) incorporates the Bush equation with photoinhibition effect.

$$\eta_{\text{photo-utilization}} = \frac{\mathrm{I_s}}{\mathrm{I_l}}[\ln\left(\frac{\mathrm{I_s}}{\mathrm{I_l}}\right) + 1] \tag{5}$$

Apart from the solar irradiation, the inherent biochemical content of microalgae which constitutes the biomass energy of microalgae ($E_{microalgae}$) is given by Eq. (6).

$$E_{microalgae}\left(\frac{MJ}{Kg}\right) = f_L * E_L + f_P * E_P + f_C * E_C \tag{6}$$

where f_L, f_P, and f_C represent the fraction of lipids (30%), proteins (35%), and carbohydrates (35%), respectively. E_L, E_P, and E_C represent the energy content of lipids, proteins, and carbohydrates which were presumed as 16.7, respectively.

The daily microalgal biomass productivity ($MB_{(daily)}$) is dependent on incident solar radiation and can be calculated by Eq. (7).

$$MP_{(daily)}\left(\frac{g}{m^2 * day}\right) = \frac{\eta_{transmission} * \eta_{capture} * SI\left(\frac{KWh}{m^2 * day}\right)}{E_{microalgae}\left(\frac{MJ}{Kg}\right)} \tag{7}$$

2.3 Evaluation of Lipid Production Potential and CO_2 Sequestration Capacity

The lipid productivity of microalgae $\left(ML_{(daily)}\right)$ is directly proportional to the biomass productivity ($MB_{(daily)}$) and is given by Eq. (8).

$$ML_{(daily)}\left(\frac{ml}{m^2 * day}\right) = \frac{f_L * MB_{(daily)}\left(\frac{g}{m^2 * day}\right)}{\rho_L\left(\frac{Kg}{l}\right)} \tag{8}$$

where f_L represents the fraction of lipids in microalgae that is assumed to be 35% and ρ_L represents the density of microalgal lipids.

The CO_2 sequestration potential of microalgae is largely strain-specific and also depends on the cultivation conditions. Assuming the algal biomass molecular formula as $CO_{0.48}H_{1.83}N_{0.11}P_{0.01}$ and applying the law of conservation of mass to microalgae result in Eq. (9).

$$4CO_2 + H_2O + \text{Nutrients} + \text{Sunlight} \rightarrow 4CO_{0.48}H_{1.83}N_{0.11}P_{0.01} + 3.5O_2 \tag{9}$$

Rate constant (K) for the reaction is calculated considering the ratio of the molar mass of CO_2 (M_{CO_2}) to that of microalgal biomass ($M_{Biomass}$) as given in Eq. (10)

$$\frac{M_{CO_2}}{M_{Biomass}} = \frac{44}{23.2} = 1.89 \tag{10}$$

Total carbon dioxide (total CO_2) fixed is given by Eq. (11)

$$\text{Total } CO_2 = K * MB * \text{fixation efficiency} \tag{11}$$

The fixation efficiency has been assumed to be 15% to guarantee the minimum amount of CO_2 captured by microalgae.

2.4 Assumptions and Limitations of the Proposed Model

The mathematical model encompasses a set of empirical equations as described in the previous section which was written and solved using Mathcad. As the productivity is a function of solar insolation received, all the calculations were carried out considering the energy of one photon. The equations used for energy balances are inclusive of the losses due to atmospheric conditions and metabolic maintenance of microalgae. The biochemical composition of microalgae, i.e., the carbohydrate: protein: lipid ratio, has been assumed to be 35:35:30. The energy content of proteins, carbohydrates, and lipids is taken as 16.7, 15.7, and 37.6 kJ g^{-1}, respectively. The density of lipids (ρ) has been considered as 0.85 kg l^{-1}. The list of constants used in the modeling along with their values as given in the previous literature is given in Table 1. Even though the model takes into account the effects of photoinhibition, still the inclusion of the effects of other parameters like the water temperature, initial microalgal concentration, reactor geometry could be done in future for improvising the current model.

3 Results and Discussion

3.1 Biomass Productivity of Microalgae as a Function of Solar Insolation

India being a tropical country receives a good amount of sunlight throughout the year. The average daily solar insolation varies from 3.25 to 6.08 kWh m^{-2} d^{-1} as illustrated in GHI map (Fig. 2a). Indian subcontinent can be divided into three different solar hotspot boundaries, i.e., regions receiving less than 4 kWh m^{-2} d^{-1}, regions receiving solar insolation between 4 and 5.5 kWh m^{-2} d^{-1}, and the regions receiving more than 5.5 kWh m^{-2} d^{-1}. The daily average solar insolation received is maximum in the regions of southern peninsula and the Western Ghats which are more than 5.5 kWh m^{-2} d^{-1}. The Eastern Ghats and central plateau regions receive a moderate range of global solar insolation daily that varies from 4.25 to 5.52 kWh m^{-2} d^{-1}. The Himalayan region receives the lowest range of daily average global insolation along with northern plains and the northeastern parts in the range of 3.25–4.29 kWh m^{-2} d^{-1}. **Sudhakar et al**. **(2012)** had reported that an average solar insolation received by most parts of India varies from 4 to 7 kWh m^{-2} d^{-1} [16].

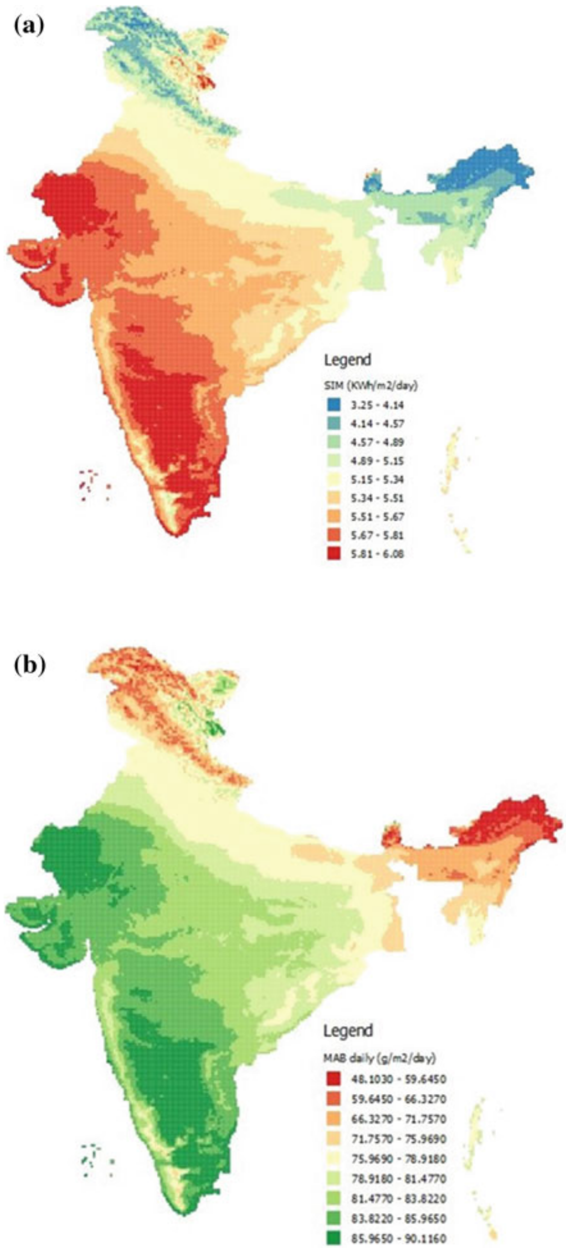
Table 1 List of constants used in the empirical equations for modeling

Parameters	Values	References
Full spectrum solar energy (E_{solar}) (MJ m^{-2} year)	5623–7349	[18]
Photon transmission efficiency[a] ($\eta_{Transmission}$)	0.43–0.44	[15]
Photosynthetically active radiation (PAR) (%)	0.45–0.47	[6]
Energy of photons (E_{photon}) (kJ mol^{-1})	225.3	[6]
Photon conversion efficiency[a] ($PCE_{PAR}/\eta_{Photosynthesis}$)	0.26–0.27	[15]
Light distribution efficiency[a] ($\eta_{light\ distribution}$)	0.96	[15]
Photon utilization efficiency[a] ($\eta_{Photon\text{-}utilisation}$)	1	[15]
Land use efficiency[a] ($\eta_{land\ use}$)	0.96	[15]
Fraction of energy used in respiration[a] (r)	0.2	[15]
Light absorption efficiency of algae[a] (α)	1	[15]
Saturation light used in photosynthesis (I_S) (μmol m^{-2} s^{-1})	200	[17]
Incident light used in photosynthesis (I_1) (μmol m^{-2} s^{-1})	200	[17]
Mean energy of 1 mol PAR (M.E of PAR) (kJ mol^{-1})	217.4	[6]
Higher heating value of microalgae (HV of CH_2O) (MJ kg^{-1})	14.21	[15]

[a]Represents dimensionless value

Since microalgae are autotrophic photosynthetic microorganisms, it is expected that the biomass productivity must be directly proportional to the amount of solar insolation received. As evident from Fig. 2b, the pattern of biomass productivity also follows a similar trend as that of the GHI map. The predicted daily average biomass productivity for the Indian subcontinent varies from 48.10 to 90.12 g m^{-2} d^{-1}. The maximum range of biomass productivity varying from 81.48 to 90.12 g m^{-2} d^{-1} was predicted in the regions of southern peninsula and Western Ghats which are receiving the maximum amount of horizontal solar insolation. Biomass productivity ranging from 66.33 to 81.48 12 g m^{-2} d^{-1} has been predicted for the central plateau regions, the Gangetic Plains, and the Western Ghats which receive a moderate range of solar

Fig. 2 **a** Daily average global horizontal solar insolation (GHI) map of India. **b** Predicted microalgal biomass productivity as a function of the received solar radiation



insolation. The northeastern regions as well as the northern Himalayan regions with less than 4 kWh m^{-2} d^{-1} are expected to have the biomass productivity in the range of 48.10–66.32 12 g m^{-2} d^{-1}. Most of the biomass productivities are consistent

Table 2 Comparison of the model output with the previous studies in the literature

Study sites	GHI (kWh m^{-2} d^{-1})	Biomass prod. (g m^{-2} d^{-1})	Lipid prod. (ml m^{-2} d^{-1})	CO_2 capture (g m^{-2} d^{-1})	References
Without the inclusion of photoinhibition effect					
Parts of India	4.5	80	18.82	–	[16]
Parts of India	5.5	97	22.82	–	[16]
Parts of India	6.5	115	27.05	–	[16]
Una, Himachal Pradesh, India	5.3	75.68	35.61	–	[14]
Chennai, Tamil Nadu, India	5.1	75.35	34.51	–	[14]
NIT Rourkela, Odisha, India	4.9	72.59	25.21	20.65	[2]
Entire Indian subcontinent	6.0	90.10	31.3	23.64	Present study
With the inclusion of photoinhibition effect					
NIT Rourkela, Odisha, India	4.9	54.1	18.8	15.4	[2]
Indore, Madhya Pradesh, India	5.1	55.9	–	15.3	[1]
Entire Indian subcontinent	6.0	60.6	21.0	17.2	Present study

with those of the previous studies as given in Table 2. Variations obtained might be attributed to the differences in climatological parameters and differences in strain of microalgae taken under consideration. The study clearly depicts the unleashed potential of different locations in Indian subcontinent that can be used for growing algae. Thus, the presented data provides estimates to be used by different policy makers for making the large-scale microalgal productivity a reality in near future.

3.2 Lipid Productivity and Carbon Dioxide Sequestration Capacity of Microalgae

Figures 3 and 4 illustrate the pattern of predicted lipid productivity profile and CO_2 sequestration capacity of microalgae for different regions of India, respectively. The lipid productivity of microalgae is determined by the biomass productivity as well as the strain-specific biochemical content of microalgae [5, 16]. The predicted lipid productivity profile follows a trend similar to that of the predicted biomass produc-

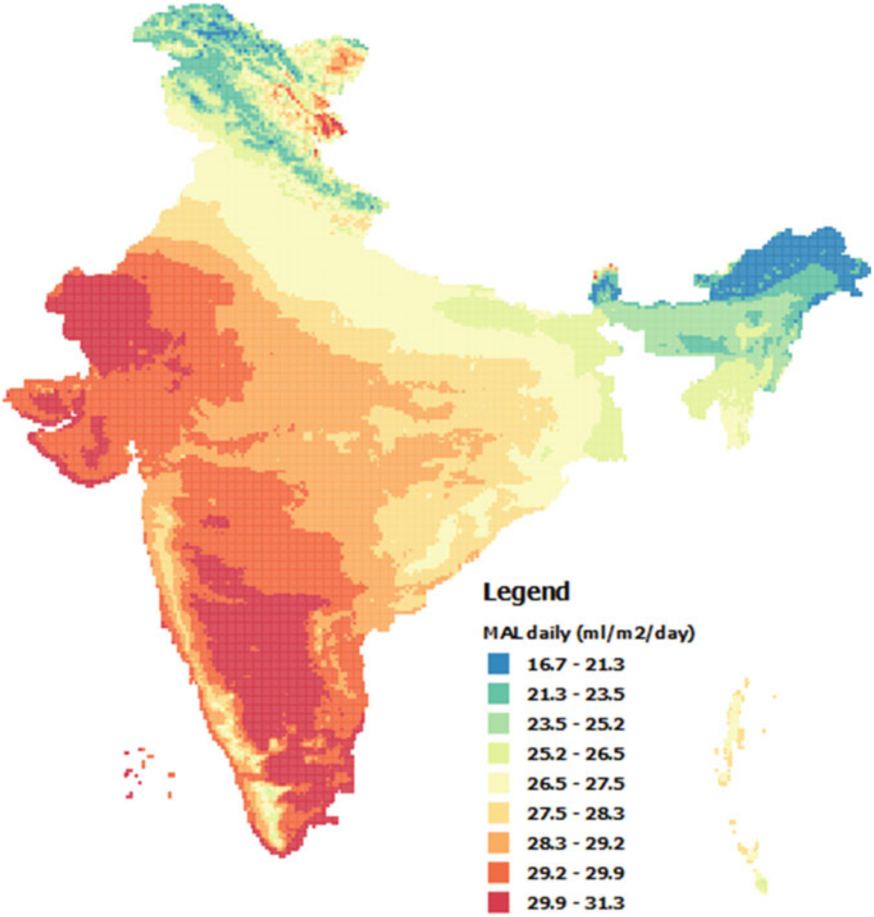


Fig. 3 Predicted daily lipid productivity for the entire Indian subcontinent

tivities with the maximum productivity achieved in the regions of southern peninsula and Western Ghats (28.3–31.3 ml m^{-2} d^{-1}). It is followed by the central plateaus (25.2–28.3 ml m^{-2} d^{-1}) and the minimum in the regions of northern Himalayan foothills and northeastern parts (16.7–25.2 ml m^{-2} d^{-1}). **Aly and Balasubramanian (2016)** have predicted a lipid productivity of 25.21 ml m^{-2} d^{-1} for NIT Rourkela, Odisha, India [2]. The lipid productivity potential of microalgae over various regions of the Indian subcontinent is evidently higher than that of the other energy crops (**Asmare et al. 2013**), making it suitable for large-scale generation of algal biofuel [4].

The CO_2 sequestration potential of microalgae is dependent largely on the biomass productivity as well as the carbon capture efficiency of the strain under study. It is noteworthy to mention that 15% CO_2 capture efficiency has been assumed for the

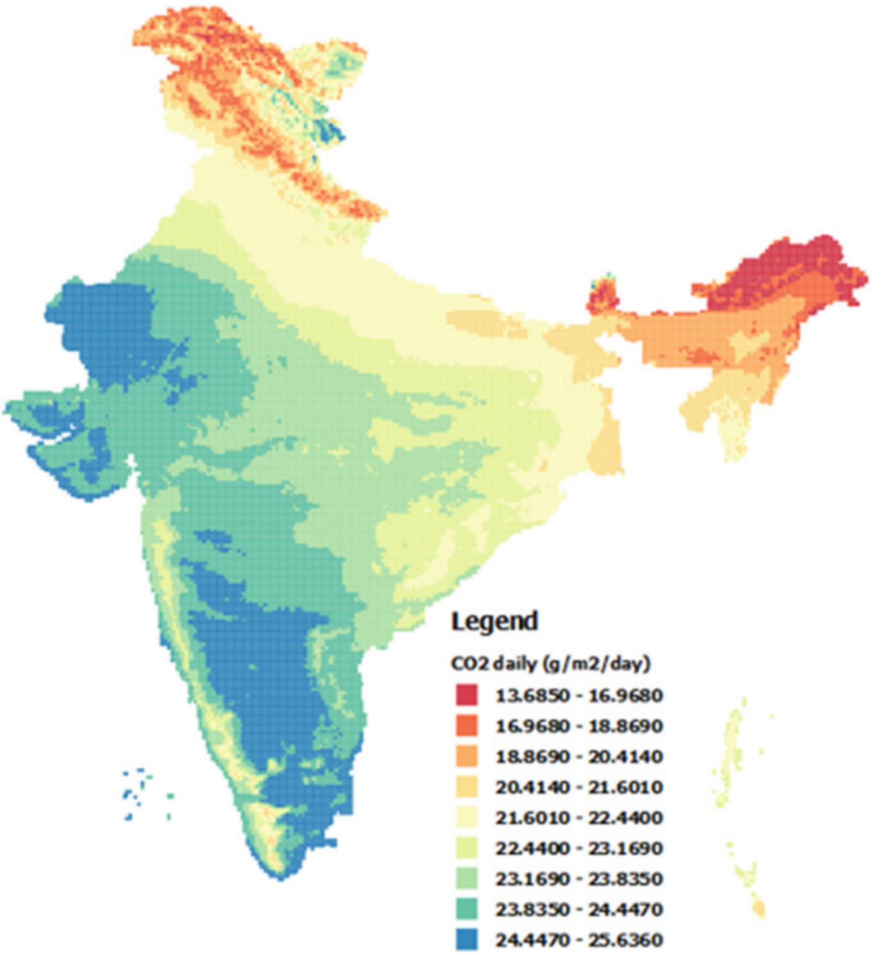


Fig. 4 Predicted CO_2 sequestration potential of microalgae in India

present study to provide the minimum possible values for CO_2 sequestration potential. The average daily CO_2 capture potential of possible large-scale microalgal cultivation ranges from 13.69 to 23.64 g m^{-2} d^{-1}. Maximum average CO_2 sequestered has been predicted for the southern peninsular India and the Western Ghats. The predicted profile for daily CO_2 captured is similar to the biomass productivity mapping. The CO_2 sequestration potential reported in the current study is several times higher than that of the capture potential of terrestrial plants [4]. It emphasizes the suitability of large-scale microalgal cultivation as a potential biological CO_2 sequestration strategy in future.

3.3 Influence of Photoinhibition Effects on Biomass and Lipid Productivity Along with Carbon Sequestration Potential of Microalgae

The photon flux density of microalgae has a direct impact on the photosynthetic rate as well as with the microalgal productivity [16]. It is expected that the photosynthetic rate and biomass productivity would be increased with the enhanced intensity of solar radiation. However, at the cellular level, there is an increase in photosynthetic activity with the increase in the amount of solar insolation only up to a certain threshold value beyond which the photosystem II becomes saturated [7]. This phenomenon is known as photoinhibition, and thus beyond the threshold level, there is no further increase in photosynthetic rate and biomass productivity. As illustrated in Fig. 5, considering the influence of photoinhibition into account, the maximum biomass productivity decreases by 32.5% from 90.1 to 60.6 g m^{-2} d^{-1}. Similarly, the maximum lipid productivity declines from 31.3 to 21.0 ml m^{-2} d^{-1} and the CO_2 capture capacity decreases from 25.6 to 17.2 g m^{-2} d^{-1} (Figs. 6 and 7). However, the generalized profile of biomass, lipid productivities, and CO_2 sequestration potential remains fairly same as that of the previous case. Thus photoinhibition shows a more realistic difference in the microalgal productivity. Similar kind of results were also reported **by Aly et al. (2017)** for 1142 locations in the entire state of Odisha using solar-trackable photobioreactor [3]. **Aly and Balasubramanian (2017)** also reported the effects of photoinhibition over spatial coordinates at ten different global locations on algal productivity, lipid yield, and carbon sequestration capacity of microalgae [1].

3.4 Model Comparison and Validation

The mathematical model was built taking into account the empirical equations relating to the photon energy balance. With the range of solar insolation varying from 3.25 to 6.08 kWh m^{-2} d^{-1} for the Indian subcontinent, the microalgal biomass productivity has been predicted to range from 66.3 to 90.10 g m^{-2} d^{-1}. The corresponding lipid productivity of 16.7–31.3 ml m^{-2} d^{-1} and CO_2 sequestration capacity of 13.69–23.64 g m^{-2} d^{-1} were also postulated in the current study. As given in Table 2, the data obtained in the present study bears resemblance and is consistent with that of data reported in the literature for the Indian scenario. Variation in the values of yields obtained in different case studies is due to the difference in geographical coordinates as well as the other parameters taken into account. Further, most of the previous studies did not consider the effect of photoinhibition. Photoinhibition causing irrevocable damage to the photosynthetic system reduces the efficiency of absorption of photons by 30–40%, thus declining the net productivity [7]. In the present study, biomass productivity declines by 32.5% while considering the effects of photoinhibition. **Aly and Balasubramanian (2016, 2017)** have also reported a decrease in

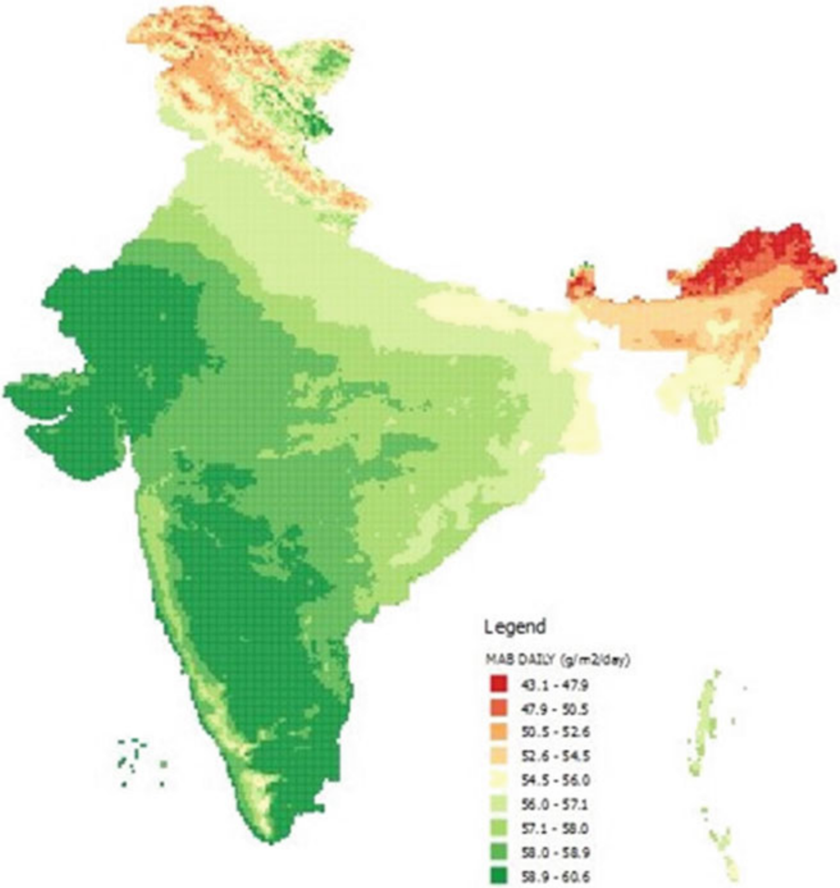


Fig. 5 Predicted microalgae productivity including the effects of photoinhibition

biomass and lipid productivity along with CO_2 sequestration potential of microalgae with the inclusion of photoinhibition effects on the model [2, 3].

4 Conclusion

The present study aimed to predict the microalgal biomass, lipid productivity and CO_2 capture potential for the entire Indian subcontinent. It is very well evident from the predicted ranges that algal technology is a potentially viable option for substituting the fossil fuels in the Indian scenario. The maximum biomass productivity predicted was 90.1 g m^{-2} d^{-1}, corresponding to the lipid productivity of 31.3 ml m^{-2} d^{-1} and CO_2 sequestration potential of 23.6 g m^{-2} d^{-1}. Microalgal biomass productivity

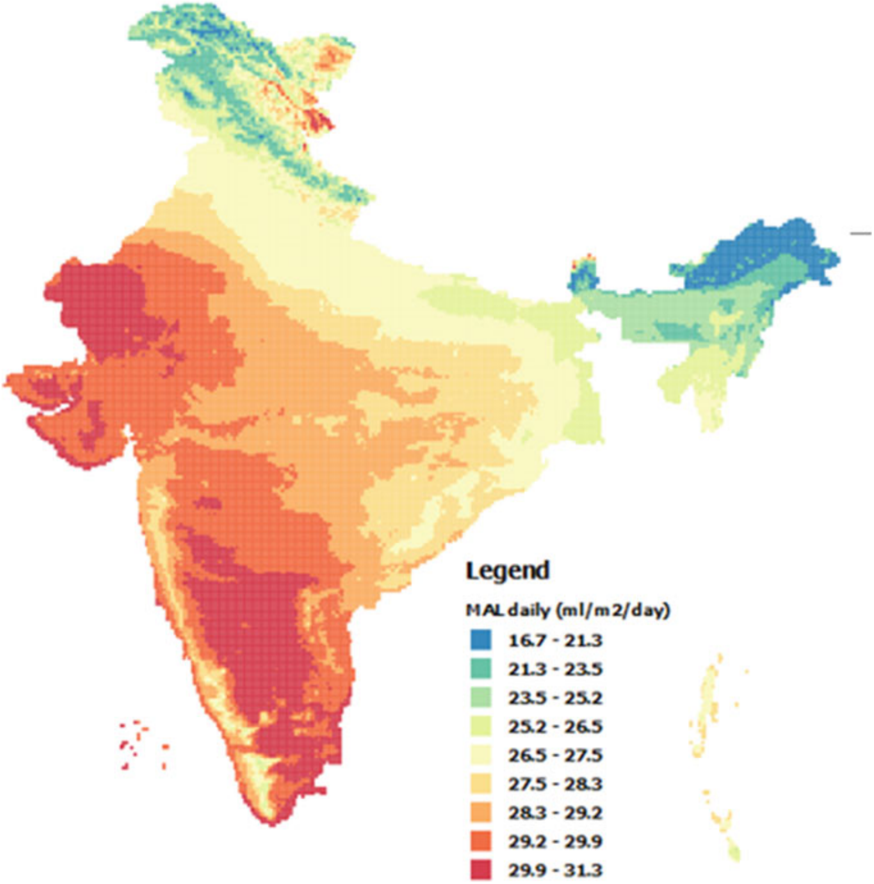


Fig. 6 Predicted microalgal lipid productivity along with the photoinhibition effect

has been found to decline by 32.5% due to photoinhibition, which also subsequently decreases the lipid productivity and CO_2 sequestration potential. However, the data obtained is limited only by solar insolation received, but the net microalgal productivity is an annexation of several other environmental and operational parameters. The inclusion of other influencing parameters like effects of hydrodynamic variation of water temperature, air temperature, initial microalgal concentration, and reactor geometry could further improvise the accuracy level of the model. Such theoretical studies would be helpful to the researchers, decision makers, and other stakeholders in accessing the algal biofuel potential in the arena of alternative energy and biological carbon sequestration.

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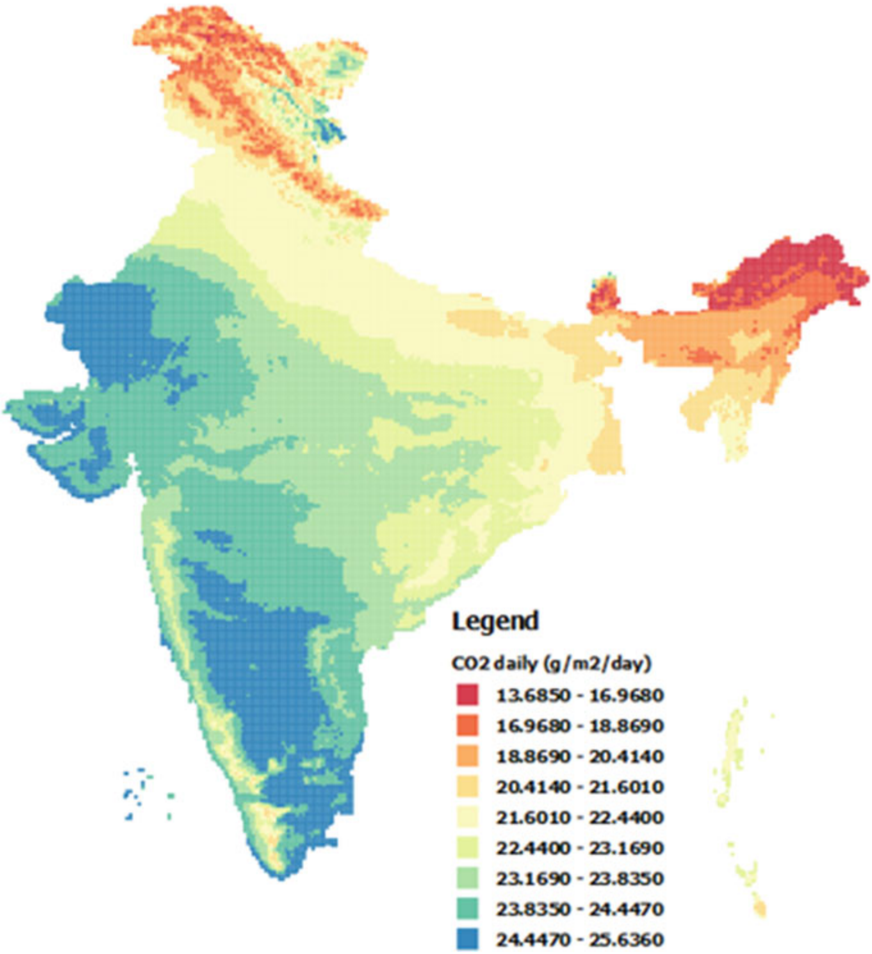

Fig. 7 Predicted CO_2 capture potential of microalgae including photoinhibition effect

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