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Biophysical model and techno-economic assessment of carbon sequestration by microalgal ponds in Indian coal based power plants

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ABSTRACT

The present study evaluated the carbon dioxide (CO_2) sequestration potential of *Thalassiosira pseudonana* using the influencing key climatic datasets of an Indian coal based power plant through a biophysical energy balance model developed on MATLAB platform with ODE45s solver. The maximum average areal biomass productivity was predicted to be 111.39 kg $ha^{-1}d^{-1}$ with maximum growth in February, leading to the CO_2 capture of 147.03 kg $ha^{-1}d^{-1}$. Further, techno-economic analysis was performed utilizing the results of the formulated biophysical model to access the process feasibility using SuperPro designer. Results revealed the technical viability and economic feasibility of the process, with the unit production price of 58.41 $ per ton with a reasonable rate of returns and acceptable short payback time of 2.81 years. A yearly carbon credits of 52 M$ could be earned by the company. Sensitivity analysis showed the process to be highly dependent over the raw material prices and facility operation. The integrated site-specific biophysical model and economic analysis are essential to provide reliable realistic estimates of the algal carbon sequestration technology that could drive the energy policies towards sustainable development.

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1. Introduction

One of the major threat to environmental sustainability and global warming is the accumulation of carbon dioxide (CO_2) in the atmosphere. Coal fired power plants are the major contributors among the anthropogenic release of CO_2. (Shahzad and Yousaf, 2017). Flue gases from industries contain around 5–25% of CO_2, based on the plant design and the fuel used in operation (Kao et al., 2014). Current technologies for post-combustion carbon capture include either the use of physical adsorbents or directing the CO_2 into deep oceans and geothermal rocks (Zhang and Huisingh, 2017). However, the conventional methods are economically unfeasible and pose storage problems along with high space requirements. Recently, microalgae have grabbed attention, not only as a promising future source of biofuel but also as a carbon capture and storage sink (Cuellar-Bermudez et al., 2015). They can be easily cultivated in open ponds with marine/wastewater localized on wastelands/inside the premises of established industries, utilizing the emitted CO_2 for their metabolism (Behera et al., 2018). The microalgal biomass generated can be further processed into biofuel, sorting out the future fuel demands and tackling the climate change issues. Reduction in CO_2 emissions can also generate revenues in terms of commercial carbon trade/carbon credits.

The idea of carbon capture using microalgal biomass dates back nearly to a decade. Kadam and Brady (1996) analysed the feasibility of algal CO_2 sequestration for 1800 MW San Juan Power Plant, New Mexico, through resource assessment study via Geographical Information System (GIS) and reported that 1000 ha algal ponds could capture 4.14 MT (CO_2) yr^{-1}. Approximately a 40 ha algal pond is required to mitigate the CO_2 emitted from 1 MW coal based power unit, at 50% capture efficiency (Sudhakar and Premalatha, 2012a).

CO_2 sequestration by microalgal biomass has witnessed tremendous scientific progress in view of the laboratory as well as pilot scale studies. Vunjak-Novakovic et al. (2005) demonstrated 50.1–82.3% CO_2 sequestration efficiency by *Dunaliella* sp. Using the flue gas from the cogeneration power plant at MIT, Cambridge 60% CO_2 sequestration efficiency was reported using the flue gas from coke oven steel plant, China Corporation, Taiwan by *Chlorella* sp. MTF-7 (Chiu et al., 2011). Kao et al. (2014) demonstrated that *Chlorella* sp. MTF-15 successfully captured about 25–50% CO_2 from

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different operation sections of a coke oven power plant at China Steel Corporation, Southern Taiwan. Very recently, Aslam et al. (2017) utilized 11.24% CO_2 from the flue gas of 4 MW coal fired boilers, Queensland, Australia to cultivate microalgae. However, pertaining to the lack of convincing data and economic challenges with relation to the process development parameters, the industrial scale application is still lacking, especially in developing countries like India. Most of the Indian coal power plants utilize E and F grade coals, and as an outset, CO_2 emissions per unit of electricity range between 0.8 and 1.8 kg kWh^{-1} (Mittal et al. 2012). Recently, Pradhan et al. (2017) demonstrated an algal productivity of 20 tons ac^{-1} yr^{-1} in a coal based power plant in NALCO, Angul, Odisha, India that resulted in carbon sequestration capacity of 32 tons ac^{-1} yr^{-1}.

To evaluate the technical potential of microalgae, it is essential to assess the productivity potential at a specific location. Weyer et al. (2010) reported the role of geospatial variables on algal production. Microalgal biomass, oil productivity and CO_2 sequestration capacity in different parts of India has been predicted by Sudhakar et al. (2012). Influence of site-specific climatological variables on microalgal productivity in hypothetical open ponds and tubular photobioreactors in Netherland, France, and Algeria was evaluated by Slegers et al. (2013a, 2013b) using *Phaeodactylum* sp. And *Thalassiosira* sp.. Asmare et al. (2013) estimated microalgal performance potential at five different regions in Ethiopia. Aly and Balasubramanian (2016) predicted microalgal productivity of 217.79 tons ha^{-1} yr^{-1} with CO_2 capture capacity of 62 tons ha^{-1} yr^{-1} in Rourkela, considering only the solar radiation received. The effects of geographical coordinates on microalgal productivity and CO_2 capture capacity have shown the productivities to be very minimal in countries present in Equator followed by those in Tropic of Cancer and was found to be highest in the countries around Tropic of Capricorn (Aly and Balasubramanian, 2017). Banerjee and Ramaswamy (2017) predicted the yearly algal productivity in different regions of the USA using the site-specific influencing variables. Aly et al. (2017) developed a model to estimate the localized effects of sunlight over the algal growth in closed photobioreactors at Rourkela, India. Behera et al. (2018a,b) predicted the algal productivity of 50.26 MT ha^{-1} yr^{-1} in open ponds at Rourkela, India integrating the geospatial coordinates with the biophysical predictive model considering the sunlight and water temperature. Though many site-specific modeling studies have been done globally for different outdoor cultivation sites, very limited studies have been focused on industrial locations, especially in Indian case scenarios, except the case study of Neyvelli power plant, by Sudhakar and Premalatha. (2012a). Also most of the above-mentioned studies have considered only one influencing variable and modelled the growth using simple empirical equations.

The aim of the current study is to assess the microalgal CO_2 sequestration potential as a function of biomass productivity considering the site-specific climatological variables at the coal based thermal power plant in Jharsuguda district of Odisha, India. A site-specific biophysical model with heat and mass transfer equations were formulated for an algal open pond using the daily averaged climatological data for 21 years to estimate the algal pond (water) temperature with time that governs the algal growth. Hydrodynamic changes in water temperature were combined with the photon energy balance to simulate the biokinetic model, predicting the algal growth rate, biomass productivity and CO_2 sequestration capacity over a period of 365 days. Furthermore, the averaged microalgal productivity and carbon sequestration obtained from the biophysical model were used as the baseline for economic analysis to determine the unit production costs and predict the revenue that could be earned by the industry. Unlike most of the previous literature which are based on only light intensity data, the present study proposes an easier way of pre-estimating the microalgal productivity under the combinatorial influence of realistic key climatic factors which governs photosynthetic carbon assimilation, that could be extended to other sites and for different algal strains. Integrating the location specific biophysical model with economic feasibility analysis provide proper insight into algal performance thus promises more realistic cost estimates to better establish the scalability and sustainability of the approach. The study will help the R&D and industrial management to consider integrated mass cultivation of microalgae with potential carbon capture facilitating environmental protection and thereby earning additional revenues through carbon credits.

2. Methodology

2.1. Site selection and climatological data collection

Odisha Power Generation Corporation Limited (OPGC) is a partially state government-owned corporation with a coal-based thermal power plant in Banharpali (21.85°N and 80.06°E), Jharsuguda, Odisha, India. It has a present capacity of 420 MW (2 × 210 MW), and current expansion is going on with two more units of 1320 MW (2 × 660 MW) capacity. The yearly emissions of the OPGC industry based on the sustainability report OPGC (2016-2017) are mentioned in Supplementary Table 1. The current strategies for mitigation of emissions in case of particulate matter (PM) is done by employing electrostatic precipitators. The oxides of sulphur (SO_x) and oxides of nitrogen (NO_x) is reduced by the use of flue gas desulphuriser and selective catalytic reduction respectively. However, no technology is being adopted to curb CO_2 emissions. Hence, this site was chosen as it could assist the research and development section of the industry to comprehend the microalgal CO_2 capture potential and adequately judge the advantages in terms of environmental protection and sustainable economic development.

Site-specific climatological datasets such as the solar insolation at a horizontal position, soil, dew and air temperature at 10 m above the earth surface and relative humidity were retrieved from NASA (National Aeronautical and Space Administration, USA) databases (Stackhouse, 2015) for a time frame of 21 years. The data were collected on a daily basis from 1st Jan' 1985–30th June '2005 [7482 data points] then averaged into 365 days to analyse the climatic fluctuations and seasonal variation and were further utilized as the baseline information for future predictions.

2.2. Model overview and definition

Most Indian plants are not equipped with the carbon capture technologies which jeopardizes the environment in terms of global warming. The current study proposes the integration of microalgal open ponds with the power plant flue gas processing strategies to mitigate the CO_2 levels (Supplementary Fig. 1). The model has been designed for open ponds considering the influencing climatological and operational factors affecting microalgal growth rate to predict the biomass productivity and CO_2 sequestration potential. The open ponds could be integrated with the flue gas generated from stacks to trap the emitted CO_2 for assimilation into biomass.

Sunlight and water temperature critically affect the performance of algal open ponds (Rangabhashiyam et al., 2017). The solar radiation available for growth and metabolism of microalgae is always less than that of the amount incident due to the dynamic reduction in the form of scattering, reflection, refraction etc. Only 47% of incident light energy out of the total spectrum is available for photosynthesis a portion of the incident sunlight transforms into heat energy and changes the pond water temperature with respect to time (Slegers et al., 2013a). Thus a comprehensive model has been formulated following an integrated approach, utilizing the heat and mass transfer equations in the solar energy balance model along with the growth kinetic model to predict the microalgal productivity and CO_2 sequestration potential.

The formulated model is a conglomeration of equations simulated via water and photon energy balance with retrieved climatological datasets as input. The water energy balance has been done by estimating the net changes in the energy fluxes associated with the heat transfer phenomenon in large open ponds that impacts the water temperature fluctuations with time. The dynamic water temperature and photon energy balance equations have been used for bio-kinetic analysis to predict the growth, thereby microalgal productivity and carbon sequestration ability. Overall methodology is illustrated in Fig. 1. The complete framework of the model relies on two sub-models, firstly, model to evaluate the algal pond temperature by solar energy balance and secondly, model to predict the potential productivity through microalgal growth kinetics. The entire code was written indigenously in MATLAB (R2015b) by the means of ODE45s solver. The detailed explanation about the model formulation as outlined in Behera et al. (2018a,b) has been used to analyse the variation in water temperature with time and its impact on the microalgal CO_2 sequestration.

2.3. Assumptions and limitations of the biophysical model

The energy balance equations have taken into account the energy losses due to extensive heat and mass transfer processes, however, there are several assumptions and limitations of the model owing to insufficient literature. Model has been built for the microalgae *Thalassiosira pseudonana* [$C_1H_{1.99}O_{0.681}N_{0.151}P_{0.093}$], with a molecular weight of 31.8, but can be well extended to other algal strain with the inclusion of specific features. To acknowledge the biochemical effects of light energy on microalgal productivity, all estimation were approximated in terms of quantum of photons. Due to the lack of sufficient literature data over the direct changes in the monitored cloud cover over the time-period of study, it has not been included in the calculation of sky temperature. Cloud cover influences the solar insolation, air temperature and the relative humidity of the location. Since, the study has analysed individually the influence of the above-mentioned variables on daily basis over the time frame of 21 years, the effect of cloud cover and its influence over the ambient temperature and incident solar insolation has thus been indirectly accounted. Their cumulative effects have been utilized through a set of empirical equations to evaluate the dynamic pond temperature. The pond water volume is regarded as constant. Further, the reactor is operated at semi-batch flow mode, and the evaporative losses in mass of water is compensated by the make-up media added at constant dilution rate. All calculations were done, assuming the reactor as unit volume, with specific residence time. The heat changes with the inflow of media has been neglected, due to the absence of sufficient literature data.

The algal growth is assumed not to be limited by pH and nutrients as done by Slegers et al. (2013a). The shading effect of sunlight due to neighbouring objects and night time respiration loss being minimal were neglected (Geider et al., 1996). Due to insufficient data, the model did not consider the effects of macro/micro nutrients which act as substrate for microalgae, however as microalgae being autotrophic mainly entraps atmospheric CO_2 assimilating into biomass, the carbon capture potential has been evaluated. The effect of NO_x, SO_x emissions and PM_{10} over microalgal growth has been neglected as the power plant employs electrostatic precipitators, and ammonia flue gas conditioner (AFGC) along with chemical desulphurisation methods [Supplementary Fig. 1] to limit their content below the permissible level in the flue gas. The flue gas NO_x first dissolves, then mixes with the sparged air and is oxidized to NO_2 that can be assimilated as the source of nitrogen by microalgae, reducing the need of fertilizers, making the process sustainable (Cuellar-Bermudez et al., 2015; Yen et al., 2015). The constraints of decrease in media pH and gradual acidification of algal ponds in due course of time with the addition of SO_x and NOx exists, with the use of the flue gas. According to the reports by Kao et al. (2014) and Vuppaladadiyam et al. (2018), the direct utilization of industrial flue gas would decrease the pH till 6.4 which could be tolerable by most algal strains, indicating relatively less negative impacts over the growth. The microalgae considered in this study could tolerate a pH range of

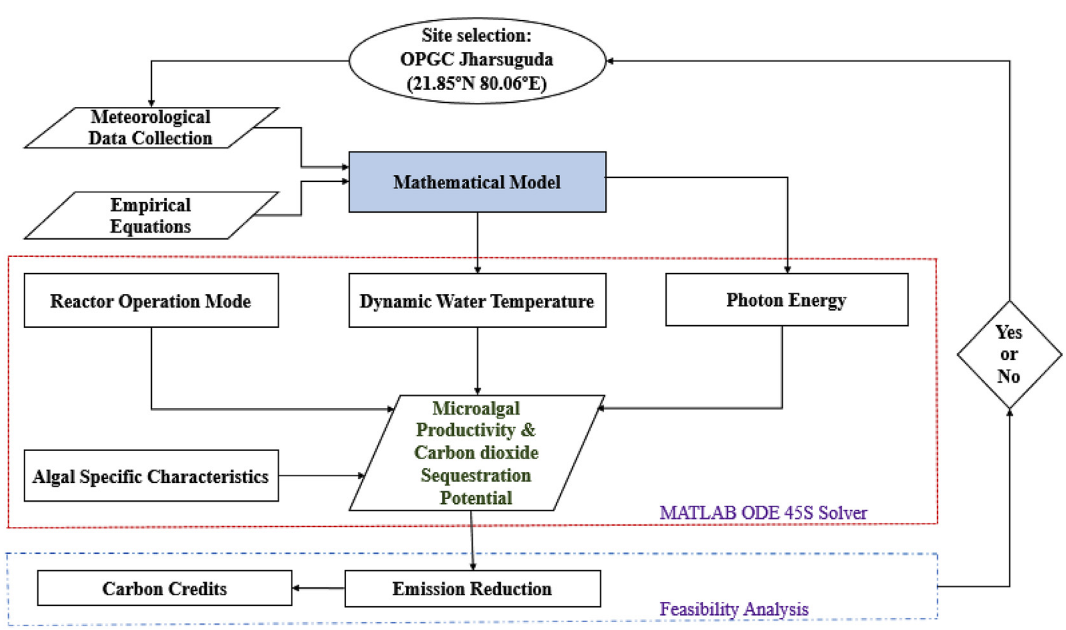


Fig. 1. Simplified flowchart showing the methodology for biophysical predictive modeling.

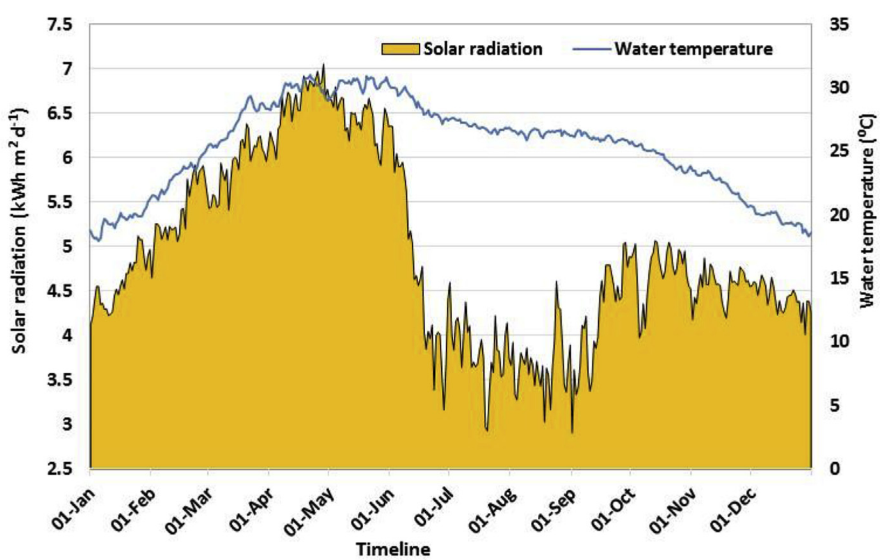
6–8.5 (Clement et al., 2017). Further, the negative impacts can also be averted by acclimatization of algal strains to tolerate acidic stress, and via optimization of process parameters like the gas flow rate and the residence time of the reactor (Yen et al., 2015). Owing to the lack of sufficient data the effects of these gases has not been accounted in this study, however the model would be further improvised in future including them.

2.4. Techno-economic analysis of industrial algae based carbon capture

The upstream processing steps of cultivation and harvesting occupy a majority of processing costs. Thus for economic analysis, the algal process chain starting from cultivation till harvesting and dewatering were considered. The comprehensive mathematical model combined with economic analysis was used to project profits which industry could earn in terms of carbon credits and from the microalgal paste that could be processed as fertilizer. The economic analysis was done using the SuperPro Designer software (Intelligen, Inc., Scotch Plains, NJ), considering the capital expenditure (CapEx) and operating expenditure (OpEx) of the industry based integration of algal cultivation to capture CO_2. The averaged biomass productivity and CO_2 sequestration data obtained from the biophysical model were used as the baseline information for simulating the unit process for subsequent economic analysis.

The baseline model was developed to capture the 3273182 MT yr^{-1} CO_2 generated by the power plant into a sets of 1 ha ponds and subsequently harvest and dewater the algal biomass. Microalgae was assumed to be grown in modular design based raceway ponds of 1 ha, having 75% working volume with process water and CO_2 from the industry as feed. The harvesting was done in two steps: sedimentation/bulk dewatering and

a).



b).

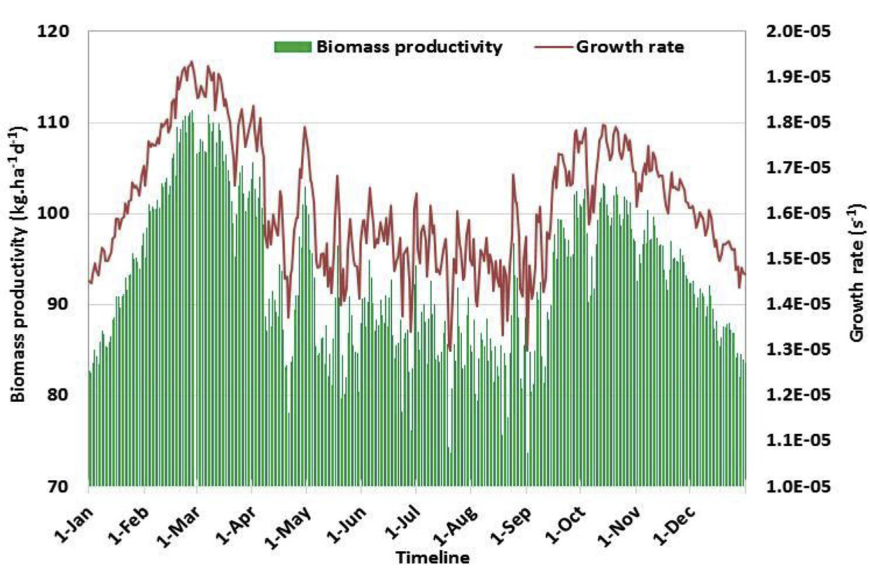


Fig. 2. A). Variation of water temperature with solar irradiance b). Predicted average growth rate and biomass productivity of algae over 365 days.

Table 1
Validation of the model by comparison with the values reported in the literature.

Sl. No.	Location	Model description	Biomass productivity	References
1	Different parts of India	Simulation model using excel spreadsheet. The model was run for 300 days at solar intensities of 4.5–6.5 kWh m^{-2} d^{-1}	Maximum biomass productivity of 111 g m^{-2} d^{-1} was obtained with solar radiation of 6.5 kWh m^{-2} d^{-1}. Average biomass productivity of 75 g m^{-2} d^{-1} was obtained in most parts of India.	Sudhakar et al. (2012)
2	Algeria, Netherland	Predictive modeling based on solar radiation, water and soil temperature. Hypothetical raceway ponds with 30 cm depth and water temperature varying from 0 to 12 °C.	8 tons ha^{-1} d^{-1} in Netherland and 14.9 tons ha^{-1} d^{-1} in Algeria for *T.psuedonana* 41.5 tons ha^{-1} d^{-1} in Netherland and 63.7 tons ha^{-1} d^{-1} in Algeria for *P. tricornutum*	Slegers et al. (2013a)
3	Addis Ababa, Awasa, Bahir Dar Mekele Nazret, Ethiopi	Predictive model using monthly average air temperature & solar radiation data using RETScreen database.	Average biomass productivity range of 73.91–90.21 g m^{-2} d^{-1}.	Asmare et al. (2013)
4	INRALBE, Narbonne (France)	*In silico* case study considering light, temperature and nutrient concentration on microalgal growth rate in open ponds.	Annual average biomass productivity of 168 tons ha^{-1} yr^{-1} was reported in June.	Muñoz-Tamayo et al. (2013)
5	**OPGC power plant, Jharsuguda, Odisha, India**	**Mathematical modeling based on climatological variables to estimate the algal pond water temperature and speculate its effect on algal productivity.**	**Maximum daily average biomass productivity was projected to be 111.39 kg ha^{-1} d^{-1} in February with water temperature of 23 °C.**	This study
	Experimental			
Sl. No.	**Location**	**Open Pond Configuration and Environmental Parameters**	**Biomass Productivity**	**References**
1	Seville, Spain	Oval fiberglass system of 3 m^2 and 0.3 m deep were used, under local climatic conditions.	Annual average productivity of 1.65 g m^{-2} d^{-1}.	García-González et al. (2003)
2	USA	Open cultures in 1 m^2 pond with 30 cm depth, with temperature of 30 °C	Maximum biomass productivity of 23.5 g m^{-2} d^{-1} was obtained in summer with temperature of 40 °C, the productivity decreased to 18.5 g m^{-2} d^{-1} in spring and declined to 9.4 g m^{-2} d^{-1} in winter.	Moreno et al. (2003)
3	Dalton, USA	Four raceway ponds of 950 L capacity, supplemented with 6% CO_2 and nitrogen (250 ppm), in batch culture for 10–12 days.	The average productivity of 2.6 g m^{-2} d^{-1} with the maximum productivity of 4.9 g m^{-2} d^{-1} in winter.	Chinnasamy et al. (2010)
4	Kharagpur, India	Open pond bioreactor of 450 L capacity and 150 L working volume, operated throughout the year in batch mode	Average biomass productivity of 5.78 g m^{-2} d^{-1} and maximum biomass productivity of 8.1 g m^{-2} d^{-1} was obtained in summer.	De Bhowmick et al. (2014)

thickening. A sedimentation rate of 95% was assumed with starch as flocculent (10 mg L^{-1} concentration) with 30 min residence time. Dewatering was done with belt filter resulting in final concentration of 200 g L^{-1}. The details of the equipment with the feed and flow rate for each step is provided in the supplementary data. The stoichiometric balance equation in the reactor was based on the data obtained from the mass balance model.

The CapEx and OpEx for running the algal production plant were estimated for trapping the entire flue gas generated by the industry, thus converting it into a carbon negative economy. The plant was assumed to run for 330 days. Price basis for all calculations were 2018. Equipment price was based on the built-in cost model in SuperPro designer. CapEx was estimated taking into account the direct fixed capital (DFC) including the contractor fees and contingency. Plant direct and indirect costs were calculated by multiplying the total equipment purchase cost with specific lang factors. Pumping and piping were based on the volumetric flow rate throughout the process. OpEx included the sum of all ongoing expenses including costs associated with raw materials, labours, consumables, utilities, waste disposal/treatment, quality control and assessment (QC/QA) and facility overhead. To make the calculations simple, the feed (i.e process water and CO_2 from the flue gas) was assumed to be generated onsite and was used, with no permits, taxes or transportation costs. The price of process water has been taken as 0.001 \$ kg^{-1}. The flocculent cost has been taken 0.7\$ kg^{-1}. In order to estimate the carbon credits which could be generated by the industry the flue gas used in the feed has been taken as the source of revenue (0.016 \$ kg^{-1}) (Singh et al., 2014). The price of algal biomass was assumed to be 0.1 \$ kg^{-1}. The levelized cost of electricity (LCOE) with and without carbon capture and the cost of CO_2 avoided were calculated to evaluate the process impact on energy costs. The profitability and cash flow analysis (over 15 years) was done to calculate the gross profit and net present value (NPV) with 7% interest.

3. Results and discussion

3.1. Evaluation of the effects of climatological parameters on open pond water temperature

Solar irradiance and water temperature play a significant role, affecting the microalgal growth rate and productivity. Fig. 2a shows the profile of average daily solar radiation received over 365 days and subsequent variation in water temperature. The region received maximal solar radiation during March until May which then decreased gradually. Water temperature also shows a strong trend with these variations. Water temperature is governed by a range of other climatological factors [as described in Supplementary Fig. 2] and the underlying energy transfer processes like the evaporation, conduction, convection and long-wave radiation. Thus, even though both these variables are interrelated, a linear relationship/proportionality does not exist over different seasons [Fig. 2a]. The month of April receives the maximum average solar insolation of 7.06 kWh m^{-2} d^{-1} corresponding to water temperature of 29.82 °C. Water temperature has been predicted to vary from 18 to 30 °C, with the fluctuations in climatic factors. Similar results were obtained by Banerjee and Ramaswamy (2017) and Behera et al. (2018a,b), highlighting the influence of climatological parameters on the temperature of water in open algal ponds. The regions in Indian subcontinent receiving sunlight in the range of 4–7 kWh m^{-2} d^{-1} could be suitable for growing microalgae Sudhakar et al. (2012b). Thus the selected industrial location can be used as a potential site for mass cultivation of microalgae. Further, as the optimum algal growth temperature ranges from 10 to 30 °C (Baek et al., 2011), the predicted range of water temperature shows the prospective potential of the site for algal cultivation. Since algal growth doubles with 10 °C temperature rise, an error of 5 °C in the prediction of water temperature might cause 40% overestimation of algal productivity (Bechet et al., 2016). This shows the importance of having a simplified biophysical model as presented in the paper to provide a realistic estimate of water temperature considering altogether the effects of various climatological variables.

3.2. Estimation of growth rate and microalgal productivity

The formulated mathematical model was utilized to simulate the average microalgal growth rate and biomass productivity with the maximum specific growth rate of 3.81×10^{-5} s^{-1}. Patterns of growth rate and biomass productivity is given in Fig. 2b. Maximum average growth rate of 1.93×10^{-5} s^{-1} has been predicted in February corresponding to water temperature of 23 °C and average incident solar insolation of 5.39 kWh m^{-2} d^{-1}. Further increase in the amount of incident radiation increases the water temperature especially in the months of March and April to about 29.82 °C resulting in a slight fall in growth rate, but the decline was very insignificant, as the optimum temperature of microalgae ranges from 10 to 30 °C (Baek et al., 2011).

The predicted values for average daily biomass productivity showed a profile well comparable to the growth rate (Fig. 2b) with the maximum daily average areal biomass productivity projected to be 111.39 kg ha^{-1} d^{-1} in February. The results obtained thus clearly portrays the role of incident sunlight and water temperature on algal productivity. It further suggests the suitability of the selected location as a possible large scale algal cultivation site. Pradhan et al. (2017) reported an experimental biomass productivity of about 20 tons ac^{-1} yr^{-1} (~122.73 kg ha^{-1} d^{-1}) in a coal based power plant in NALCO, Angul, Odisha of India. As far as our knowledge goes there are only very few published articles on such feasibility studies based on the empirical equations governing the microalgal growth at industrial locations. Real time data are also limited owing to industrial perceptions resulting in lack of retrofitting algal cultivation system inside industrial premises. However, areal algal biomass productivities predicted in several other studies at different locations (both experimental and predicted) in Table 1 portrays the consistency of the data as reported by the current predictive model. Marsullo et al. (2015) predicted a microalgal productivity of 191.78 kg ha^{-1} d^{-1} in Petrolina, Brazil. Behera et al. (2018a,b) reported biomass productivity of 170.28 kg ha^{-1} d^{-1} in September at NIT Rourkela, Odisha, India. It is quite evident that

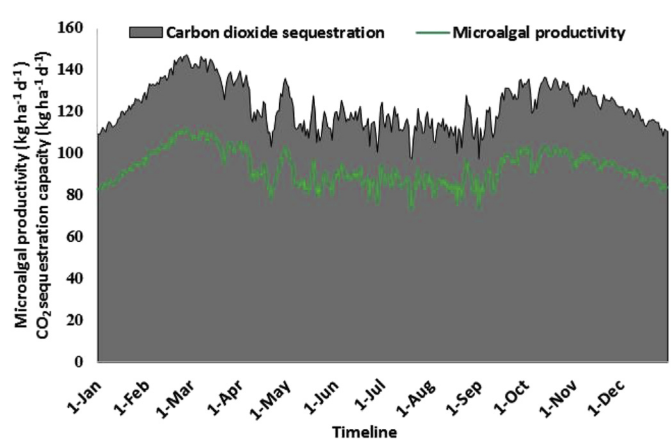


Fig. 3. Averaged carbon sequestration potential of microalgae using the predicted biomass productivity over 365 days.

there is site-specific seasonal fluctuations in productivities. Thus the formulated model could be used further to identify the potential hotspots (climatic variations) to be focussed in order to achieve the desired yields.

3.3. Evaluation of CO_2 sequestration potential of microalgae

The carbon capture potential of microalgae is largely dependent upon biomass productivity. Thus the pattern of CO_2 sequestration follows a profile comparable to that of the biomass productivity (Fig. 3). The predicted maximum average CO_2 sequestered corresponds to a value of 147.03 kg ha^{-1} d^{-1} in February which also showed the highest areal biomass productivity because of the maximum growth rate witnessed during this period. 32 tons ac^{-1} yr^{-1} (~193.98 kg ha^{-1} d^{-1}) CO_2 was reportedly sequestered by large scale algal cultivation (at 89.9% fixation efficiency) in NALCO captive power plant, Angul, Odisha, India (Pradhan et al., 2017). Behera et al. (2018a,b) reported carbon sequestration potential of

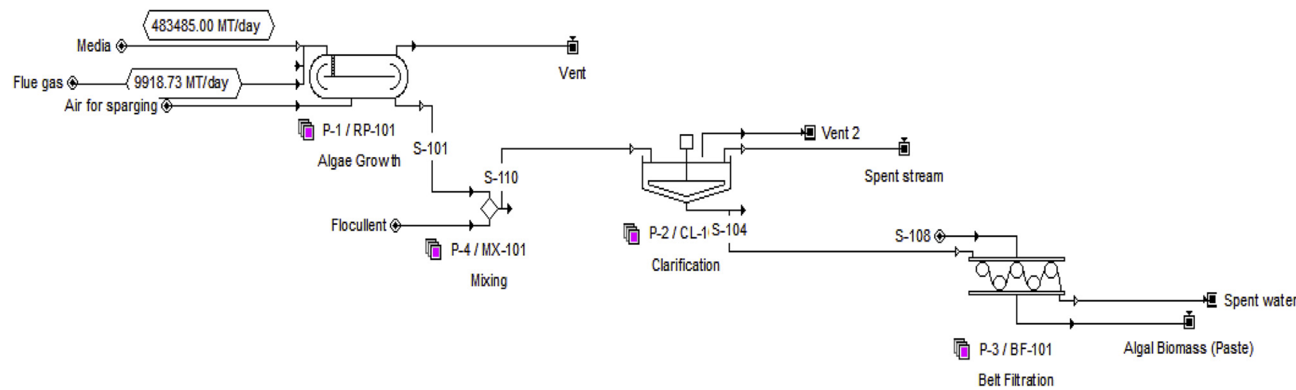


Fig. 4. Process simulation design for integrated microalgal cultivation and biological carbon sequestration at OPGC India.

Table 2
CapEx and OpEx for microalgae based industrial CO_2 sequestration.

Capital Expenditure (CapEx)				
Sl. No.	Equipment Description	Units	Costs/Unit (in M\$)	Total Cost (in M\$)
1	Raceway Pond with area of 1 ha	279	0.16	45.48
2	Clarifier with surface area of 2180.26 m^2	7	0.99	6.36
3	Belt Filter with belt width 3.50 m	202	0.24	48.48
4	Mixer with throughput of 699 MT h^{-1}	29	0.01	0.29
***Plant Direct Cost (PDC)* [in M\$]**				
1.	Equipment purchase cost		125.76	
2.	Installation		49.24	
3.	Process piping		44.02	
4.	Instrumentation		50.31	
5.	Insulation		3.77	
6.	Electrical		12.58	
7.	Buildings		56.59	
8.	Yard improvements		18.86	
9.	Auxiliary facilities		50.31	
	Total PDC		411.43	
***Plant Indirect Cost (PIC)* [in M\$]**				
1.	Engineering		102.86	
2.	Construction		144.00	
	Total PIC		246.86	
	Total Plant Cost (TPC = Total PDC + Total PIC)		658.30	
	Total Contractor's fee (A)		32.92	
	Total Contingency (B)		65.83	
	Direct Fixed Capital (DFC = TPC + A + B)		757.04	
Annual Operating Expenditure (OpEx) [in M\$]				
1.	Raw Materials		160.61	
2.	Labour Costs		16.18	
3.	Facility-Dependent		167.76	
4.	Laboratory/QC/QA		2.43	
5.	Consumables		0.14	
6.	Waste Treatment/Disposal		90.76	
7.	Utilities		2.12	
	Total		439.98	

224.77 kg ha^{-1} d^{-1} at Rourkela, Odisha. Carbon capture ability of microalgae is 100 times higher than the terrestrial plants (Chisti, 2007). As carbon sequestration capacity is a function of algal metabolism and biomass productivity, the difference in sequestration percentage can be witnessed in several studies by Kao et al. (2014), Aslam et al. (2017) and Aly and Balasubramanian (2017). In nutshell, the projected productivities highlight the essentiality of integrating the algal cultivation system at the industrial site for reducing CO_2 emissions, thereby promising a substantial decrease in environmental pollution and alleviation of climate change.

3.4. Economic analysis results

The technique of integrated algal production with CO_2 sequestration was evaluated from the techno-economic perspectives. The process model design for economic analysis is given in Fig. 4. The unit production cost for microalgal paste was determined via stoichiometric calculations using the averaged biomass productivity and carbon sequestration data from the biophysical model and specific assumptions. The annual production capacity of the plant was 4565 metric tonne (MT) of algal paste [wet] based on the operation for 330 days, with CO_2 sequestration capacity of 9918.73 MT d^{-1}. The details of the number of requisite units for each process, and the CapEx and OpEx are represented in Table 2. The net capital investment was calculated to be 819 M$ and operational costs were 440 M$ per year. The equipment purchase, installation and construction occupy 64% of the DFC. CapEx are directly proportional to the equipment purchase costs. The highest costs are associated with the belt filter followed by the reactors, clarifier and the mixing tank. The breakdown of the OpEx is shown

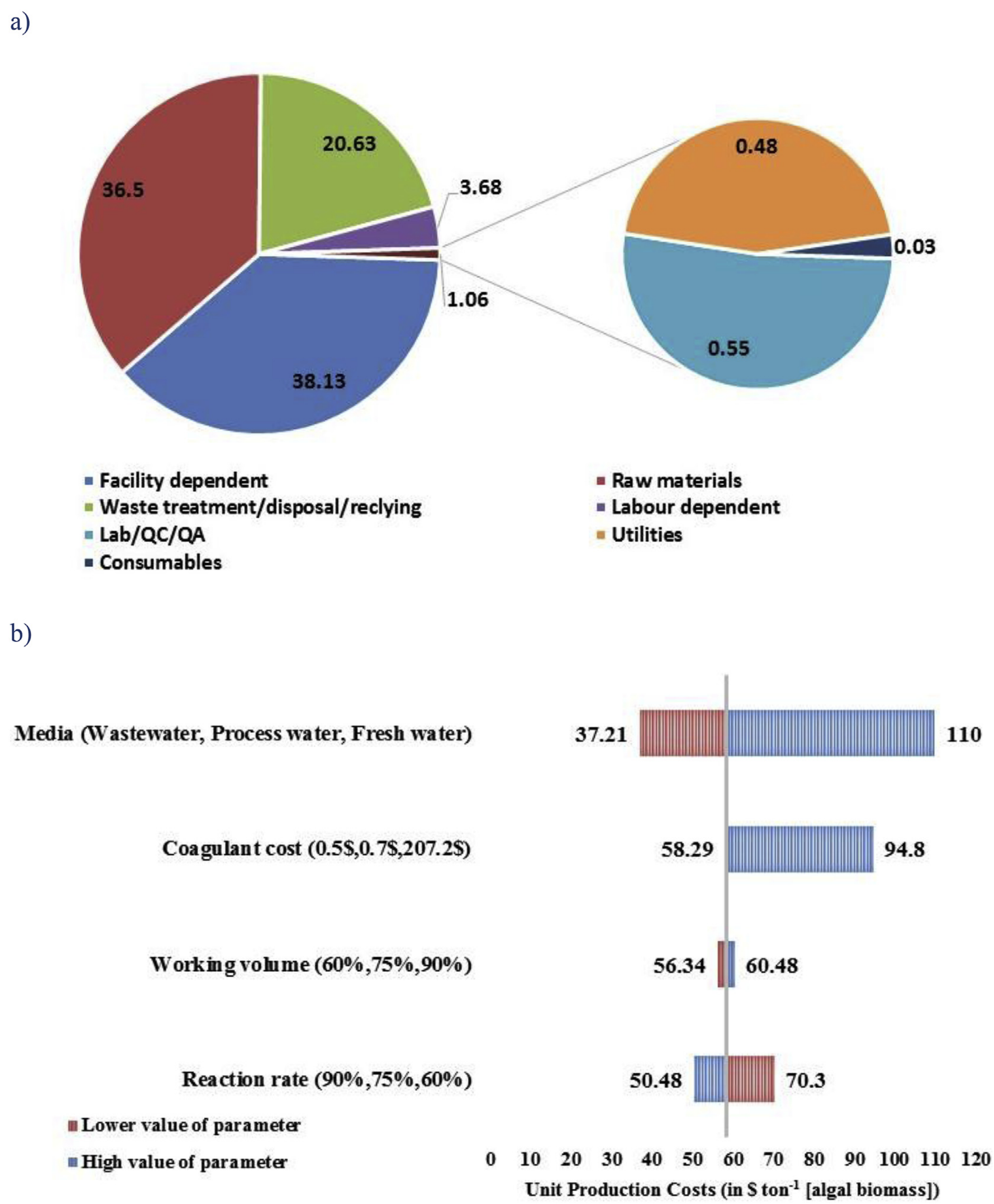


Fig. 5. A). Breakdown of the OpEx b). Sensitivity analysis of the integrated microalgal cultivation and CO_2 sequestration.

in Fig. 5a. Facility dependent costs including depreciation of fixed capital investments, maintenance costs, property/land taxes and other overhead charges account for 38.13% of overall costs. The raw material costs are the second most essential, accounting for 36.50% of the total OpEx. Thus, prices and fluctuations in these two categories would influence the process feasibility. Since the process generates spent water and emissions, additional 20.63% costs are associated with redirecting the wastes for further treatment. Utilities (electricity and steam) occupies less than 1% of the costs, as the process chain does not include any step requiring significant amount of heat. Other categories occupy marginal amount as the process and unit operations involved are simple with no additional complications. Similar reports were also presented in the studies by Banerjee and Ramaswamy (2017) and Juneja and Murthy (2017).

In the base case, the unit production cost is 58.41 $ for 1 MT of algal biomass (paste). The annual carbon credits of 52 M$ could be obtained by the industry with additional revenues of 753 M$ in terms of algal paste which could be used as fertilizer. The gross profit margin of 45.38% was obtained resulting in a payback period of 2.81 years. Overall economics and profitability analysis is presented in Table 3. Acceptable short payback time and reasonable rate of returns is attributed to the relatively low cost of OpEx compared to the yearly revenues. The cash-flow analysis results for a life-time of 15 years is presented in the Supplementary Table 2. The NPV amounts to 1262 M$ at 7% interest rate with IRR of 26.80%. Thus, the proposed method of microalgal carbon sequestration will not only provide environmental protection but would also earn profits in terms of carbon trade.

For the proposed process chain, the LCOE with carbon capture was predicted to be 32.89 $ MWh^{-1} which was 21% higher than the reference plant without carbon capture [LCOE of 27.11 $ MWh^{-1}]. The LCOE for the power plant with carbon capture is larger than the reference plant without carbon capture, due to the additional cost incurred during the capture of CO_2. The cost of CO_2 avoided was projected to be 31.32 $ per tonne of CO_2. Since there are no extensive study related to the retrofitting the algal carbon capture and utilization studies at Indian power plants, the literature related to the LCOE of algal carbon capture is currently unavailable. However, the LCOE reported here is lower than that of values reported for the post-combustion carbon capture at power plants by Viebahn et al. (2014); Hammond and Spargo (2014) and Pieri et al. (2018). Supedkar and Skerlos (2015) projected a 64% increase in LCOE for a pulverized coal power plant incorporating post-combustion carbon capture. The increment in LCOE depends on the type of power plant and the carbon capture technique that is being implemented (Pieri et al., 2018). Thus, the biological carbon capture via microalgae is expected to be a more sustainable method for carbon sequestration which would help in controlling the greenhouse emissions and thereby the climate change.

As different factors involved in the study have a level of uncertainty associated with them and could be subjected to changes, a sensitivity analysis was performed to access the influence of different parameters on the unit production cost. Results obtained from the sensitivity analysis were presented in Fig. 5b. The raw materials costs constitute the major economic drivers of the entire process chain. Cheaper wastewater resources as media, can bring down the unit production costs to 37.21 $ MT^{-1} (algal biomass). Similarly, the use of costly flocculants like chitosan (207.2 $ kg^{-1}) could extend the unit production costs by 62%. Juneja and Murthy (2017) also reported that the economics are dependent on the operational conditions. More efficient the reactor and better the process conversion, higher the reaction rate for the conversion of CO_2, the unit production cost can be brought down to 50.48 $ MT^{-1} (algal biomass).

It is noteworthy to mention that the most of the techno-economic studies reported so far (Rickmann et al. 2013; Juneja and Murthy, 2017) are restricted to the algal growth under laboratory scale and cost of corresponding materials as starting points, thus provide variable estimates. At industrial scale, performance of the system depends on the individual unit performance that is directly dependant on the site-specific algal productivity and carbon sequestration capacity. For instance, Stephan et al. (2002) reported the requirements of 360 ha algal ponds (with sequestration capacity of 14.1 $g\,m^{-2}\,d^{-1}$) to capture the flue gas from 550 MW coal fired power plants in North Dakota, United States. Lindblom and Larsson (2011) proposed 78 ha algal ponds to capture the flue gas from 100 MW power plant at Melbourne, Australia using algae having carbon sequestration capacity of 46.1 1 $g\,m^{-2}\,d^{-1}$. The present study proposed 279 ha algal ponds to capture the flue gas from the 420 MW power plant in Odisha, with microalgal sequestration capacity of 14.7 $g\,m^{-2}\,d^{-1}$. Thus, the algal ponds requirements and the subsequent processing units required are dependent over the power plant capacity, the location as well as the algal performance. This justifies the essentiality of evaluating the microalgal productivity using the site-specific biophysical model including the environmental variables and using it as the base for techno-economic calculations. With the changes in the spatiotemporal variables, the performance of the microalgae thus the carbon sequestration capacity would be changing, hence the requisite number of algal raceway ponds to capture the emitted flue gas would be varying, thus impacting the overall cost economics. Development of location specific growth model with underlying changes in climatologic and environmental variables helps us to determine the algal productivity providing more realistic estimates.

Table 3
Profitability analysis report for microalgae based industrial CO_2 sequestration.

Sl. No.	Categories	Amount
1.	Direct Fixed Capital (A)	757.04 M$
2.	Working Capital (B)	24.52 M$
3.	Start-up Cost (C)	37.85 M$
4.	Total Investment (A + B + C)	819.41 M$
5.	Annual operating costs (D)	439.98 M$
6.	Annual carbon credits (E)	52.37 M$
7.	Annual revenues from algal biomass (F)	753.23 M$
8.	Total Revenues earned per year (G = E + F)	805.60 M$
9.	Net Unit Production Cost (per 1 MT)	58.41 $
10.	Net Unit Production Revenue (per 1 MT)	110 $
11.	Gross profit per year (H = G − D)	365.62 M$
12.	Taxes (in 40%) per year (I)	146.26 M$
13.	Net Profit (H − I + Depreciation)	291.29 M$
14.	Gross margin	45.38%
15.	Return on Investment	35.55%
16.	Payback Time	2.81 years
17.	Internal Rate of Returns (IRR) after taxes	26.80%
18.	Net Present Value (NPV) at 7% interest	1261 M$

4. Conclusions

The biophysical predictive model was formulated conglomerating the physical energy balance and biological growth kinetic equations to predict the microalgal productivity and CO_2 capture capacity at an industrial location. The conclusions obtained are summarised below:

➢ The maximum daily average areal biomass productivity was predicted to be 111.39 $kg\,ha^{-1}\,d^{-1}$ with the maximum growth rate in February resulted in the capture of 147.03 $kg\,ha^{-1}\,d^{-1}$ of CO_2. The industrial site was suitable for mass microalgal cultivation acting as carbon sink for the capture of flue gases.

➢ The proposed technology had unit production cost of 58.41 \$ MT^{-1} with reasonable rate of returns and acceptable short payback time of 2.81 years.
➢ The LCOE with algal carbon sequestration process was 21% higher than the reference process without carbon capture, thus ensuring sustainability of the proposed strategy compared to other post-combustion carbon capture strategies with higher margins after carbon capture strategies.
➢ Yearly carbon credits of 52 M\$ could be earned by the company. Algae based carbon capture technology offers financial benefits while controlling GHG emissions.
➢ Sensitivity analysis revealed that utilization of waste resources and cheaper raw materials with optimal facility/process conditions for better efficiency could improve the overall process economics.

The study is among the first of its kind which integrates the biophysical mathematical model and techno-economic analysis for an Indian coal based power plant. The results presented are promising and can be extended to other industrial locations to access the feasibility of algal carbon capture technology. The results of techno-economic assessment could act as a baseline for implementing algal based industrial carbon sequestration systems.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.02.263.

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