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ABSTRACT

Formidable increase in atmospheric carbon dioxide (CO_2) levels and the economic and environmental unfeasibility of the existing industrial carbon capture technologies have diverted the focus towards microalgae which can trap CO_2, grow and, are processed into value-added products. Despite the enormous potential, the real-time adoption of algae-based industrial carbon capture is still lacking due to the uncertain economics and resource feasibility. Most studies done so far have analysed the economical aspect of microalgal carbon sequestration under varying concentrations of CO_2 and not the percentage of emitted flue gas to be captured. To provide a better insight into the magnitude of scalability of microalgae-based industrial carbon capture the present study aims to evaluate the economic feasibility of capturing 1%, 10%, and 100% of the emitted industrial flue gas. Economic feasibility concerning the product to be harnessed and the uncertainties and risks linked with the input and output cost variables were analysed Algal productivity data obtained from the site-specific biophysical model was used as the input for techno-economic analysis and process simulation in SuperPro Designer® to produce 1 metric tonne of algal biomass as functional unit. Economic analysis revealed the decline in operating costs with decrease in the load of the emitted flue gas. 10% of the emitted flue gas capture scenario was considered favourable in terms of the 75% gross profit margin and lowest payback time (0.93 years). Capture of 1% of the emitted flue gas, reduced the operating expenditure, but, revenues generated are not sufficient enough for the process feasibility. Further, algal biorefinery scenarios were considered more feasible than a single product exploration. Uncertainty analysis showed 75% chances for profitability with variation in operating and capital expenses along with alteration in revenues. Such studies aid in real-time implementation of algae-based industrial carbon capture technologies.

1. Introduction

With the growing population and rapid industrialization, along with having the largest coal reserves, Indian coal consumption as a source of energy has almost doubled from 2006–2007 to 2017–2018 (Trivedi, 2020). India produced 3.1 Gt of carbon dioxide (CO_2) equivalent in 2016, with 50% (1.1 Gt of CO_2) contributed by the coal-based thermal power

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plants (Trivedi, 2020). Indian coal-based power plants contribute to 850–1340 g CO_2 eqv kWh^{-1} electricity depending on the technology and the grade of coal utilized (Nagarkatti and Kolar, 2021). With 6.5% of global CO_2 emissions share, India being the second largest global carbon emitter, followed by China, has experienced detrimental effects of global warming and biodiversity loss, thus the country has committed to reducing its carbon emissions by 60%–85% by 2050 (Viebahn et al., 2014). Over years, the carbon capture and storage (CCS) techniques are regarded as an essential strategy to transform the highly polluted environment and the fossil fuel-dependent scenario into an eco-friendly and clean era (Jin et al., 2020). Tremendous research over the last 20 years has led to the deployment of pre-combustion, post-combustion, and oxy-combustion technologies in developed countries, however, several questions linked to their resource consumption and economic feasibility still exists (Rezvani et al., 2016). An increase in flue gas generation, chemical conversion, and enhanced oil recovery-based mitigation techniques under long-term scaled-up conditions account for more than 1% and approximately 4.8% of CCS (Mac Dowell et al., 2017). However, the above-mentioned processes, similar to the conventional and commonly utilized geological carbon sequestration have challenges linked with the magnitude of measurement of parameters linked to the reactive transfer model during scale-up (Dai et al., 2020). Recently, advanced materials like nano-casted carbon monoliths (Singh et al., 2020), hyper cross-linked adsorbents (Najafi et al., 2021), and polymeric membranes (Khaki et al., 2021) have also been utilized for sequestering CO_2, but unfeasible economics hinders their field-scale usage and long-term implementation in industries.

Alternatively, the typical concentration of 5%–15% CO_2 in flue gas is considered an essential source of carbon for the robust cultivation of algal biomass that could be processed as fuel or in the form of feed/fertilizers, thus generating revenues in addition to environmental protection (Jin et al., 2020). Several laboratory-scale investigations have portrayed a prominent uptake of CO_2 and an increase in microalgal biomass productivity. Yadav et al. (2019) reported a biomass growth of 1.52 g L^{-1} for *Chlorella sp*., with CO_2 fixation of 187.65 mg L^{-1} d^{-1} using 5% v/v of coal-fired flue gas. Aslam et al. (2017) showed that the mixed consortium of microalgae dominated by *Desmodesmus sp*., can be cultured with flue gas containing about 11% v/v of CO_2. Many modelling studies on microalgae have also projected the prominent carbon sequestration capability of microalgae. Gonçalves et al. (2016) through mathematical modelling assessed the effect of different concentrations of CO_2 (4% v/v to 10% v/v) over microalgal growth, thereby projecting an optimal CO_2 concentration of 5.35% v/v is sufficient enough to facilitate growth and nutrient uptake in *C. vulgaris*, *P. subcapitata,* and cyanobacteria *Synechocystis salina* and *Microcystis aeruginosa*. Lababpour (2018) designed a dynamic mass transfer model to simulate real-time mitigation of flue gas predicting systematic removal of CO_2 by *C. vulgaris* in semi-batch mode. Even though this strategy is prophesized to be efficient, the large-scale operation of such facilities is still at its nascent stage owing to the lack of information on economic feasibility risks and uncertainties. Thus there is a need that the simultaneous microalgal growth and carbon capture scenarios must be technically and economically validated to promote its scale-up by attracting investors. Hendriks et al. (2013) reported that the algal production cost could be reduced by a factor of 5–10 times through the utilization of the industrial flue gas for culturing microalgae. Rickman et al. (2013) through an indigenously developed software for techno-economics and life-cycle assessment based on a modular approach predicted that algae-based carbon mitigation technologies are sensitive to the CO_2 gas concentrations and utilization efficiency as well as the total pond area. Rezvani et al. (2016) performed TEA of three different power plant scenarios with CO_2 concentration varying between 4%–14% v/v and with photosynthetic efficiency of microalgae varying from 2% to 6%. The study through sensitivity analysis predicted the variation in selling price in the range of 440–1028 \$ $tonne^{-1}$ under low and high cost scenarios. Behera et al. (2019) predicted a yearly carbon credit of 52 M\$ that could be earned via algae-based carbon sequestration at an Indian coal-based power plant and the process to be sensitive to raw material and operational costs. A recent study by Jaumard et al. (2021) through techno-economic assessment of microalgal carbon sequestration of 1 metric tonne CO_2 per year using a modelled production plant predicted a production cost of 1190 Euros per tonne resulting in 163 kt per year of biofuel.

Over, the last decade, several studies (Thomassen et al., 2018; Valdovinos-García et al., 2020) have been done on techno-economic assessment (TEA) of microalgae as a bioenergy feedstock, but very few as listed above have focused on the factors influencing the industrial microalgal flue gas sequestration. Also, most of these studies consider just the base case (a single carbon capture scenario with different CO_2 concentrations for the entire production chain), without assessing the risks associated with the variation in input percentage of the emitted flue gas or the products to be harnessed that influences the forecasts or the net yearly revenues earned. Since, in a single process, variation in revenues and net present values (NPV) is dependent on the process assumptions, inconsistent boundary conditions often result in inaccurate estimates (Yao et al., 2017). Many of these economic models often follow sensitivity analysis, wherein one input parameter is varied to study the influence over the output variable (Hossain et al., 2019). However, in complex economic models, wherein the profits earned are a function of the costs associated with several input parameters, it is necessary to study the cause and effect process with the simultaneous variation of different cost factors. In lieu of the above-mentioned disadvantages, the Monte Carlo simulation tool is used to generate the probability distribution function for each of the input variables, under a localized scenario to study their effect on the profits earned (Yao et al., 2017). Dai et al. (2014) utilized Monte-Carlo simulation proving 2000 iterations of input parameter set for global sensitivity analysis showing CCS process to be sensitive to reservoir permeability, the distance between injection and production rate, and water alternating with gas cycles. Sharma and Mahapatra (2018) performed probabilistic modelling under multiple constraints to understand the effects of different parameters on amine-based carbon capture systems showing 75% of the capital costs linked with the water cooling facilities. Apart from conventional CCS techniques, the uncertainty analysis and the risk assessment strategies have also been well applied to estimate the variation in the net profits and algal biofuel prices (Tang et al., 2018; Jiang et al., 2019). However, there are no systematic studies until now projecting the variation in carbon credits or total revenues to be earned by the coal-based thermal power plant especially for the Indian sub-continent via analysis of different microalgal carbon sequestration technology scenarios. There is an immense need to perform stochastic TEA data analysis to evaluate the model in a decision-oriented manner to predict the process economics based on the changes in assumptions and input variables to facilitate its real-time implementation.

The present study in order to project the scalability potential of the microalgae-based carbon capture technologies analyses the magnitude of variation in the unit production cost and the enviro-economics of the process chain under different scenarios linked to the percentage of the emitted flue gas that could be redirected into the microalgal ponds keeping the photosynthetic capacity of microalgae constant. The profits earned and the pay-back time variations under different product consideration scenarios, under the biorefinery approach compared to only harnessing a single product are also discussed. The study also analyses the uncertainties associated with the variation in NPV along with the changes in operating and capital costs as well as the revenues earned via risk analysis. Prior to the above-mentioned objectives, the authors in their earlier study (Behera et al., 2019) have simulated the microalgal productivity and carbon capture potential of microalgae using a biophysical model considering the climatological data of a coal-based power plant located in the Jharsuguda district of Odisha, India. The data from the study was utilized as the baseline information to formulate the techno-economic model to assess its feasibility in predicting the revenues that could be earned by the power plant with 100% capture of the emitted flue gas. However, an assessment of the economics linked to a single case scenario (full capture of the emitted flue gas) might not present a profitable and attractive investment for the industry. Thus, as an extension to the previous study, the current research adds a new dimension via the inclusion of the uncertainties and risk analysis to demonstrate different technological scenario-based profitability assessment and facilitate the interests among the industrialists to adapt algal carbon sequestration technologies.

2. Methodology

2.1. Process description and modelling

An integrated microalgae-based carbon sequestration process was considered for the present study. The simulation model is an integration of the biophysical predictive growth and the economic simulation model. The initial section of the study as published earlier (Behera et al., 2019) involved estimating the growth and productivity of microalgae in open ponds as a function of the solar energy and water temperature, considering the fact that only 47% of the incident sunlight is available for photosynthesis and the rest through heat transfer process influences the water temperature. Empirical equations based on the mass-energy balance model taking the average climatological data averaged over the past 20 years as detailed in Behera et al. (2018) were utilized to determine the algal growth rate as a function of solar irradiation and water temperature. The photosynthetic efficiency of 3.26% was obtained accounting for the photoinhibition effects. The biomass productivity and the carbon sequestration were evaluated considering the algal growth kinetics, which has been explained in detail in Behera et al. (2019). The study has considered *T. psuedonana* (being the representative model algae with well-established physiological and growth-related parameters) having the biochemical formulae of $CH_{1.99}O_{0.68}N_{0.15}P_{0.093}$ and molecular weight of 31.8 as the model organism. However, the model could be easily extended to other microalgal strains via the inclusion of specific biochemical and growth parameters. The model assumed several features to reduce the process complexity. The influence of variation of cloud cover which affects the sky temperature via variation in air temperature and relative humidity of a location has not been considered. But, the above limitations were compensated as the model directly accounted for the daily variation in the air temperature and relative humidity. The open pond reactor was assumed to be operated under the semi-batch mode, with the intermittent supply of water and nutrients at a constant dilution rate to restrict the evaporative loss. The entire reactor was assumed to behave as a single unit (unsegregated model) with a specific residence time. The kinetic model does not take into consideration of nitrate or phosphorus consumption, and the growth of algae is expected not to be limited by these nutrients. The shading effect of sunlight due to the neighbouring objects is considered negligible and the night-time respiration loss during the algal growth has also not been accounted for in the study.

The second portion of modelling utilized the average biomass algal productivity and carbon sequestration data to simulate the bioprocess operation starting from microalgal cultivation to harvesting the microalgal wet biomass that could be utilized in the form of biofertilizer. The process flow chain along with the system boundaries for the entire process is shown in Fig. 1. The flue gas from the coal-based thermal power plant (Odisha Power Generation Corporation) situated in the Jharsuguda district of Odisha was assumed to be supplied into the raceway ponds as a carbon source for promoting photo-heterotrophic growth of microalgae. The CO_2 adsorption rate in the microalgal growth medium is dependent on the pond design and operational parameters like the temperature, mixing rate, and other hydrodynamic conditions. The effect of these hydrodynamic parameters along with the pond design considerations influencing the microalgal growth and thereby the CO_2 sequestration capacity have already been accounted for and discussed in detail in the previous studies by the authors (Behera et al., 2018, 2019). Since the study is an extrapolation of the previous work by the authors as mentioned above, wherein the biomass productivity and carbon sequestration data has been integrated into the techno-economic model, the influence of these parameters on CO_2 adsorption rate as well as the overall biomass productivity

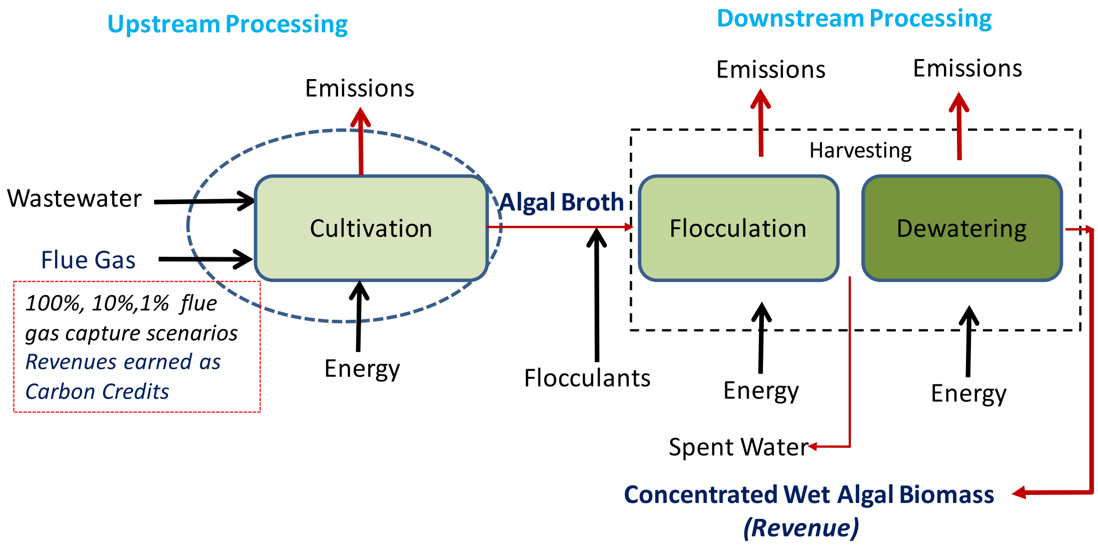

Fig. 1. Process chain and system boundary to be utilized for simulating the techno-economic model [Cultivation stage utilizes the data obtained from the biophysical model as described in Behera et al. (2019)].

and thereby the carbon sequestration capacity has already been considered during the biophysical model formulation. It is assumed that to avoid the inhibitory influence of variation in the adsorption rate of gas with the change in the volume of CO_2 fed into the algal ponds, hydrodynamic parameters like a consistent gas inflow rate and composition was maintained at optimum in each of the scenarios avoiding substrate inhibition in the medium. A similar process strategy has also been outlined in the study by Lababpour (2018). No additional pre-processing steps of flue gas were included based on the fact that the power plant employs electrostatic precipitators to reduce the particulate matter [PM_{10}] and desulphurizer and ammonia flue gas conditioners for limiting the sulphur and nitrogen emissions into the atmosphere respectively (OPGC sustainability report, 2016-2017, 2017). The nitrous oxides left untreated were assumed to be dissolved in the water to form nitrate providing a possible nitrogen source for the microalgal growth (Yen et al., 2015). Even though the addition of nitrous oxides (NO_x) and sulphur oxides (SO_x) is expected to increase the acidic content of medium resulting in the decline of pH to 6.4. Most microalgae are robust enough to sustain well at a pH range of 6.4–8.5 once well acclimatized to the growth conditions, thus resisting the medium changes (Cuellar-Bermudez et al., 2015). Due to the limited data regarding the effect of these gases over the algal growth, their detailed influence has not been simulated here, however, will surely be included during the future improvisations of the model. Further, it was assumed that an optimum gas flow rate and inlet velocity of the flue gas was maintained to keep the pH within the range of 6.4–8.5 so that the amount of CO_2 dissolved will be adequately converted into carbonate and bicarbonate to support the requisite photosynthetic efficiency and biomass growth.

2.2. Goal description and scope of the economic model

The data obtained from the biophysical model was utilized as the input to evaluate the carbon capture capacity of the algal cultivation system as a revenue source, assumed to be co-located inside the industrial premises of a coal-powered power plant in the Jharsuguda district of Odisha, India. The credits to be earned annually were evaluated through the economic simulation model using *SuperPro* Designer software (Intelligen, Inc., Scotch Plains, NJ). The entire process chain for economic simulation consisted (i). mass cultivation of microalgae in open raceway ponds; (ii). harvesting with organic flocculants (iii). dewatering with belt filter to obtain microalgal paste (wet algal biomass) which will be used as algal biofertilizer. The schematic representation of the upstream and downstream processing steps simulated in *SuperPro* has been shown in Fig. 2. The goal of the project was to continuously sequester the flue gas (3.2 million metric tonne produced annually) and grow microalgae, which could be later harvested and utilized in the form of biofertilizer. 1 Metric tonne of wet algal biomass generated to be utilized as fertilizer was taken as the functional unit. It is noteworthy to mention that the heavy metals like As, Pb, Cr, Cu, Co, Ni, Zn, Se present in flue gas due to coal combustion will be injected, and metabolized into the assimilatory form to be utilized during the algal growth in raceway ponds (Hess et al., 2017). The study by Napan et al. (2015) showed that the inorganic heavy metal contaminants upon appropriate dilution will have no negative impacts on the growth of microalgae. Also, as per the safety standards, the study by Napan (2015) on assessment of heavy metal contaminants from flue gas over the end-use of microalgal biomass projected that under the optimum dilution of flue gas in algal ponds, the concentration of most of these ions in the biomass was much below the permissible limit for its utilization as biofertilizers during land application. Thus, the carbon-rich algal biomass obtained

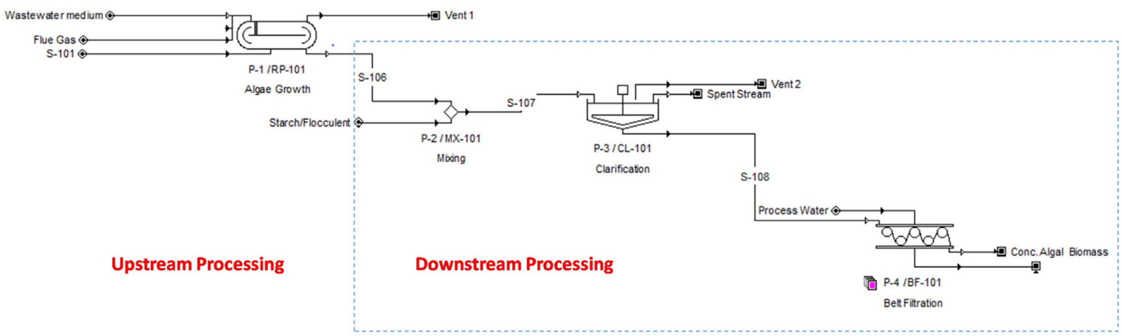

Fig. 2. Process flowsheet generated in *SuperPro* Designer including the upstream (cultivation) till downstream processing stage (generating wet algal biomass as concentrated paste).

via CO_2 sequestration with the minimal amount of heavy metal ions could be utilized as a bio-fertilizing agent, where these ions would also be metabolically aiding plant growth.

The details of the equipment utilized in each of the process steps can be referred to in the previous study by Behera et al. (2019). The purchase costs of equipment were based on the built-in cost model in the *SuperPro* designer software. The algal paste in the form of biofertilizer is taken as the major source of revenue, with carbon credits to be earned per tonne of CO_2 sequestered as the secondary source of revenues for the industry. The profitability of the project was assessed in terms of the cash flow analysis over a period of 15 years to evaluate the gross profit margin, net present value (NPV), and internal rate of returns (IRR). The break-even price and the profitability index were estimated using Eqs. (1) and (2) respectively.

$$Break\,Even\,Price\,(\$) = \frac{Fixed\,costs\,(\$)}{\frac{Contribution\,Margin}{Price\,of\,Product\,(\$) - Variable\,cost\,(\$)}} \tag{1}$$

$$Profitability\,index = \frac{Cash\,Outflows\,(\$)}{Cash\,Outflows\,(\$) + NPV} \tag{2}$$

2.3. Uncertainties evaluation and predictions

Most techno-economic models proposed by the researchers in literature (Rezvani et al., 2016; Behera et al., 2019) often present different contradictory results because of the variation in the system boundaries. Further, the overall economics of any system is also subjected to variation due to the changes in process conditions as well as the operational costs involved and the annual revenues that could be earned. In an attempt, to negate the above-mentioned issues, the present paper has considered different feasibility scenarios based on the variation in the process operation indirectly influencing the economics and the impact of the revenue streams under the biorefinery approach. Risk assessment based on the changes in the overall operational and sales costs through probabilistic distribution function was also evaluated.

The first phase of the uncertainty study evaluated the changes in the economics of the process with the variation in the feed or the percentage of the emitted flue gas that could be directed for capture into the raceway ponds. The scenario for directing the entire flue gas (100%) generated by the power plant over a year was considered as the base case (Scenario S100). Two different case scenarios were evaluated by changing the flue gas amount to be injected per year to 10% and 1% of the total flue gas emitted were considered as Scenario S10 and Scenario S1 respectively. The changes in the total electricity consumption, as well as the environmental impacts in terms of the gaseous emissions, aqueous and organic waste generated with changes in operational process, was also analysed. To the best of the authors' knowledge unlike the previous studies (Rickman et al., 2013; Rezvani et al., 2016), where only the variation in the concentration of CO_2 injected into the photobioreactors were considered, the present study is one of the first of its kind to study the variation in revenues with changes in feed related to the percentage of the emitted flue gas injection. The major aim of the study was to evaluate the influence of the magnitude of scaling down the microalgae-based biological industrial carbon sequestration to access the different feasibility scenarios, that would generate profitability for the industry. Since, piloting at 1% to 10% of the full manufacturing scale provides unique benefits and risk reductions (Crater and Lievense, 2018), the present research interpolated the 100% volume of flue gas that could be injected into the raceway ponds for simultaneous carbon sequestration and microalgal cultivation. The entire process chain has been kept the same, with the bioprocess simulations and techno-economic validation being done with a scale of 1%–10% to mimic the laboratory scale that could remain as close as possible to the real-time process conditions. The scenario represented as S100, S10 and S1 represent the variation in the volume of injected flue gas with each having 8%–15% CO_2 concentration that is being fed under optimal flow rate into the microalgal raceway ponds, facilitating the appropriate dissolution of the gas into carbonate and bicarbonate ions, which could be assimilated by microalgae. Keeping the pond design and microalgae-specific parameters constant, to treat the requisite fraction of flue gas, the study projects the minimum amount of raceway

Table 1
Assumptions utilized for the economic model.

Parameters	Value
Total no. of working days	330 days
No of unit process	4
System	Continuous microalgal carbon sequestration
Plant life for cash flow analysis	15 years
Method for cash flow analysis	Straight line depreciation method
Taxes	40%
Inflation rate	4%
Equity	100%
Installation costs	20% of equipment purchase cost
Maintenance costs	20% of equipment purchase costs
Working capital	3% of fixed capital costs
Start-up cost	5% of fixed capital costs
Piping	10% of plant direct costs
Building and Yard improvement	18% of plant direct costs
Contractor fee	8% of plant direct costs
Contingency	16% of plant direct costs

ponds needed, and subsequently, the clarifier and the belt filter units to process the algal biomass. Furthermore, analysing the net investment made to the project in each case and evaluated the profitability associated with each of the scenarios.

The second phase of analysis for assessing the process economic feasibility involved three different scenarios considering (i). the algal paste and the carbon credits as the source of revenues (Scenario R1) (ii). Only the microalgal paste as biofertilizer as the revenue (Scenario R2) (iii). Only the carbon credits earned as the revenue source (Scenario R3).

The third phase of the study evaluated the uncertainties and risks associated with the overall changes in operational and capital expenses as well as the revenues earned annually. The cash flow analysis data from the base case of trapping 100% of the emitted flue gas was modelled using the Monte Carlo simulations through forecast for the probability distribution function in Oracle Crystal Ball software. The risks were evaluated by varying the operating and fixed capital costs by $\pm$ 50% assuming a triangular distribution. The variation in overall revenues was assumed to follow the normal distribution. The taxes in the range of 40%–60% were considered with a uniform probability distribution assumption. The cost assumptions followed here were similar to the studies done by Lundquist et al. (2010) and Davis et al. (2014). The overall influence of the above-mentioned parameters was studied from the frequency distribution curve considering the NPV as the forecast parameter. The sensitivity analysis was also done to access the level and degree of influence of the individual input variables over the NPV.

2.4. Assumptions and limitations of the model

The overall project lifetime was assumed to be 15 years, with a 2-year construction period during the cash flow analysis for all the case scenarios as described previously. During the construction period, a straight line capital depreciation was assumed. The tax rate was assumed to be at 40% based on the current practices for tangible assets. The costs of piping, warehousing etc. have been accounted for in the fixed capital calculation as the indirect expenditure. Details of the assumptions made in the economic model are provided in Table 1. Unlike other models available in literature as those presented by Rezvani et al. (2016) and Pérez-López et al. (2018), the present simulation provided the simplified basic sequential four-unit process, intending to capture the industrial flue gas and obtain 1 metric tonne of algal biomass that could be sold as biofertilizer. The Odisha Power Generation Corporation (OPGC) occupies a total project area of 1416.4 ha, a large fraction of the area remains for non-forest activity (OPGC annual report, 2018-2019, 2019). About 34% of the area is covered with plantations and green belts. Thus, algal open ponds with 100 times higher sequestration potential than the terrestrial counterparts are expected to provide an added advantage of increased carbon capture, thus facilitating the company not only to meet the corporate social responsibility but also to earn tax reductions thereby positive incentives. Assuming the algal carbon sequestration system to be co-located inside the industrial premises, no additional costs incurred by the land occupation was considered based on the exemption and relaxation of the floor area or additional land cost as per the Odisha Land Reforms Act, 1960 (Directorate of Industries, Odisha, 2012). Since, the company as per the land acquisition policies, applicable acts, and rules of the Industrial Infrastructure Development Corporation or the Government of Odisha/District Collector already pays the land and associated service charges, it is assumed that no extra charges will be needed (OPGC annual report, 2018-2019, 2019). Also, no additional expenditure related to the development of infrastructure for redirecting the flue gas into the algal ponds was included assuming the industry that has necessary provisions.

3. Results and discussion

The base case scenario to capture the net flue gas generated annually via microalgae-based growth has also been elucidated previously. The algal growth rate and the biomass productivity thereby the carbon sequestration capacity

Table 2
Economic assessment of different emitted flue gas capture scenarios.

Parameters	100% flue gas [S100]	10% flue gas [S10]	1% flue gas [S1]
Total capital investment ($)	819,406,000	52,473,000	8,789,000
Operating cost ($/year)	439,984,000	29,125,000	5,566,000
Total revenues ($/year)	805,599,000	110,012,000	11,029,000
Cost basis annual rate (kg/year)	7,532,284,019	1,100,122,246	110,287,353
Gross margin (%)	45.38	74.73	51.82
Return on investment (%)	35.55	107.21	49.56
Payback time (years)	2.81	0.93	2.02
IRR (after taxes) (%)	26.80	68.52	34.30
NPV (at 7.0% interest) ($)	1,261,381,000	3,497,350,000	21,543,000

is influenced by the local solar irradiance received and its subsequent effect on the water temperature of open algal ponds (Behera et al., 2018). The detailed description of the variation of algal growth rate as a function of incident solar insolation and water temperature and its effect on biomass productivity and carbon sequestration capacity has already been explained by Behera et al. (2019). The scalability of the project and further the process stability and consistency under different process operations as well as variation in costs incurred during different scenarios of the project have been presented in subsequent sections.

3.1. Uncertainties associated with the process conditions of varying flue gas capture scenarios

3.1.1. Variation in investment and rate of returns considering different percentages of the emitted flue gas capture scenarios

Considering the supply of 100% of the emitted flue gas into the algal carbon sequestration facility (Scenario S100), total capital expenditure of 819 M$ will be incurred, with an operating expense of 439 M$. With 4 unit steps and the concentrated microalgal paste as a source of major revenue along with the sequestered flue gas as a source of secondary revenue, the industry is projected to earn 805 M$ per annum with 52 M$ as carbon credits. To study the influence of flue gas supply percentage over the process economics, two different case scenarios were also modelled with the emitted flue gas supply of 10% and 1% into the algal sequestration ponds, named as Scenario S10 and S1 respectively. It was observed that the reduction in the emitted flue gas supply to 10% keeping the photosynthetic capacity of microalgae constant, results in a decline in capital and operating expenditures by 94% each, thereby improving the process economics. In the second case (Scenario S10), 110 M$ of revenues could be earned annually resulting in a payback time of 0.93 years. Assuming the capture of the entire flue gas emitted over a year, the number of algal ponds required was 279, while in case of the capture of only 10% of the total emitted flue gas released in a year, the number of algal ponds was reduced to 3 and just 1 pond was needed to trap 1% of the net industrial emissions respectively. It is well evident that the decline in the number of equipment results in a decrease in capital and operating costs, which in turn increases the internal rate of returns (IRR). It could be envisioned that the large land requirement and initial investment involved with the 100% capture of the emitted flue gas might not be favourable enough for the industry, however, with just 10% injection of the emitted flue gas, the process economics are much more attractive to convince the stakeholders for real-time implementation of the carbon sequestration technologies. Further decline in the supply to 1% of the total emitted flue gas, as evident in Table 2, even though the capital and the operational costs reduced compared to the first two scenarios, the payback time was found to be more (2.02 years) than that obtained with 10% of the total flue gas supply. This might be attributed to the fact that with the decline in the supply of flue gas, the amount of microalgal wet biomass generated declines, thus the revenues earned is not sufficient enough to balance the investment costs incurred, thereby resulting in higher payback time and a lower rate of returns in case of Scenario S1 compared to Scenario S10. Changes in the amount or type of input raw materials or processes under the same time horizon can influence the investment scenarios, and these uncertainties have an overall impact on the returns as well as the payback time (Junqueira et al., 2017). The uncertainty assessment study done by Pérez-López et al. (2018) reported that microalgal productivity and efficiency of production are sensitive to the process conditions during the growth and cultivation stage.

3.1.2. Profitability assessment in different flue gas capture scenarios

The economics of industry is dependent on the process conditions. The profitability of an industry depends on different metric factors like the break-even price (BEP), gross profit margin, and probability index (PI) (Fig. 3). Break-even price (BEP) is the minimum pricing of a product that would be sufficient enough to generate revenues for the company to start making profits. For 100% of the emitted flue gas capture, the BEP was found to be 632 $ per tonne of algal biomass, which was observed during the start-up of the company after 2.81 years of payback time. A reduction in BEP to 304 $ and 436 $ was achieved for a tonne of algal biomass, with 1% and 10% flue gas capture respectively after 0.93 and 2.02 years respectively. The above trend can also be easily corroborated with the gross profit margin and the profitability index. A higher gross profit margin and a profitability index greater than 1 are desirable for attracting investors or venture capitalists to invest in the scheme. For the first scenario (S100), a gross margin of 45% was obtained with a profitability

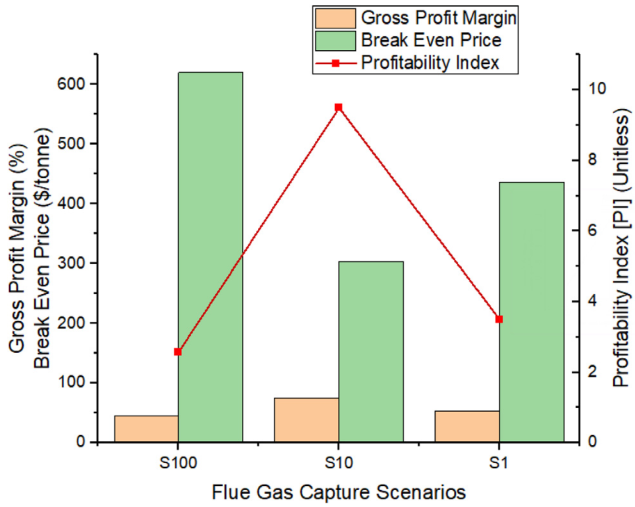

Fig. 3. Gross profit margin, break even price and profitability Index for 100%, 10%, and 1% of the emitted flue gas capture scenarios represented as S100, S10, and S1 respectively.

Table 3
Energy and environmental impacts of different emitted flue gas capture scenarios.

Parameters	S100	S10	S1
Electricity consumption (Thousand kWh/year)	2120	178	84
Aqueous wastes (Million tonnes/year)	9966	788	157
Organic wastes (Tonnes/year)	822	60	8
Emissions (Million tonnes/year)	29.8	1.112	0.112

S100 represent the scenario for 100% flue gas capture; S10 represents 10% flue gas capture scenario; S1 represents 1% flue gas capture scenarios.

index of 2.57 was obtained. The gross profit margin and profitability index increased to 75% and 9.49 respectively for 10% of the emitted flue gas capture and was subsequently declined to 52% and 3.50 respectively with 1% flue gas supply. Thus, the study shows that 10% of the emitted flue gas capture might represent the appropriate scenario or portfolio to earn additional revenues for the company. In case of values less than 1% of flue gas injection volume i.e. 0.1% and 0.01% (data not presented in the present study), the net present value was found to be negative as the total biomass obtained and carbon credits earned might not be sufficient enough to overcome the expenditure met by the company. Thus, going below 1% capture might not be favourable enough for the industry to earn the requisite profits and incentives. Also, it is noteworthy to mention that intermediate capture of any volume of flue gas between S100 to S10 (100% and 10% of volume of flue gas) and further decline to S1 (1% of the volume of flue gas) will show a similar trend of the profitability metrics. Similar, to the present conclusion, the report published by the U.S. Department of Energy on microalgae farming for carbon capture and utilization, Algae cultivation for carbon capture and utilization workshop summary report (2017) through an attendee poll survey reported that the percentage of flue gas emissions captured that would benefit the emitter was found to be 10%–30%, compared to the capture of 100% and less than 1% of the emitted flue gas.

3.1.3. Evaluation of the energy and environmental emissions based of different flue gas capture scenarios

A major share of the costs incurred during the process is determined by the amount of energy consumed during the different unit processes. As evident from Table 3 due to the decline in the amount of flue gas that has to be processed by the microalgal sequestration system, the amount of equipment utilized declined, thus the electricity consumption also declines gradually from Scenario S100 to S10. In all the scenarios, cultivation consumed the highest energy ranging from about 60%–78%, followed by belt drying or dewatering. Thomassen et al. (2016) and Pérez-López et al. (2014) also reported that the maximum energy requirements to be linked with the supply of CO_2 and mixing during the cultivation phase of microalgal biorefinery.

SuperPro designer categorizes the total waste streams generated during the simulation into three different categories i.e. (i). Organic waste (ii). Gaseous emissions (Carbon and Nitrogen emissions) and (iii). Aqueous wastes. The assessment of the overall environmental impacts (Table 3) revealed that the total emissions along with the organic waste generation also declines drastically with the change in process conditions. Maximum emissions were linked with the cultivation process in all the case scenarios, while the maximum organic wastes were generated in the clarification or the flocculation stage. Pérez-López et al. (2014) reported that 93% of environmental impacts are associated with the cultivation stage followed

Table 4
Economic assessment of different product revenue scenarios.

Parameters	Scenario R1	Scenario R2	Scenario R3
Total capital investment ($)	819,406,000	819,406,000	819,406,000
Operating cost ($/year)	439,984,000	439,984,000	439,984,000
Main revenue ($/year)	753,228,000	753,228,000	52,371,000
Other revenues ($/year)	52,370,912	0	0
Total revenues ($/year)	805,599,000	753,228,000	52,371,000
Cost basis annual rate (kg/year)	7,532,284,019	7,532,284,019	3,273,182,000
Unit production cost ($/Tonne)	0.06	0.06	0.13
Unit production revenue ($/Tonne)	0.11	0.10	0.02
Gross margin (%)	45.38	41.59	−740.13
Return on investment (%)	35.55	31.71	−38.53
Payback time (years)	2.81	3.15	N/A
IRR (after taxes) (%)	26.80	23.83	N/A
NPV (at 7.0% interest) ($)	1,261,381,000	1,035,765,000	−3,023,312,000

R1 represents the scenario with algal biomass (as biofertilizer) and carbon credits as the revenue source; R2 represents scenario with only algal biomass as biofertilizer as the source of revenues; R3 represents scenario with only carbon credits.

by the inoculation and sterilization process. 2996 million tonnes per year of aqueous wastes were generated from the spent stream from the belt dryer and clarifier in S100, followed by 788 million tonnes per year in S10 and 157 million tonnes per year in S1. Thus, it shows the enormous potential of the spent water that is being produced and could be recycled and utilized as a culture medium during the process of cultivation. Thomassen et al. (2016) also showed that the recycling of the spent water with unused nutrients back into the cultivation phase not only reduces the nutrient demands and the water footprints but also decreases the costs linked with its disposal. Thus, the microalgal carbon sequestration generates avenues with much lower water consumption compared to the amine-based capture process which has huge water footprints (Sharma and Mahapatra, 2018).

3.2. Impact of the biorefinery based scenarios over the process economic feasibility

The economic feasibility of a process depends on the revenues obtained from the product streams (Table 4). With 100% of the emitted flue gas capture scenario, considering the wet algal biomass that could be applied as biofertilizer and carbon credits (Scenario R1) as the sources of revenues, a gross margin of 45.38% and rate of returns (ROI) of 35.55% was obtained, resulting in a payback period of 2.81 years. With only wet algal biomass as the revenue stream (Scenario R2), the gross margin reduces to 41.59% increasing the payback time to 3.15 years with 31.71% ROI. In the case of Scenario R3, with only carbon capture as the source of revenues, the process seems to be economically unfeasible with a negative gross profit margin, payback time, and ROI. This could be attributed to the fact that the revenues earned were less than that of the costs invested for the process, thus cannot generate any profits. This verifies the fact that the biorefinery concept with the exploration of multiple products/process is always more feasible compared to the profitability earned with only one targeted product. Similar to the present study, Batan et al. (2016) described that the economic feasibility of a process is sensitive to the coproducts allocation under different market scenarios. AlMahri et al. (2019) also reported that the utilization of only proteins will have a payback period of 6.38 years, whereas the inclusion of proteins, pigments, and fatty acids in a biorefinery approach would improve the process feasibility and bring down the payback time to 2.62 years. Thomassen et al. (2018) showed that the biorefinery approach of exploring β-carotene as well as biofertilizers is techno-economically more favourable and also might reduce the uncertainties in costs during the project start-up attracting more funding agencies.

3.3. Risk assessment for algal carbon sequestration scenario

The supply of 100% flue gas into the algal ponds with 10%–15% CO_2 concentration is considered a favourable scenario for algal growth (Nagappan et al., 2019). However, the technical uncertainties causing variation in operational costs as well as the market uncertainties influencing the prices of revenues earned and the capital expenses influence the process feasibility. The inherent variability in the input parameters influences the model prediction, thus uncertainty and sensitivity analysis is done to take into account the impact of simultaneous changes in each factor over the output/response (Pianosi et al., 2016). Statistical risk assessment was done using the Monte Carlo simulation method to evaluate the impact of variation in capital and operating expenses over the profits of the overall process. The impact of process parameters was evaluated through uncertainty and sensitivity analysis. The uncertainties associated with the frequency of the NPV considering 50% variation in the operating and capital expenses, assuming a normal and uniform distribution of the revenues and taxes respectively were analysed. As evident from Fig. 4a. there is a 75% certainty that the process will be profitable with a positive NPV and a 25% chance that the variation in operational and capital costs with relatively fewer revenues might cause a failure/loss resulting in a negative NPV. Unlike uncertainty analysis, which determines the variation in NPV, the sensitivity analysis shows the impact/relative contribution of the factors to the

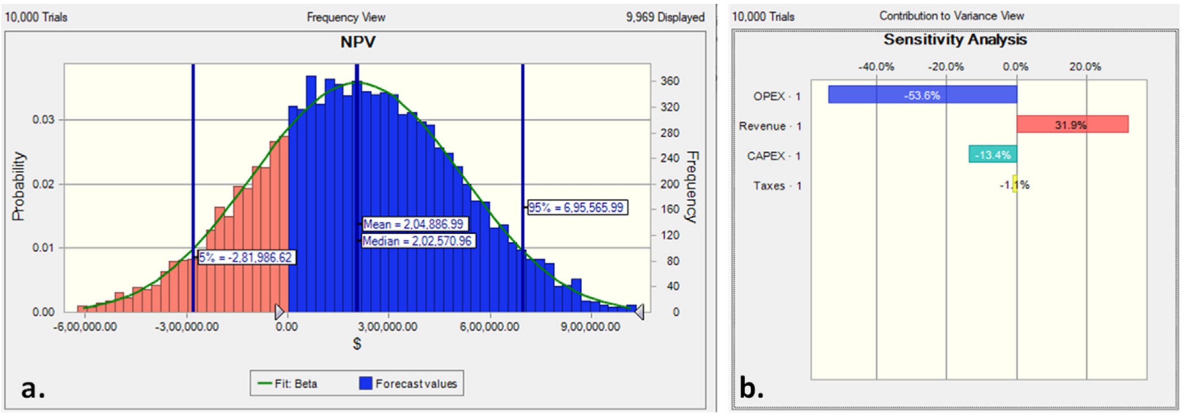

Fig. 4. (a). Probability distribution and (b). Sensitivity analysis of variation in influencing factors over Net Present Value (NPV).

overall variation in output observed (Campolongo et al., 2011). Further, the sensitivity analysis (Fig. 4b) revealed that the process is significantly influenced by the operating costs (53%) followed by the revenues (33%) earned and the changes in capital expenses (13%). Apart from the cost-related parameters, the overall process economics of microalgae-based carbon sequestration can also be influenced by the microalgal growth conditions. The economic variations concerning the factors like the microalgal growth medium, the reactor volume, and the harvesting agent have been previously described in detail by Behera et al. (2019). The microalgae-based carbon sequestration process was found to be sensitive to the cost of the raw materials utilized during the process of cultivation and harvesting. Economics of the entire process could be reduced via the utilization of wastewater resources during cultivation. Similarly, an increment in process costs by 62% was evident with the utilization of costly synthetic organic flocculants. Also, the reactor volume and the facility-dependent conditions were found to have a significant impact on the entire production cost.

4. Conclusion

The present study evaluated the magnitude of scalability of the microalgae-based industrial carbon capture by varying the percentage of the emitted flue gas to be captured via algal open ponds, and analysing the stability of the technology in terms of the products harnessed and, risks linked with the investments and revenues of the process chain. The economic feasibility was found to be dependent on the process conditions that influenced the capital and operational expenses as well the total revenues earned. 10% capture of the emitted flue gas was considered to be the most environmentally friendly and profitable scenario with total revenue of 110 Million US $ per year, having a payback time of 0.93 years. This would also aid in helping the industry to fulfil corporate social responsibility, thereby enhancing the positive incentives and resulting in significant tax reductions. An adequate amount of flue gas supply was necessary to generate an appropriate amount of algal biomass that could be sold as additional revenue, generating profits. The energy consumed as well as the environmental impacts were also found to be influenced by the process conditions. The cultivation step had the major share of energy consumption followed by the dewatering stage. The biorefinery scenario with the exploration of multiple revenue streams as in wet concentrated algal biomass as biofertilizer and carbon credits was found to be more profitable than the use of a single product. A simultaneous variation of the capital, operating expenditure along with the revenues earned by the companies showed the process to be 75% certain to generate profits. The economic model being simple and comprehensive can easily be extended to other industrial locations and estimate the carbon capture potential of different microalgal species. Despite the process simplicity and variability, the conclusions obtained can easily be corroborated with the state of art algal carbon capture technologies. Since it is cumbersome to convince the industrial stakeholders with a single microalgae-based carbon capture process chain, evaluation of different possible technological alternatives and risks linked with the investments is essential to provide a clear-cut idea about the profits or incentives to be earned herewith. Such uncertainty evaluation can provide a more systematic and robust understanding of the profitability metrics of microalgae-based industrial flue gas capture scenarios, thereby averting the confusion regarding the investments/funding needed for industry-level process implementation especially in Indian scenarios.

CRediT authorship contribution statement

Bunushree Behera: Conceptualization, Experimentation, Data analysis, Writing – original draft. **Balasubramanian Paramasivan:** Conceptualization, Investigation, Funding acquisition, Writing – review & editing, Final approval.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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