Optimization upstream CO_2 deliverable with downstream algae deliverable in quantity and quality and its impact on energy consumption

Ziyu liu[1,2], Chaozong Liu[2], Shujun Han[1], Xiaoyi Yang[1]*

1.School of Energy and Power Engineering, Energy and Environment International Centre,
Beihang University, 37 Xueyuan Road, Haidian District, Beijing, P.R. China, 100191
2. Research Department of Materials and Tissue, University College London, UK

* Corresponding Author: Xiaoyi Yang
Address: 37 Xueyuan Road, Haidian District, Beijing, P.R. China, 100191
Tel.: +86-01-82317346
Fax: +86-01-82317346
E-mail: yangxiaoyi@buaa.edu.cn

Highlight

- Establish quantitively relationship of algal growth and CO_2 fixation efficiency
- Correlation of upstream flue gas and downstream CO_2 biofixation product choice
- Effects of algae growth rate and protein contents on energy consumption
- Effects of initial CO_2 concentration on algal products quality
- key impact factors extracted by the sensitive uncertainty analysis

Abstract

Algae CO_2 biofixation provides a promising opportunity due to earn carbon credits and valuable end uses. For balancing technology, energy and economy issues in practical utilization, this approach quantitively interprets the contradictions from upstream CO_2 source with a wide range of initial concentration to downstream CO_2 biofixation product including edible algae and algal biomass. The influence of upstream CO_2 deliverable on algal quantity and quality have been assessed, and the influence of CO_2 concentration on CO_2 transport mode choice has been also assessed coupling the transportation distance. In downstream algal fixation, quantitively relationship of algal growth have been established. The assessment discovered that direct energy consumptions complied with logarithmic relationship with specific productivities while both direct energy and indirect energy consumption complied with linear relationship with protein content. According to sensitive uncertainty analysis, initial CO_2 concentration is a critical parameter to influence significantly energy consumption in upstream CO_2 deliverables and algal quality while the contents of protein and specific productivity are the critical sensitive parameters in downstream algae deliverables. Potential modification systems are achieved for significantly reducing energy consumption by improving specific productivity and carbon abundance with low protein content in algae.

Keywords: LCA; CO_2 biofixation, CO_2 transportation, CO_2 purification, edible algae, energy consumption

1. Introduction

Algae-based CO_2 mitigation provides a promising opportunity to reduce CO_2 and earns carbon credits due to valuable end uses and lower safety requirement in comparison with CO_2 storage. As higher efficiency of photosynthesis means higher carbon dioxide consumption, algae fix CO_2 10–50 times faster than terrestrial plants by solar energy (Packer, 2009). Moreover, algae can be cultivated as nutrients for healthcare (Toledo-Cervantes et al., 2018) or as feedstock for biofuel (Kassim and Meng, 2017). However, there are lack of the quantitively assessments to balance technology, energy and economy issue for fixation product choice of edible algae or algal biomass.

Spirulina platensis has been considered as the most promising algae strains to fix CO_2 due to fast growth rate, good tolerance on high concentration of CO_2 and insensitive to high temperature, nutrient deficiency and pH flocculation. In addition, *Spirulina platensis* takes an advantage in economic competitiveness due to highly valuable bioactive compounds with improving the immunity of organism (J. Matos et al., 2017) and preventing aging (Shabana, et al., 2017).

From the respect of algal CO_2 fixation, CO_2 concentration and pollutant limitation are critical research hotspots (Fu et al., 2019, Ma et al., 2019). Flue gas from coal power industries and coal chemical engineering activities usually contain a small amount of SO_X and NO_x, which can inhibit algae growth by direct or indirect toxicity (Negoro, et al.,1991). SO_2 above 60 ppm in flue gas inhibited the growth of almost all species of microalgae (Zhao, et al., 2014), and all species were completely inhibited when the flue gas contained SO_2 200 ppm (Hauck, et al.,1996). Some kinds of algae have showed good tolerance to NO_X and some even conducted the limited positive effect when NO_X below 300 ppm (Kumar, 2010). However, the dissolution of NO in the aqueous phase is the rate-limiting step and thus further define NOx concentration in flue gas. CO_2 concentration influences have been controlled pH flocculation by CO_2 provision but CO_2 absorption efficiencies changed from 75% at CO_2 15% to 90% at pure CO_2 (Lundquist et al., 2010). The current research indicates that CO_2 source as algae cultivation should achieve SO_X less than 60ppm, NO_x less than 300ppm, and NO less than 60ppm but with a wide range of CO_2 concentration.

In respect of CO_2 transportation requirement, tanker or pipeline is usually carried CO_2 in liquid phase except on-site utilization because the volume of liquefied CO_2 is only 1/500 of CO_2 gas. In order to ensure a stable single-phase flow through the pipeline for avoiding plug in two-phase flow, CO_2 pipeline with long distance have to be controlled above CO_2 95% (Forbes, et al., 2008). For supercritical form, CO_2 should be further compressed above 8 MPa at ambient temperature (Ancel, et al., 2009) for reduction of the volume. In order to optimize mass/volume ratio for CO_2 transportation by pipelines, liquid at pressurized or supercritical conditions is the preferred state for

CO_2 as dense phase (Johnsen, et al., 2011). The current research indicated that tankers are more competitive for shorter distance and lower volume loads while pipelines transport conduct attractively for high volume load through long distances at wide deployment.

The LCA methodology has been applied to optimize complex system in order to obtain benefit in environmental, economic and energetic performance. LCA had been carried out to enhance CO_2 sequestration by storage but less research focuses on algal biofixation from CO_2 source and its related with the algae quality. Although research of LCA had been carried out to modify algae product, but most mainly focused on the final product, such as jet biofuel (Yang, et al., 2016, 2017), biodiesel (Dickinson, et al., 2017), nutrient (Chensong, et al., 2018). The system boundaries usually initiate from algae cultivation to algae-related product with CO_2 only as the input of material. There is lack of the detail discussion of the relationship of upstream of CO_2 capture and purification to downstream algae in quality and quantity.

Whatever the final product of CO_2 fixation is edible algae or algal biomass, a low energy consumption with an economical feasible system is critical in CCU (Leung, et al., 2014). The aim of this work is to assess the potential reduction in energy consumption related with upstream flue gas source to downstream CO_2 fixation product. The energy consumptions in the whole life cycle have been quantitatively based on *Spirulina platensis* cultivation. The potential modification systems of CO_2 biofixation were discussed for reducing the total energy consumption and benefit for biofixation product choice.

2. Methodology

2.1 Goal definition and system boundary

To obtain benefits in energy consumption and algae in quantity and quality, the boundary of life cycle started from CO_2 source with a wide range of initial concentration and terminated at CO_2 biofixation product including edible algae and algal biomass, given in Fig.1. The functional units were set at energy consumption per kilogram of carbon dioxide fixation (MJ/ kgCO_2) and energy consumption per kilogram of algae (MJ/ kg algae) in life cycle assessment.

Fig. 1. System boundary definition of CO_2 algal fixation

For edible algae, CO_2 source after purification for algae cultivation should match edible safety requirements. For algal biomass, CO_2 source should achieve algal growth requirement. The purification of CO_2 source should comply with the requirement of CO_2 transportation, including low pressure pipeline, pressured pipeline, supercritical pipeline, heavy duty truck, and medium duty truck.

In compliance of CO_2 as basic substance flow in life cycle, the system boundary was classified into 4 stages, including CO_2 capture and purification, CO_2 transport, CO_2 distribution and absorption, and CO_2 biofixation product. The input and the output of energy and material have been involved in the system.

2.2 Computational framework and methods

The computational framework contains sub-models based on 4 stages including CO_2 capture and purification, CO_2 transport, CO_2 distribution and absorption (algae cultivation), and CO_2 fixation (*Spirulina platensis*).

In sub-model of CO_2 capture and purification, flue gas with a wide range of CO_2 concentration were captured and purified to edible requirement or algal cultivation requirement by technologies including absorption, adsorption, member separation, and cryogenic distillation. In sub-model of CO_2 transport, feasible transportation modes are involved in this study including tankers and pipelines related with the distance and CO_2 concentration. In sub-model of CO_2 distribution & absorption, raceway pond and photobioreactor are chosen to cultivate *Spirulina platensis* for CO_2 absorption. In sub-model of CO_2 fixation product, edible algae or algal biomass, can be obtained by a series of processes including harvesting by coagulation or floatation, further dewatering by press filter or centrifuge, and dry by thermal spray.

The following setups have been conducted in the model based on practical industry and basic theory. CO_2 transport is set up 99% efficiency despite by truck and by pipeline. Nutrients are supplement to be consumed stoichiometrically based on element ratio of carbon: nitrogen: phosphorus (C: N: P) in *Spirulina platensis* with around 5% N-nutrient loss in volatilization. Although the media usually contain excess nutrient concentrations relative to the algae concentration, the nutrient consumption is only considered as the supplement due to water recycled. The harvesting section chose dewatering by coagulation deposit while further dewatering chose press filter to obtain slurry in compliance with the characteristic of *Spirulina platensis*. *Spirulina platensis* slurry was conducted to algae powder by an industrial spray dryer.

2.3 Life cycle inventory data

In stage 1, LCI data on CO_2 capture and purification from flue gas with CO_2 10% - 15% derived from coal power station industries and CO_2 10%-99% derived from coal chemical industries, have been collected from literature (Zhang, et al., 2016) and practical industries. The energy consumption of CO_2 purification by cryogenic fractionation were obtained from literature (Liu X, et al., 2015), which have been simulated based on mathematics model, seen in section 3.1.

In stage 2, CO_2 transport mode including pipeline and ground tanker by truck have been collected from literature (Abbas, et al., 2013; Gao, et al., 2011). The LCI data for pipeline is derived from literature (Khoo, et al., 2006), which points that some additional energy is required for recompression of CO_2 due to the pressure drop. The LCI data for ground tanker by truck is derived from Greet (Argonne National Laboratory, 2018).

In stage 3 of CO_2 distribution and absorption (algae cultivation), the LCI data of raceway pond was collected by the actual *Spirulina platensis* powder production plant in China. The data of raceway ponds and other photobioreactor were collected (Das, et al.,2012; Frank, et al., 2012). The energy consumption for pumping CO_2 is related with the type of bioreactor and the depth of bioreactor. The mixing energy demand is proportional to the entire volume and algae density. CO_2 absorption efficiency in raceway pond was considered in the range of 75 - 90% (Lundquist et al., 2010) due to a small amount release into air.

In stage 4 of CO_2 fixation product, LCI data was derived from algae powder production plant in China. Due to cultivation scale and characteristics of *Spirulina platensis*, coagulation deposit is used to reduce the concentration of water and results in the solid content from 0.5% to 5.0-6.0 %. The solid content of *Spirulina platensis* increases to 18% - 20% by press filtration while the solid content increases to 20 %-22% by centrifuge. *Spirulina platensis* slurry was further dried to obtain *Spirulina platensis* powder (80%) through thermal spray with the energy consumption at heat provision.

3. Results and discussion

3.1 Effects of CO_2 deliverables quality on algal product

CO_2 deliverables should comply with CO_2 source as edible requirement considering algae as the feed or the health care while as algae growth requirement considering algae as biomass for CO_2 fixation.

For algal growth requirement, CO_2 source should achieve $SO_X \leqslant 60ppm$, NO_x

$\leqslant$300ppm, and NO$\leqslant$60ppm for algal biomass. For long distance transportation by tanker or as purely as edible requirement, CO_2 purification needs to be confined as liquid phase with $CO_2 > 95\%$, $H_2S < 2\%$, $N_2 < 2\%$, $CH_4 < 2\%$, $H_2O < 0.24 g/m^3$. Four typical technologies of CO_2 capture and purification can be applied to provide CO_2 deliverables for algal biomass while only cryogenics process can achieve to provide CO_2 deliverables for edible algae, shown in Fig.2.

Fig.2 Energy consumption in CO_2 capture and purification

a. CO_2 deliverables for algae biomass; b. edible CO_2 deliverables

From the respect of CO_2 deliverables for algal biomass, shown in Fig.2(a), the energy consumptions in chemical absorption for capturing CO_2 were estimated at 1.19–1.22 MJ/kg CO_2 coupling with heat requirements and solvent regeneration. In physical swing adsorption, the energy consumptions in capturing flue gas are estimated to be 0.58-0.66 MJ/kg CO_2 with 85 % - 90% recovery efficiency. In membrane separation, CO_2 in the flue gas can pass through the membrane wall and results in isolating impurities by commercial polymeric gas separation membranes with energy consumption 0.25-0.27 MJ/kg CO_2 at typical removal rates 82%-88%. In cryogenic fractionation, flue gas is cooled CO_2 in liquild phase and subsequently separated from other impurities. CO_2 recovery efficiency can reach approximately 90%-95% with purified 99.9% CO_2. Since the process is conducted at extremely low temperature and high pressure, it is an energy intensive process and the energy consumption is related with the freezing point, which is further related significantly with concentration of CO_2 in the flue gas and compositions of impurities. For the view of CO_2 deliverable for algal biomass, the membrane separation performs the lowest energy consumption in comparison with the chemical absorption and physical swing adsorption.

From the respect of CO_2 deliverables for edible algae, only cryogenics can comply with CO_2 source as purely as edible requirement. Energy consumptions in cryogenics technology are closely related with initial CO_2 concentration and pressure, which decrease with the increase of initial pressure and the increase of initial CO_2 concentration, shown in Fig.2(b). The effects of initial pressure on energy consumption decrease with the increase of initial CO_2 concentration. As a result, cryogenics is much more appropriate for CO_2 capturing and purification with high initial CO_2 concentration and pressure. Moreover, the concentration of CO_2 purification can achieve above 95% for transportation in long distance.

CO_2 source for transportation is required not only to prevent corrosion and other defects in pipelines or tankers but also to keep a stable single-phase flow because of the impurities on the boundaries of pressure and temperature envelope. Therefore, CO_2 capture and purification should comply with the requirement of algae product quality and CO_2 transportation. Low pressure pipeline and pressured pipeline can be used to transport CO_2 with wide range of concentration, but the energy consumptions decreased exponentially with the increase of CO_2 concentration in pipeline transportation, given in Fig.3. Supercritical pipeline and truck can be only used on transport with above 95% CO_2. For flue gas with above 95% CO_2, trucks take an advantage in energy consumption in comparison with pipelines.

Fig. 3 Energy consumption in CO_2 transportation

3.2 Effects of algae growth rate and protein contents on energy consumption

Direct energy consumption in algae cultivation including CO_2 distribution, power for algae suspension, power for pumping nutrient and water provision. Indirect energy consumption mainly takes place on nutrient consumption as P and N resource. The growth rate and content of *Spirulina platensis* are mainly influenced by controllable parameters and uncontrollable parameters. Controllable parameters contain CO_2 distribution, pH, and nutrient concentrations, which keep artificially at optimization condition, while uncontrollable parameters contain radiation and temperature, which usually control at the optimization condition in lab scale but depend on the geographical conditions in practical scale.

The effects of specific productivity and algae contents on energy consumption were assessed quantitively, given in Fig.4(a). Direct energy consumptions were related with specific productivities in compliance with logarithmic relationship. The empirical equations of direct energy consumptions with specific productivities and algal contents are established as following:

$$Y_{alage} \text{ (energy consumption, MJ/kg algae)} = -0.951\ln[x] + 3.7258 \qquad [1]$$

$$Y_{CO_2} \text{ (energy consumption, MJ/kg } CO_2) = (-0.564 \sim -0.659)\ln[x] + 2.2074 \qquad [2]$$

Where x is specific productivity and Y is energy consumption.

The results indicated that direct energy consumption based on algae growth is only the function of specific productivity, given in equation [1]. The direct energy consumption based on algae yield can reduce by 58% with the increase of the specific productivity from 14 $g/m^2.d$ to 24 $g/m^2.d$. However, direct energy consumptions based on CO_2 biofixation are the function of specific productivity and carbon content in algae, given in equation [2]. Although direct energy consumptions based on CO_2 biofixation reduce with the increase of the specific productivity, the high protein content with low carbohydrate can also benefit in energy consumptions based on CO_2 biofixation due to higher carbon abundance in algae. The results indicate that the reduction of direct energy consumption in CO_2 biofixation should improve the specific productivity and carbon abundance in algae.

Considering both direct and indirect energy consumption, given in Fig.4(b), energy consumptions increase with protein content in compliance with linear relationship. When diammonium hydrogen phosphate is used as nutrient for supplement of P and N resource, indirect energy consumption derived from nutrient input can deduce with the decrease of protein content and keep at 16% protein content. Further reduction of protein content cannot reduce the indirect energy consumption of nutrient due to the restriction of P resource requirement. Indirect energy consumptions are in the range of 0.292-3.219 MJ/kg CO_2 while direct energy consumptions are in the range of 0.427-0.855 MJ/kg CO_2. The results indicate that the reduction of protein content could get the benefit in the reduction of energy consumption.

Fig.4 Energy consumption in biofixation related with specific productivity and content a. direct energy consumption; b. direct and indirect energy consumption

3.3 Sensitive analysis of uncertainty parameters in life cycle

For further reduction the energy consumption and modification the system, the key impact factors should be extracted for modification. The sensitive uncertainty analysis of whole life cycle has been assessed quantitively, given in Fig. 5.

Fig.5 Sensitive analysis of uncertainty parameters

a. edible algae (protein 65%, initial CO_2 98%, specific productivity 20g/m^2.d);

b. algal biomass (protein 20%, initial CO_2 15%, specific productivity 20g/m^2.d)

Despite edible algae or algal biomass, shown in Fig. 5(a) and (b), protein contents perform the most sensitive to energy consumption. The high protein contents lead to the increase of nutrient consumption and subsequently results in high indirect energy consumption. The energy consumption of nutrient consumption occupied 94% at protein 65.3% and 13.5 % at protein 10% while occupied 24.1 % at protein 65.3% and 2.41 % at protein 10% in comparison with total energy consumption of algae slurry.

Another sensitive uncertainty parameter is related with CO_2 capture and purification. For edible algae, the sensitive uncertainty parameter is in cryogenic process related with initial CO_2 concentration and pressure of CO_2 source. For algal biomass, the choice of purification method influences mainly the energy consumption.

Specific productivity of algal biomass conducted more sensitive to energy consumption than edible algae. The energy consumption on algal biomass cultivation occupied 40% at 14 g/m^2.d and 28 % at protein 24 g/m^2.d while on edible algae occupied 13.1% at 14 g/m^2.d and 8.1% at protein 24 g/m^2.d in comparison with total energy consumption of algae slurry. The absorption efficiency is not sensitive to energy consumption in both life cycle of edible algae and algal biomass.

3.4 *Optimizing CO_2 biofixation system*

For achieving the reduction of energy consumption, the energy consumptions in life cycle from CO_2 source to CO_2 fixation product, are modified stage by stage according to final products of edible *Spirulina platensis* slurry and powder, as well as

Spirulina platensis slurry and powder, given in Fig.6.

Fig.6 Energy consumption in whole life cycle

a. edible algae; b. algal biomass

Algal biomass can reduce 2.52 MJ/kg CO_2 in the total energy consumptions compared with final products of edible algae at same level of protein content with same specific productivity. The reason is mainly at stricter CO_2 purification requirement for edible algae, which can only use completed purified CO_2 but algal biomass can use CO_2 in a wide range. For flue gas with 15% CO_2, the possible transportations conduct 0.0587 MJ/kg.km by low pressure pipeline and 0.086 MJ/kg.km by pressured pipeline. Moreover, some additional energy is required for recompression of CO_2 per 100 km due to the pressure drop. For above 100 km transportation distance and cryogenics in compliance with long distance transportation, energy consumption enhanced largely in CO_2 purification and transportation. Although member separation performs the lowest energy consumption while cryogenics conduct the highest energy consumption, cryogenics can obtain liquid CO_2 while the others get condensed CO_2 gas and can comply with CO_2 transportation requirement on long distance, the energy consumption of which is closely related with initial CO_2 concentration. Flue gas with 15% CO_2 is available for on-site biofixation and cultivate algal biomass. Flue gas with above CO_2 90% is available for long distance biofixation and cultivate edible algae. The method of capture and purification related with concentration of CO_2 source is the crucial parameters to influence the quality of algae.

From the view of algae cultivation just for CO_2 fixation, the protein content can further decrease around 16% for reduction of indirect energy consumption while the specific productivity and carbon abundance in algae improve for reduction of direct energy consumption. The optimization of energy consumptions in CO_2 biofixation stage can reduce to around 0.72 MJ/kg CO_2.

Considering the final phase as powder, the crucial energy consumption unit is in the dry process, which cost 14.88 MJ/kg algae, which indicate that algae slurry should be further developed to put directly practical use such as fish food due to the reduction of energy consumption in comparison with algae powder. Coupling optimization in the energy consumption of the whole life cycle, the total energy consumptions can reduce to 1.49 MJ/kg CO_2 for *Spirulina platensis* slurry while can reduce to 2.69 MJ/kg CO_2 for edible *Spirulina platensis* slurry at low protein level.

From the view of economy, the protein in edible algae should usually keep at high level above 60% as healthcare product. Accordingly, indirect energy consumption derived from nutrient supplement should cost at least 4.89 MJ/kg algae, namely 2.94 MJ/kg CO_2. Moreover, as CO_2 purification requirement for edible food, the energy consumption derived from purification of flue gas source above 95% CO_2 concentration should cost at least 0.59 MJ/kg CO_2. The total energy consumptions cost at least at 4.24 MJ/kg CO_2 (7.04 MJ/kg algae) for edible *Spirulina platensis* slurry and 13.71 MJ/kg CO_2 (22.75 MJ/kg algae) for edible *Spirulina platensis* powder.

4. Conclusions

The correlation among carbon dioxide concentration in flue gas, microalgae quality, yield and carbon sequestration were established in the whole life cycle of carbon sequestration.

CO2 capture and purification should comply with the requirement of algae product quality and CO2 transportation. Flue gas with 15% CO_2 is appropriate for on-site biofixation and cultivate algal biomass while flue gas with above CO_2 90% is available for long distance biofixation and cultivate edible algae.

The empirical equations of direct energy consumptions with specific productivities and algal contents are established in algae cultivation stage. The results indicated that direct energy consumption based on algae growth is only the function of specific productivity while direct energy consumptions based on CO_2 biofixation are the function of specific productivity and carbon content in algae. As energy consumptions increase with protein content in compliance with linear relationship, protein contents play an important role in energy consumption of CO_2 fixation despite edible algae or algal biomass.

Algal biomass can reduce 2.52 MJ/kg CO_2 in the total energy consumptions compared with final products of edible algae at same level of protein content with same specific productivity.

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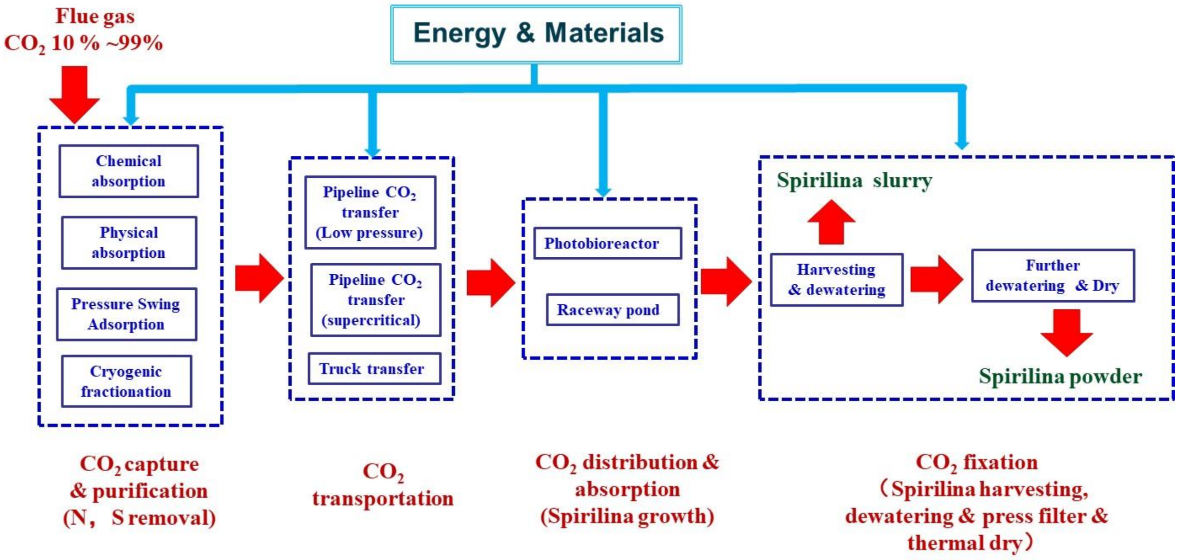
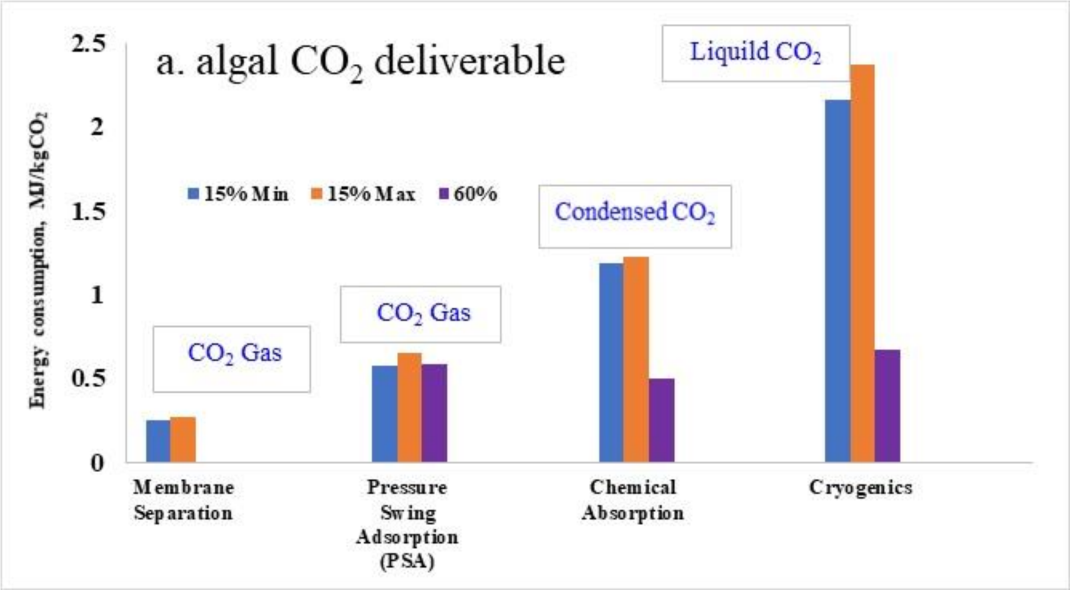


Fig. 1. System boundary definition of CO_2 algal fixation



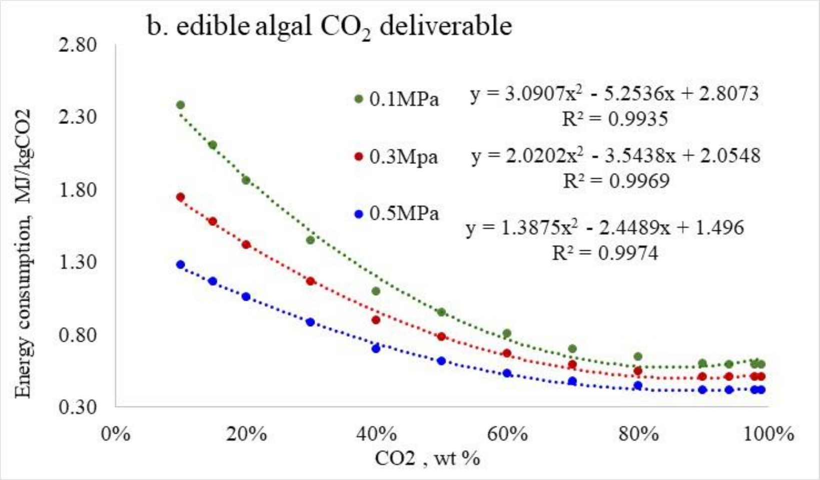


Fig.2 Energy consumption in CO_2 capture and purification

b. Algal CO_2 deliverables; b. Edible CO_2 deliverables

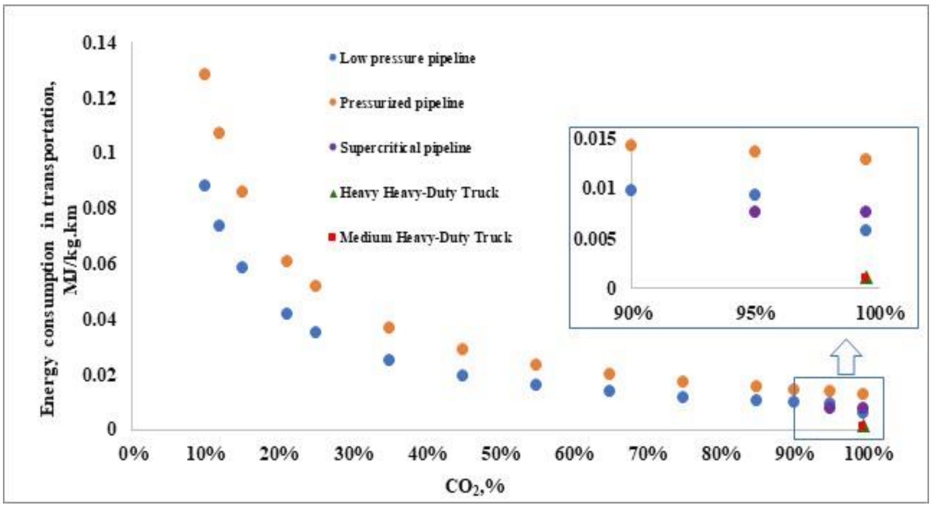


Fig. 3 Energy consumption in CO_2 transportation

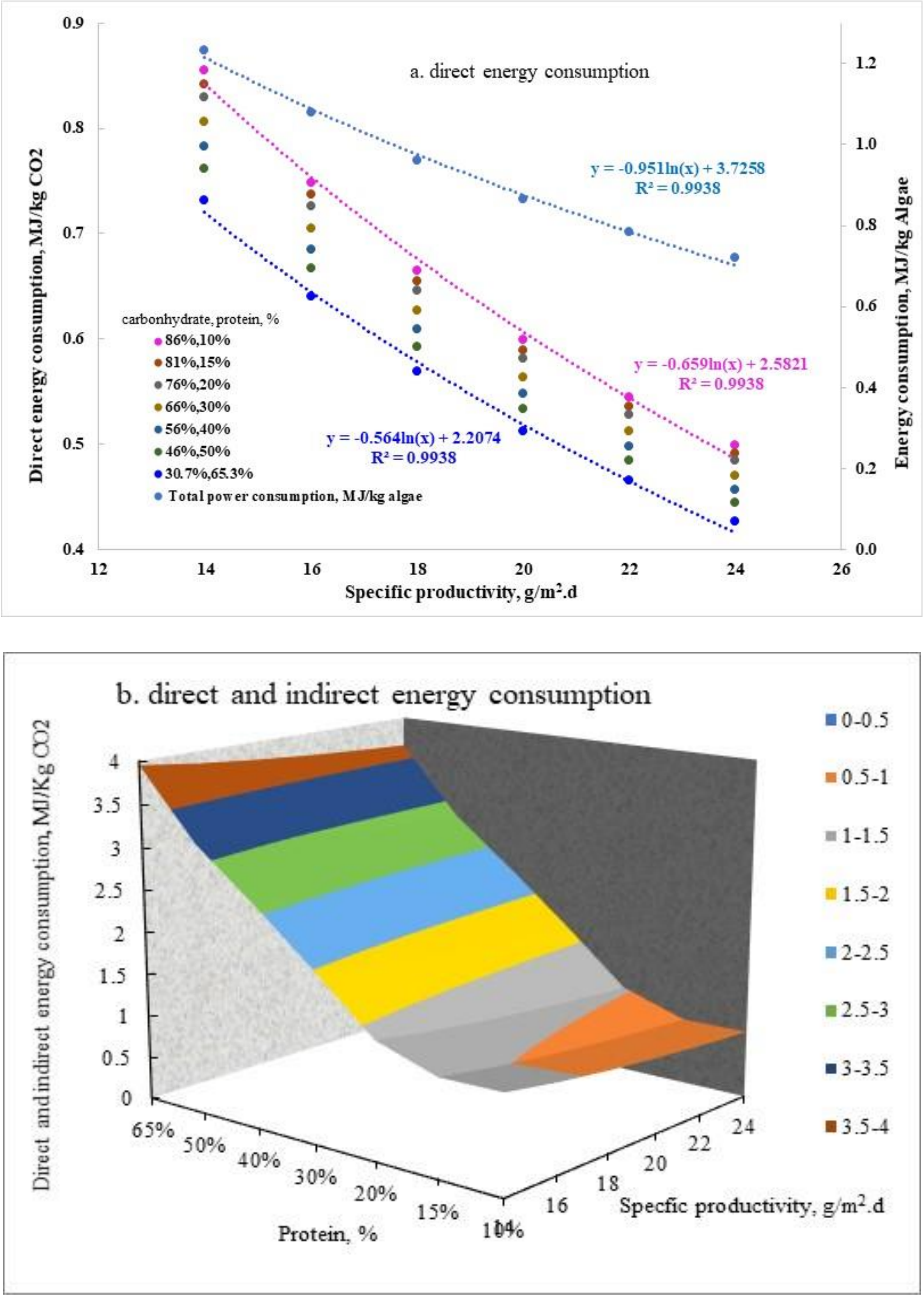


Fig.4 Energy consumption in biofixation related with specific productivity and content a. direct energy consumption; b. direct and indirect energy consumption

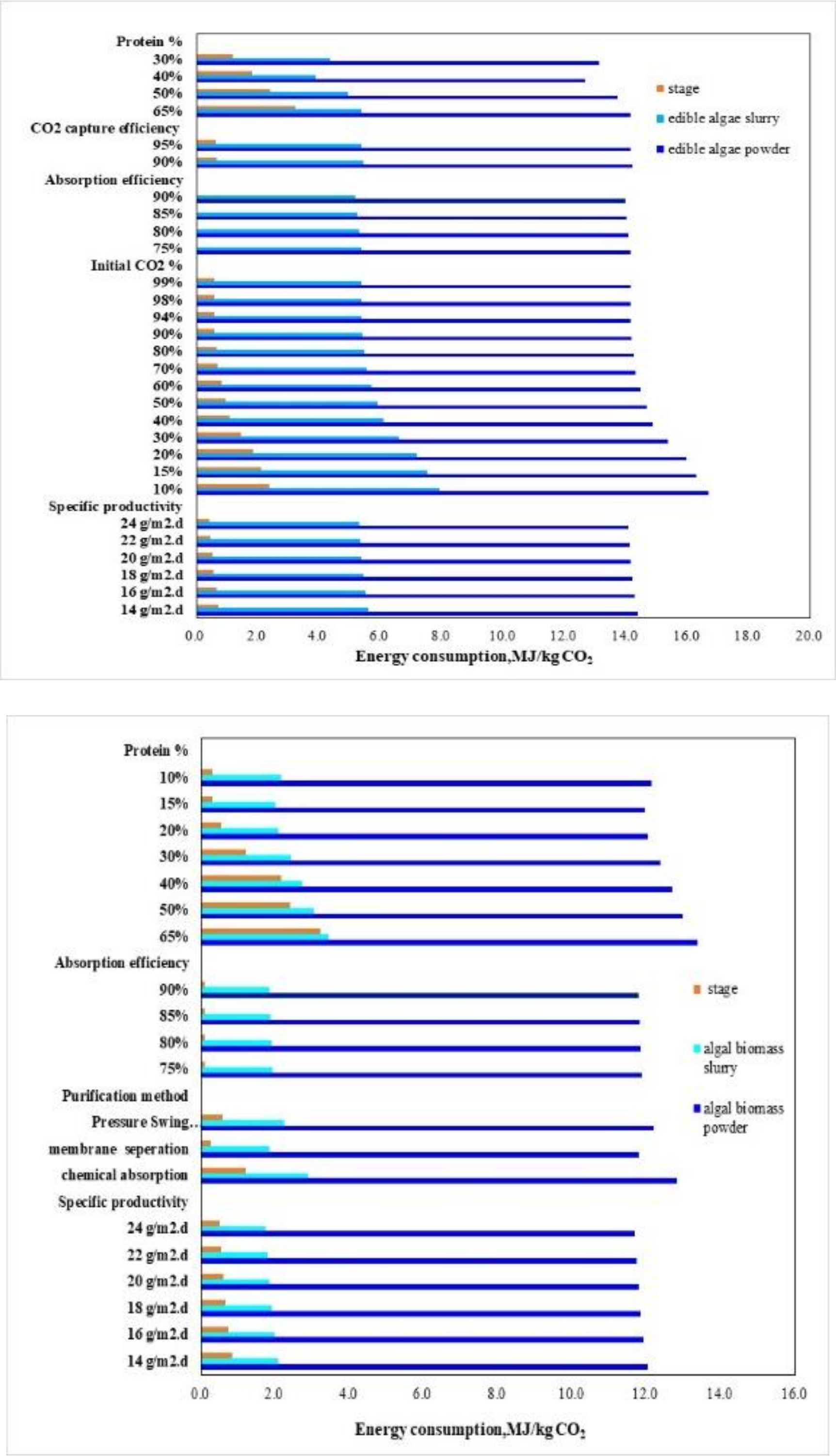


Fig.5 Sensitive analysis of uncertainty parameters

a. edible algae (protein 65%, initial CO_2 98%, specific productivity 20g/m^2.d);

b. algal biomass (protein 20%, initial CO_2 15%, specific productivity 20g/m^2.d)

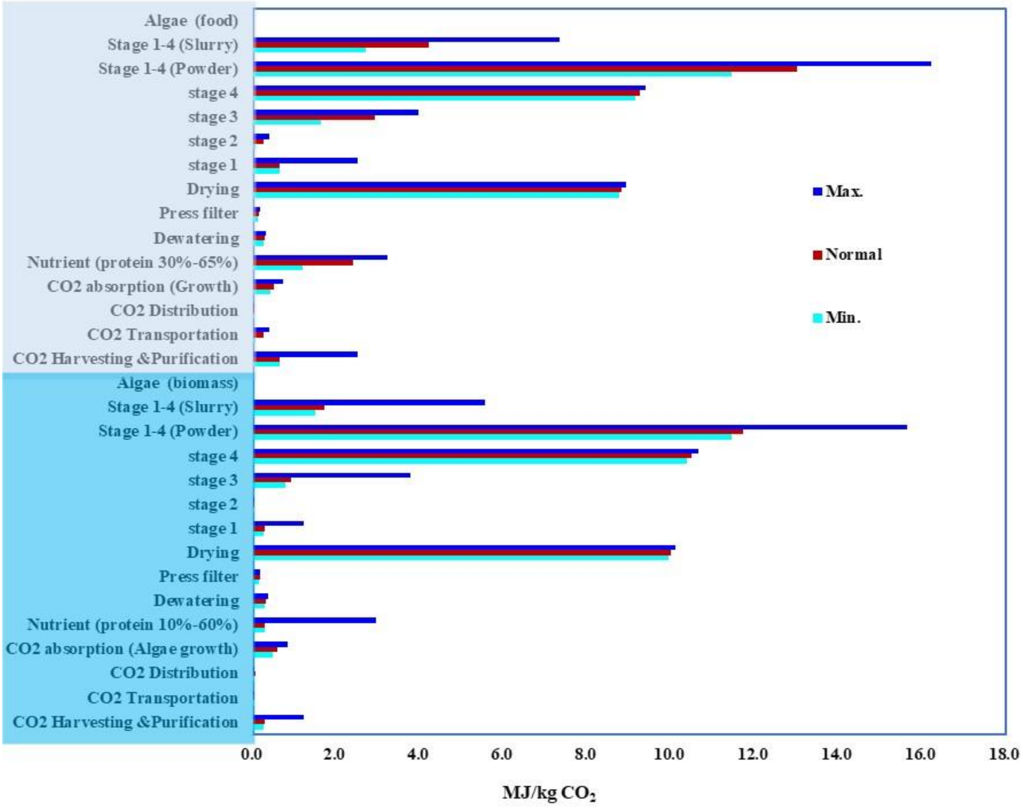


Fig.6 Energy consumption in whole life cycle