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Flue Gas CO_2 Capture by Microalgae in Photobioreactor: a Sustainable Technology

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This paper addresses the development of pilot scale sustainable technology for microalgae capture of CO_2 from power plant flue gas in alkaline solutions to produce biodiesel from algal oil. A combination of computer tools for process simulation, economic evaluation, and environmental impact allow sustainable process assessment. Laboratory scale experiments for growth and culture for algae in laboratory photobioreactor are considered. Based on them, CO_2 biocapture, biomass harvesting and algal oil extraction are evaluated. Process flowsheet for pilot scale CO_2 biocapture from flue gas, growth and separation of biomass, as well as algal oil separation is implemented in *SuperProDesigner® v8.5* simulator. Solvent is recovered by distillation and recycled. Experiment information allows to setup flowsheet, unit operations and unit procedures mass balance. As semi-batch process is considered, feedstock quantity/ flowrate and processing times are calculated. Process simulation predicts for ~ 1,400 kg CO_2/y biocapture with ~45 % yield, ~200 kg algal oil/y is produced. Technology sustainability is evaluated by economic and environmental performance. Process economics is evaluated with *SuperProDesigner®* and environmental impact with WAR software tool.

1. Introduction

Capture and storage of CO_2 from large local sources, such as fossil fuel power plants, represents an important measure to reduce global warming (Klemeš et al., 2007, Klemeš et al., 2010). Algae are suggested as good candidates for CO_2 capture. One alternative is to produce biodiesel, due to their higher photosynthetic efficiency, higher biomass production, and faster, growth compared to other energy crops. Microalgae need only sunlight, water, CO_2, and minerals for their growth in photobioreactors. Most of the research on algal biofuel has come from the analysis of laboratory-based small scale and pilot scale cultures, presenting that biodiesel production is both economically and environmentally sustainable. (Molina et al., 2003; Stephens et al., 2010).. However, there are some sceptical views (Chen et al., 2011; Lam and Lee, 2012). Overviews for biodiesel production by microalgae, include various cultivation modes (Huang et al., 2010; Demirbas, 2011). Different approaches for investigation of process sustainability were identified in literature. Pfromm et al., 2011 propose an engineering mass balance/unit operation approach to investigate bioprocess from techonological point of view. Life Cycle Analysis approach is used for sustainability evaluation taking into account environmental, economical and safety aspects (Dinh et al., 2009). Other integrated algorithm for development of sustainable bioprocesses is proposed by Heinzle (2006), as presented in

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Figure 1. The bioprocess model should be developed in close relation to process design, using data from literature and laboratory experiments.
Sustainability of bioprocess can be evaluated in terms of economic and environmental assessment.

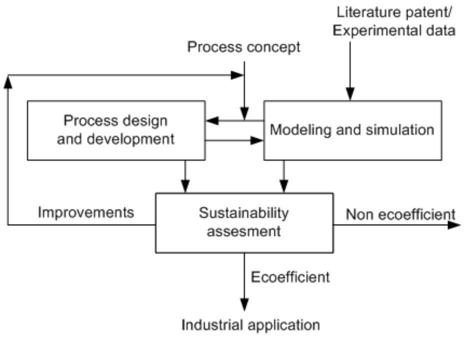


Figure 1: Integrated algorithm for sustainable bioprocess development (Heinzle et al., 2006)

This paper is focused to simulate a pilot scale new bioprocess to obtain algal oil by capture of CO_2 from flue gases by green algae in a culture medium of Na_2CO_3/$NaHCO_3$, observing above algorithm and using as guidelines laboratory experiments. Process simulation is very effective in realistic design, tradeoffs evaluation and decision support for early stages process development. As economics represent important aspect of sustainability, the study assesses costs for algal biofuel production with high productivity. Then environmental impact evaluation allows selecting most promising alternatives.

2. Laboratory experimental data

2.1 Selection of microalgae species

Preliminary experiments indicate three possible candidate microalgal species (*Chlorella homosphaera, Chlorobotrys simplex and Scenedesmus opoliensis*). The last is selected for CO_2, capture and biodiesel algal oil production (Velea et al., 2009). This species is among the most vigorously growing with optimal cell growth, higher photosynthetic efficiency, larger biomass and algal oil production.

2.2 Microalgal nutrition medium

As recommended growth medium for the green algae, nutrient BBM (Bold Basal Medium) standard, supplemented with $NaHCO_3$ and $NaNO_3$ is used.

2.3 Microalgal culture system

Biomass is cultivated in semibatch operated laboratory scale photobioreactor *BIOSTAT PBR 2S Sartorius*. Main operating conditions: suspension volume 3 L, temperature 28°C; light intensity 240 $\mu E/m^2s$; flue gas composition: 7 % CO_2, 14 % O_2 and 79 % N_2 at 20 mL/min. To reduce energy consumption, electroflocculation is chosen. 80 %-95 % of microalgae is separated. Biomass suspension is collected continuously (approximately 300 mL/d, i.e. 10-12 mL/h), floculated, and then filtered/ washed with distilled water to remove remaining salts and nutrient medium. Lipids are extracted (18 g ie less than 45 % of dry biomass) with $CHCl_3$ from 80 % moisture biomass .

3. Simulation of algal oil process

Pilot plant is simulated with *SuperPro Designer*® *v8.5* software. For each operation within a unit procedure the simulator performs material/energy balances and equipment sizing evaluation. From laboratory scale experiments information are used for flowsheet design. There are three sections: CO_2 capture and algae cultivation, biomass harvesting and algal oil extraction.

3.1 Algae cultivation section

Photobioreactor implementation in *SuperPro Designer*® operates as two CSTR unit procedures, under continuous CO_2 bubbling. Inoculum growth in BBM nutrition medium lasts for 8-10 d at room temperature, until reaching exponential growth phase in first unit procedure. Then biomass growth continues in second unit procedure (volumetric ratio 1:9 inoculum to nutrient). Stoichiometric model for CO_2 algae capture into biomass in Na_2CO_3/ $NaHCO_3$ solution (biomass $CH_{1.98}O_{0.49}N_{0.2}$) :

$$1\ CO_2 + 0.2\ NaNO_3 + 1.09\ H_2O \xrightarrow{Na_2CO_3/NaHCO_3} 1\ \text{Biomass} + 1.5\ O_2 + 0.2\ NaOH \qquad (1)$$

The algal suspension (4 g/L biomass concentration) is transferred to harvesting section.

3.2 Biomass harvesting section

Unit procedures for biomass harvesting implementation in *SuperPro Designer®* are: electrofloculation, decanting, and filtration/washing. Those techniques are suited for effective separation of small algae as *Scenedesmus o*. Liquid phase from electrofloculation is continuously recycled to the photobioreactor. The biomass is concentrated into decanter (40 g/L) and then filtered/washed to get 80 % humidity.

3.3 Algal oil extraction section

Algal oil separation from biomass is implemented as solvent extraction unit procedure, using $CHCl_3$. Remaining biomass is discharged as solid waste, to be reused as animal food or bioethanol production. Solvent is recycled by a distillation unit procedure.

Process flowsheet is illustrated in Figure 2. Summary for overall material balances (30 d batch time) is given in Table 2 for both laboratory experiments and *SuperPro Designer®* pilot plant simulation. Laboratory scale experiments are as g/batch, whereas simulations at pilot plant scale are as kg/batch. Given the particularities of larger scale, some figures are different, but the final result is reasonable.

Table 2 Overall mass balance per batch

Section	Material	Experimental (g/batch)		Simulation (kg/batch)	
		IN	OUT	IN	OUT
Algae culture *(Biomass – 4g/L)*	Medium nutrient (BBM)	11,700	-	7,200	-
	Inoculum	300	-	300	-
	Flue gases	1,200	1,100	1,200	1,207
	Biomass suspension	-	1,200	-	1,200
	Liquid waste	-	10,900	-	6,293
Total Algae cultivation Section		**13,200**	**13,200**	**8,700**	**8,700**
Biomass Harvesting *(Biomass- 80g/L)*	Biomass suspension	1,200	225	1,200	225
	Water wash	100	-	100	
	Liquid waste		1,075	-	1,075
Total Biomass harvesting Section		**1,300**	**1,300**	**1,300**	**1,300**
Algal-oil Extraction	Biomass suspension	225	-	225	-
	Solvent	85	-	83	-
	Algal cake	-	292	-	290
	Algal oil (Product)	-	18	-	18
Total Algal oil extraction Section		**310**	**310**	**308**	**308**

4. Economic analysis

Different production costs of algal biomass grown in photobioreactors are reported from 2.85 US$/kg (Chisti, 2007) to 30–70 US$/kg (Molina Grima et al., 2003), depending on climate, species, growing systems and other conditions. Algae biofuel production cost consists of: algae with high oil content cultivation costs, nutrients medium cost, harvesting and separation of wet biomass cost, algal oil solvent extraction cost, algal oil conversion to biodiesel cost and other by-products cost. Each of above cost components depend of specific parameters and conditions. For example algae cultivation (CO_2 capture) cost depends on culture techniques, i.e. photobioreactor (highest cost) or open pound (lower cost). In literature, Chisti (2007) and Molina Grima et al. (2003) reported algal oil cost, when production is based on photobioreactors ranging from 2.8 to 352 US$/L. For pilot plant flowsheet implemented, *SuperPro Designer®* software performs economic analysis. Figure 3 summarises annualised cost components for algal oil. For each section raw material cost, annualised equipment cost, utilities, consumables, electricity and labour cost are considered.

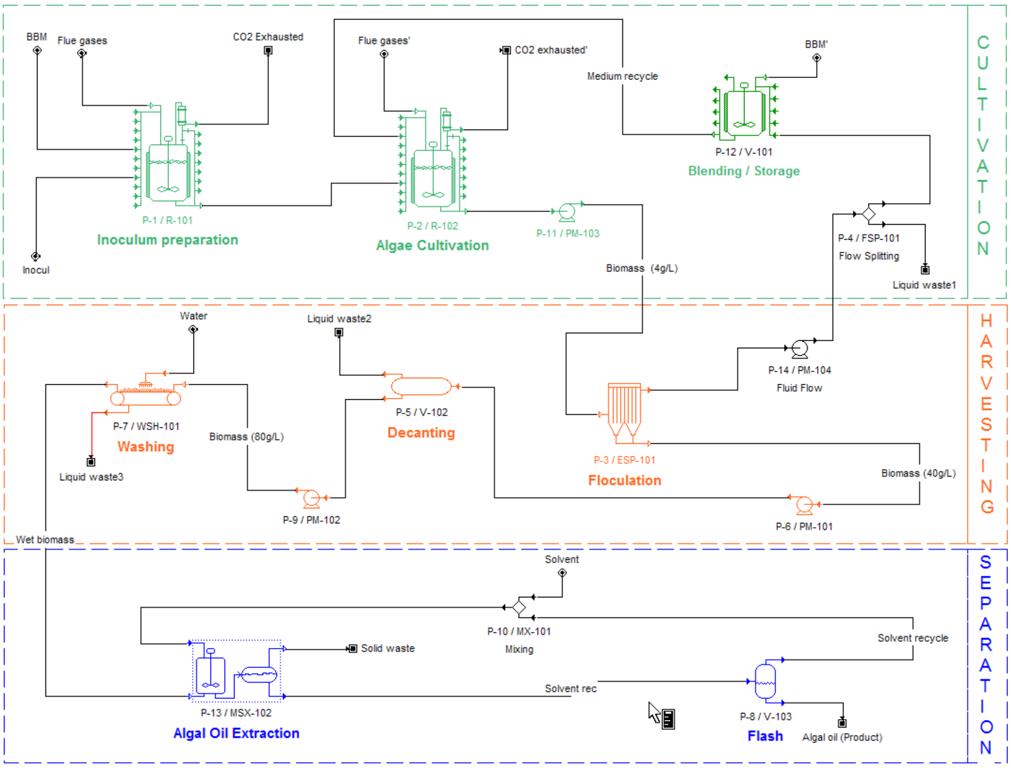
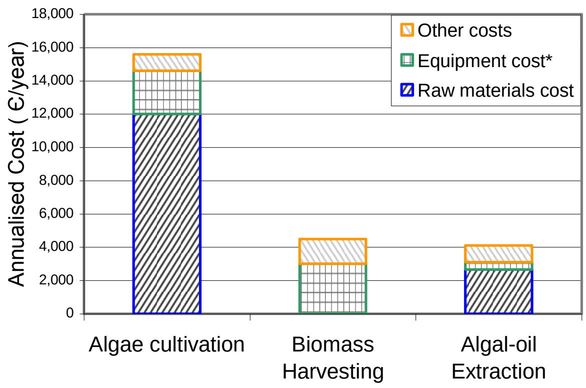


Figure 2: CO_2 photobiocapture pilot technology flowsheet

65% of production cost is allocated to algae cultivation, 18.5 % to harvesting and 16.5 % to algal oil separation. Total production cost for pilot plant capturing ~1,400 kg CO_2/y, and producing ~200 kg algal oil/y is estimated to ~ 24.600 €/y.



* *Depreciation time is 10 years*

Figure 3 Annualised costs for algal oil production

5. Environmental analysis

Algae cultivation pilot plant captures CO_2 from industrial flue gas, generating algal oil, exhausted biomass and waste waters. WAR algorithm and software (Yang and Cabezas, 1999) are used to evaluate environmental impact. The analysis is based on indexes that characterise the generation of potential impact index (PEI) by each process component as a relative measure of substances effects on human health or environment. For this process PEIs are calculated based on process stream mass per batch, composition and relative impact potential, underlying main sources of environmental impact. In Table 3 main environmental impact effect of each source is presented.

Table 3 Environmental impact effect

Section	Stream	Pollutant	Environmental impact effect
Algae cultivation	Emissions from photobioreactor	CO_2	Global warming potential (GWP)
Biomass harvesting (Liquid wastes depending of harvesting techniques employed)	Liquid waste 1 from tank storage	Nutrients, sodium hydroxide, metals	Eutrophication potential (EP) , Aquatic toxicity potential (ATP)
	Liquid waste 2 from decanting	Nutrients, biomass traces	Eutrophication potential (EP) , Aquatic toxicity potential (ATP)
	Liquid waste 3 from washing	Nutrients, biomass and oil traces	Eutrophication potential (EP), Aquatic toxicity potential (ATP)
Oil extraction	Solid waste	Algal cake, Solvent	Terrestrial Toxicity Potential (TTP) Human toxicity by ingestion potential (HTPI) Human toxicity by inhalation potential (HTPE)

In photobioreactor, only 45 % of CO_2 is considered to be captured by algae, reducing Global Warming. Waste water containing residual nutrients, chemicals or flocculants, needs treatment before discharge or recycle. Nutrients may cause eutrophication of receiving water bodies and excessive algae growth as well as algae mineralization, with production of death in aquatic life, by oxygen depletion. Solvent for algal oil extraction has human toxicity. Applying the WAR algorithm, the effects of pollutants and CO_2 capture are quantified as increased/decreased PEI number/kg of product (Figure 4).

6. Conclusions

CO_2 photobiocapture technology for pilot plant is simulated as semi-batch process and sustainability in terms of economic and environmental performance is assessed. Laboratory experiments data published earlier is used to develop process flowsheet with *SuperPro Designer®* software. Three sections (algae culture and CO_2 photobiocapture, biomass harvesting and algal oil extraction are considered. Process simulation predicts for ~ 1,400 kg CO_2/y biocapture with ~45% yield, ~200 kg algal oil/y produced. Total production cost for pilot plant is estimation by process simulator ~ 24,600 €/y. Main environmental impact indexes evaluated by WAR algorithm are Global Warming Potential, Eutrophication potential, Aquatic Toxicity potential and Human Toxicity potential. CO_2 photobiocapture ensures a strong benefic environmental impact to pilot plant. Pilot plant technology proves sustainability assessment. Biodiesel production from biomass obtained by CO_2 capture by microalgae provides technical, economic and environmental impact feasible at pilot plant scale.

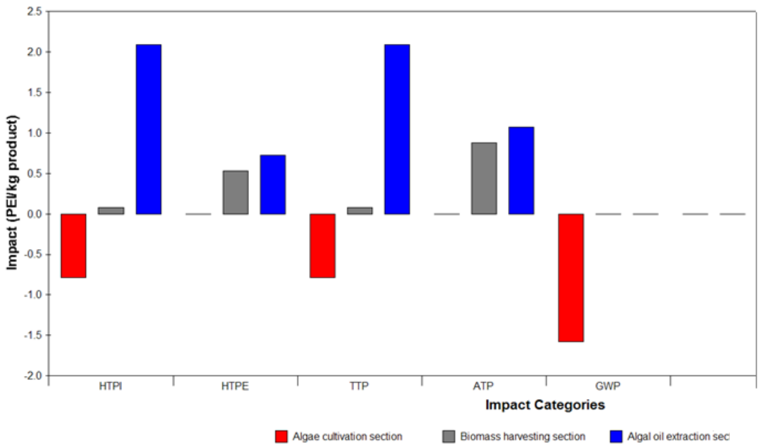


Figure 4: Environmental impact of CO_2 photobiocapture technology

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