Flue Gas CO₂ 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 CO₂ 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, CO₂ biocapture, biomass harvesting and algal oil extraction are evaluated. Process flowsheet for pilot scale CO₂ 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 CO₂/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 CO₂ from large local sources, such as fossil fuel power plants, represents an important measure to reduce global warming (Klemes et al., 2007; Klemes et al., 2010). Algae are suggested as good candidates for CO₂ 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, CO₂, 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 technological 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 Heinze (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 CO₂ from flue gases by green algae in a culture medium of Na₂CO₃/NaHCO₃, 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 CO₂ 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 NaHCO₃ and NaNO₃ 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 μE/m²s; flue gas composition: 7 % CO₂, 14 % O₂ and 79 % N₂ at 20 mL/min. To reduce energy consumption, electrofloculation is chosen. 80 %-95 % of microalgae is separated. Biomass suspension is collected continuously (approximately 300 mL/d, i.e. 10-12 mL/h), flocculated, 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 CHCl₃ 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: CO₂ 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 CO₂ 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 CO₂ algae capture into biomass in Na₂CO₃/NaHCO₃ solution (biomass CH₁₇₆₆O₉₄₅N₂): 

$$\text{CO}_2 + 0.2 \text{NaNO}_3 + 1.09 \text{H}_2\text{O} \rightarrow \text{Na}_2\text{CO}_3 / \text{NaHCO}_3 \rightarrow 1 \text{ Biomass} + 1.5 \text{O}_2 + 0.2 \text{NaOH}$$ (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 CHCl₃. 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

<table>
<thead>
<tr>
<th>Section</th>
<th>Material</th>
<th>Experimental (g/batch)</th>
<th>Simulation (kg/batch)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Algal culture</td>
<td>Medium nutrient (BBM)</td>
<td>11,700</td>
<td>-</td>
</tr>
<tr>
<td>(Biomass – 4g/L)</td>
<td>Inoculum</td>
<td>300</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Flue gases</td>
<td>1,200</td>
<td>1,100</td>
</tr>
<tr>
<td></td>
<td>Biomass suspension</td>
<td>-</td>
<td>1,200</td>
</tr>
<tr>
<td></td>
<td>Liquid waste</td>
<td>-</td>
<td>10,900</td>
</tr>
<tr>
<td>Total Algae cultivation Section</td>
<td></td>
<td>13,200</td>
<td>13,200</td>
</tr>
<tr>
<td>Biomass Harvesting</td>
<td>Biomass suspension</td>
<td>1,200</td>
<td>-</td>
</tr>
<tr>
<td>(Biomass- 80g/L)</td>
<td>Water wash</td>
<td>100</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Liquid waste</td>
<td>-</td>
<td>1,075</td>
</tr>
<tr>
<td>Total Biomass harvesting Section</td>
<td></td>
<td>1,300</td>
<td>1,300</td>
</tr>
<tr>
<td>Algal-oil Extraction</td>
<td>Biomass suspension</td>
<td>225</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Solvent</td>
<td>85</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Algal cake</td>
<td>-</td>
<td>292</td>
</tr>
<tr>
<td></td>
<td>Algal oil (Product)</td>
<td>-</td>
<td>18</td>
</tr>
<tr>
<td>Total Algal oil extraction Section</td>
<td></td>
<td>310</td>
<td>310</td>
</tr>
</tbody>
</table>

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 (CO₂ 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: CO₂ 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 CO₂/y, and producing ~200 kg algal oil/y is estimated to ~ 24,600 €/y.

Figure 3 Annualised costs for algal oil production

* Depreciation time is 10 years
5. Environmental analysis

Algae cultivation pilot plant captures CO₂ 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>
<thead>
<tr>
<th>Section</th>
<th>Stream</th>
<th>Pollutant</th>
<th>Environmental impact effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Algae cultivation</td>
<td>Emissions from photobioreactor</td>
<td>CO₂</td>
<td>Global warming potential (GWP)</td>
</tr>
<tr>
<td></td>
<td>Liquid waste 1 from tank storage</td>
<td>Nutrients, sodium hydroxide, metals</td>
<td>Eutrophication potential (EP). Aquatic toxicity potential (ATP)</td>
</tr>
<tr>
<td></td>
<td>Liquid waste 2 from decanting</td>
<td>Nutrients, biomass traces</td>
<td>Eutrophication potential (EP). Aquatic toxicity potential (ATP)</td>
</tr>
<tr>
<td></td>
<td>Liquid waste 3 from washing</td>
<td>Nutrients, biomass and oil traces</td>
<td>Eutrophication potential (EP), Aquatic toxicity potential (ATP)</td>
</tr>
<tr>
<td>Oil extraction</td>
<td>Solid waste</td>
<td>Algal cake, Solvent</td>
<td>Terrestrial Toxicity Potential (TTP) Human toxicity by ingestion potential (HTPI) Human toxicity by inhalation potential (HTPE)</td>
</tr>
</tbody>
</table>

In photobioreactor, only 45 % of CO₂ 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 CO₂ capture are quantified as increased/decreased PEI number/kg of product (Figure 4).

6. Conclusions

CO₂ 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 CO₂ photobiocapture, biomass harvesting and algal oil extraction are considered. Process simulation predicts for ~ 1,400 kg CO₂/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. CO₂ photobiocapture ensures a strong benefic environmental impact to pilot plant. Pilot plant technology proves sustainability assessment. Biodiesel production from biomass obtained by CO₂ capture by microalgae provides technical, economic and environmental impact feasible at pilot plant scale.
Figure 4: Environmental impact of CO₂ photobiocapture technology

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