Cost efficient algal cultivation systems – A source of emission control and industrial development (MICROALGAE)
Period covered: 01.02.2014 – 31.01.2017

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Background and objectives

Production and wider use of microalgae biomass has mainly been restricted by high cost for commercialization of especially the low-value algae-derived products, e.g. biofuels. Most of the current applications are centered on high-value products (i.e. cosmetics, pharmaceuticals, food and feed additives) (Pulz and Gross, 2004). Therefore, more efforts are needed for commercialization in order to make the production of algal biomass cost-efficient. It is possible by integrating algal cultivation system design with the delivery of multiple products (e.g. fertilizers, high-value products, biofuel) and services (e.g. nutrient harvesting from wastewaters) and by internalizing social and environmental benefits of algae cultivation and its biomass.

Large scale production of microalgae biomass requires constant and controlled yield that can be obtained through cultivation in ponds or photobioreactors (Seppälä et al., 2012). Low temperatures and too intense or limited light conditions inhibits the cell growth rate. Therefore, Nordic conditions are assumed to be not congenial for algae production in uncontrolled natural conditions in ponds, although it is relatively low cost installation and operation. Furthermore, low biomass density of the culture greatly increases the costs for harvesting that is crucial for waste water treatment in order to remove nutrients and other substances. By contrast to open pond, closed systems of photobioreactors enable better controlling of the culturing conditions and substantially reduce the chance of contamination by unneeded species, thereby providing higher productivity over the open systems.

Wastewaters provide both the growth medium as well as the necessary nutrients required for cultivation of algae. Wastewater composition is a very important factor when considering microalgae treatment as a potential step within a wastewater treatment process. Nutrient uptake by algae can vary a lot (Cai et al. 2013; Kwon et al. 2013) depending on the species as well as the quality of wastewaters, e.g. the content of nutrients and their ratio. Therefore, use of microalgae species a promising tool for partial nutrient recovery from wastewaters. Actual use requires selection of suitable microalgae-wastewater combinations.

The main research objectives of the BONUS MICROALGAE project were:
- identification of suitable microalgae cultivation systems for algae biomass production;
- assessment of the effectiveness of algae to remove nutrients and pollutants from waste streams and to abate eutrophication;
- assessment of the potential and possible innovative solutions for industrialisation.
Identification of potential wastewater streams and cultivation systems

To reach these goals, representative industrial and mixed municipal/industrial wastewaters for microalgae treatment were selected based on the previous research and monitoring results in the Baltic Sea Area and analysis of typical concentration ranges for nutrients and micropollutants. Mixed influent industrial/municipal wastewater from Kohtla-Järve, Estonia was selected for testing with algae, based on the assumption that it represents typical conditions in larger municipalities where industrial and municipal wastewaters as well as storm water are mixed and then treated together.

The results on identification of wastewater streams were made publicly available by a Report on the selection of wastewaters (Deliverable 1.1.) and in popular scientific publication Local runoff sources and wastewaters in the Baltic Sea Area (Deliverable 5.1). Selection of local sites for further scenario simulation was based on the socio-economic and environmental indicators. Major factors to reduce nutrient loads to the Baltic Sea by considering the recovery of nutrients from wastewaters taking into account economic and cost efficiency were identified (Deliverable 4.1).

Selected wastewaters were analysed for nutrients and hazardous compounds. The screening with a number of microalgal species (autotrophic and/or heterotrophic) for their potential to grow and to produce algal biomass in the selected wastewaters with different dilution rates was performed using an innovative method on microplates (Figure 1). The method allow testing of many different conditions at the same time. The results of this research were demonstrated in Report on selection of microalgae/wastewaters combinations (Deliverable 1.2.).

Figure 1. Screening of different microalgal species/wastewaters combinations (De Francisci et al., 2017).

Microalgae species C. sorokiniana showed higher specific growth rate over S. obliquus at all conditions used (Figure 2).
Scaling up and tests at photo-bioreactor

Next step of the study involved the tests at a flat-panel photo-bioreactor on the microalgal species *Chlorella sorokiniana* which appeared to be more promising for the treatment of wastewaters based on the microplate screening tests and considering the growth rate with different dilutions. The photo-bioreactor was designed to be scalable, so that the gathered data could be applied to an industrial scale. Several different conditions were studied (temperature, pH, CO₂ and organic loading rate, nutrients levels etc.) with respect to: 1) growth performance of the cultures, 2) composition of the resulting biomass and 3) nutrient removal efficiencies.

The study revealed that the lowest dilution rate provided the highest biomass concentration up to 1.44 g l⁻¹. The productivity peak was estimated to be 1.52 g l⁻¹ d⁻¹ at the dilution rate of 2.41 d⁻¹ based on the fitting curve obtained from four measured points (Figure 3).

The efficiency of algae to remove plant nutrients and micropollutants was assessed based on the water quality data before and after the algae test. The highest removal efficiencies (> 90%) of pollutants were observed at the lowest dilution rate. However, the removal of COD for all dilution
rates is only around 50% (Figure 4). The removal efficiencies of zinc at different dilution rates varied considerably being more than 30% at the lowest dilution rate. The algae treatment at the lowest dilution rates is comparable to the treatment efficiencies of the conventional removal of the total phosphorus (TP). The removal of the total nitrogen (TN) and the chemical oxygen demand (COD) did not perform that well and provided 65 to 42% weaker results, respectively, compared to the conventional treatment.

![Figure 4: Effect of dilution rates on nutrient removal efficiencies (De Francisci et al., 2017).](image)

The dilution rate 1.8 d\(^{-1}\) appeared to be optimal, both for the biomass production and for the removal of nitrogen and phosphorus from wastewaters.

The lab-scale analytical data (described in deliverables 2.1, 2.2 and 2.3 and in popular scientific publication providing information on the microalgae treatment and water quality control - deliverable 5.3) were upscaled in order to determine the sustainability of the entire process.

**Cost-efficient industrialisation and optimal productivity measures**

A basic economic potential analysis was performed based on the assumption that biomass production with flat panel photobioreactor takes place at a plant scale 100 hectare, the annual operation period is 330 days and the energy consumption for artificial light is 209 W m\(^{-2}\). Nitrogen and phosphorus provided by wastewater were considered to be free of charge.

The cost for producing a kilo of microalgae is assumed to be 12.5 € kg\(^{-1}\). Power consumption for artificial light is responsible for the majority (ca 95%) of the production costs. The revenue generated from cultivating *C. sorokiniana* is estimated to be 3.27 € kg\(^{-1}\) dry biomass (Table 1). More than 80% of revenue could be obtained from the production of valuable bioproducts. Significant contribution (19.6%) to the overall profit was generated by the removal of N and P from the wastewater.

Thus, the cultivation strategy could be economical only by avoiding operational costs for lightning and by using open raceway pond system in the expense of uncontrolled environmental, including lightning conditions and reduced algae concentration in the media.
Table 1. Estimated value of the algae cultivation and biomass (De Francisci et al., 2017)

<table>
<thead>
<tr>
<th>Product</th>
<th>Yield</th>
<th>Productivity</th>
<th>Revenue</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biomass</td>
<td>1.52 g L⁻¹d⁻¹</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FAME (B100)</td>
<td>0.062 g g⁻¹</td>
<td>0.01 g L⁻¹d⁻¹</td>
<td>0.46 € kg⁻¹</td>
</tr>
<tr>
<td>Amino acid fertilizer (54.4%)</td>
<td>0.388 g g⁻¹</td>
<td>0.59 g L⁻¹d⁻¹</td>
<td>0.16 € kg⁻¹</td>
</tr>
<tr>
<td>Lutein (80%)</td>
<td>1.03 mg g⁻¹</td>
<td>1.57 mg L⁻¹d⁻¹</td>
<td>0.29 € kg⁻¹</td>
</tr>
<tr>
<td>Chlorophyllin (95%)</td>
<td>11.81mg g⁻¹</td>
<td>18.01 mg L⁻¹d⁻¹</td>
<td>1.95 € kg⁻¹</td>
</tr>
<tr>
<td>β-carotene (95%)</td>
<td>0.44 mg g⁻¹</td>
<td>0.67 mg L⁻¹d⁻¹</td>
<td>0.18 € kg⁻¹</td>
</tr>
<tr>
<td>Sum</td>
<td></td>
<td></td>
<td>2.63 € kg⁻¹</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wastewater treatment</th>
<th>Removal</th>
<th>Quantity</th>
<th>Revenue</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wastewater</td>
<td>52.1%</td>
<td>0.319 kg kg⁻¹</td>
<td>0.04 € kg⁻¹</td>
</tr>
<tr>
<td>COD</td>
<td>57.5%</td>
<td>0.044 kg kg⁻¹</td>
<td>0.36 € kg⁻¹</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>68.8%</td>
<td>0.008 kg kg⁻¹</td>
<td>0.24 € kg⁻¹</td>
</tr>
<tr>
<td>Sum</td>
<td></td>
<td></td>
<td>0.64 € kg⁻¹</td>
</tr>
<tr>
<td>Total revenue</td>
<td></td>
<td></td>
<td>3.27 € kg⁻¹</td>
</tr>
</tbody>
</table>

Unfortunately conditions suitable for optimal microalgae growth and biomass productivity are not necessarily the same that are needed to provide high value products in the biomass. Therefore, the development of two-phase cultivation strategies, in which microalgae are first kept in optimal growth conditions to generate high biomass yield, and then stressed to increase the high added value products content in the same biomass could be feasible. Low-value products, e.g. biofuels are not yet economically feasible unless considerably enhanced cost-efficient technologies for algae biomass production emerge.

Reports on upscaling the analytical results considering suitable technologies and economics were provided in the deliverables 2.4, 3.1, 3.2 and 3.3. The deliverable 4.2. provide a guidelines on the internalisation of negative externalities from an environmental economic perspective. The results suggest that the internalisation of negative externalities could be feasible by adopting microalgae cultivations by WWTPs in the catchment area of the Baltic Sea, although local variations on incoming wastewaters, as well as economies of scale and economies of scope in individual WWTPs affect optimal conditions for the adoption of microalgae as an abatement technology for handling of wastewaters. Moreover, a new abatement technology for wastewaters may not contribute to further abatement in some countries in the BSA. Therefore, guidelines and recommendations (Deliverable 4.3) regarding solutions for more cost-effective handling of wastewaters, application of nutrient trading as a policy instrument and cultivation of microalgae by WWTPs coupled to bioenergy and carbon dioxide assimilation were proposed.
Wider societal implications and continuity
The project contributes to achieving the goals set by the EC Renewable Energy Directive (2009/28/EC) that requires to fulfil at least 20% of total energy needs with renewables by 2020. A proposal for a revised Renewable Energy Directive sets even more ambitious target of at least 27% renewables in the final energy consumption in the EU by 2030. Wider use of microalgae and other bio-resources could contribute to the achievement of the marked goals. Further reasearch and coordinated activities are therefore needed within the clusters of excellence and bioeconomy networks, e.g. Submariner, BioEconomy Network, etc.

Cultivation and harvesting of microalgae is not specifically regulated in the Baltic Sea area, although there are legal requirements established regarding land-use, handling of wastewaters and introduction of alien species that involves microalgae. Local algae species should be preferred due to their better adaptation to Nordic climate and lower risks when escaping from the production unit. Industrial scale algae cultivation in open ponds requires a considerable land area and the use of microalgae for treatment of wastewaters is heavily impacted by the established thresholds for effluents of WWTPs and treatment efficiencies. Moreover, large scale installations for algae cultivation could also require implementation of the environmental impact assessment.

Conclusions
- Wider use of microalgae could be enhanced by supporting research on cost-efficient industrialization of algae production following the wastewater based algae-to-fuel approach, conducting market surveys about potential products, by creating markets for new products and increasing public awareness about the products and accompanied environmental services.
- Commercialization of microalgae could be enhanced by integrating the delivery of multiple products (e.g. fertilizers, high-value products, biofuel) and services (e.g. nutrient harvesting from wastewaters) and by internalizing social and environmental benefits of algae cultivation and its biomass.
- Development of two-phase cultivation strategies in which microalgae are first kept in optimal growth conditions (e.g. closed photobioreactors) to generate high biomass yield, and then stressed to increase the high added value products content in the same biomass could be feasible. Two stage system of closed photobioreactors that feed biomass into open systems could also provide a cost-efficient solution.

References