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Environmental assessment of co-location alternatives for a microalgae cultivation plant: a case study in the city of Kingston (Canada)

Massimo Collotta[a]*, Pascale Champagne[b], Warren Mabee[b], Giuseppe Tomasoni[a], Marco Alberti[a], Leonardo Busi[a], Gustavo B. Leite[b]

[a]*DIMI, Department of Industrial and Mechanical Engineering, University of Brescia, via Branze 38, 25123 Brescia, Italy*
[b]*Department of Civil Engineering Queen's University, Ellis Hall, 58 University Avenue, K7L 3N6 Kingston, Ontario, Canada*

Abstract

In recent years there has been growing interest in the use of microalgae as a feedstock for biofuels, particularly for biodiesel. The production process of biodiesel from microalgae generally consists of five different phases: cultivation, harvesting, drying, lipid extraction and transesterification. While existing technologies are available to undertake each of these phases, the process would benefit from enhanced sustainability achieved by reducing environmental impact and costs. One process innovation currently under consideration is the use of waste products as inputs to the process, including CO_2 captured from industrial flue gas, or nutrients from wastewater. These could be employed in algae cultivation. The co-location of an algae cultivation plant with other industrial facilities, such as a cement plant or a wastewater treatment facility, could result in significantly reduced atmospheric emissions and improve wastewater effluent discharges. A comparative life cycle assessment approach is used to examine two different, realistic alternatives for the co-location of an algae cultivation plant with an existing cement plant or wastewater treatment facility near Kingston, Ontario, Canada. The study seeks to identify a preferred siting option from the perspective of minimizing environmental impacts. The first alternative involves the co-location with the Lafarge Cement plant, on the north shore of Lake Ontario, near Bath Ontario. The second alternative consists in the co-location with the Ravensview wastewater treatment facility east of the city of Kingston on the St. Lawrence River. The algae production plant is based on an open pond technology and is assumed to have a production capacity of about 120 tons of dry microalgal biomass per year.

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Keywords: life cycle assessment; microalgae cultivation; plant co-location; wastewater; CO_2

* Corresponding author: Tel.: +393287493932; fax: +390303702448
E-mail address: m.collotta@unibs.it

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1. Introduction

Renewable energy has shown great potential to assist us in meeting our global sustainable energy demands, particularly in countries and regions with a low availability of fossil fuels and nuclear energy [1]. Consequently, there has been growing interest in the development of techno-economically sound bioenergy systems, in particular, a recent focus on the derivation of biofuels from algal biomass, both micro and macro [2, 3], which is considered the third generation biofuel feedstock. In particular, algal biomass has the potential to be cultivated year-round and presents higher solar energy yields. Moreover, microalgae can realistically produce 40 tons ha^{-1} $year^{-1}$ of oil at large scale, a production ratio which is 20 to 90 % higher than other terrestrial plants, depending on the species and conditions [1].

Microalgae also presents other benefits, such as the ability to be cultivated on non-arable land, which avoids the competition with food crops. Hence, the use of algal biomass feedstocks would not contribute to the rise in deforestation rates and damages to biodiversity, or the rise of food crop prices. Additionally, microalgae can be cultivated in lower quality waters (e.g. salt water, wastewater or recycled water) and marginal lands. Microalgae can also be employed to remove certain water pollutants in wastewater and they can affect water chemistry and biochemical composition under appropriate conditions [4]. Finally, photosynthesis fixes CO_2 in the growth of the feedstock, providing a carbon neutral biofuel compared the fossil fuel alternatives [1, 5–7].

For these reasons, this sector may play a fundamental role in the future energy systems. However, it is important to demonstrate that microalgal-based processes can be economically and environmentally sustainable in the long term [8] and this depends on the implementation of innovative technologies for their cultivation and transformation, toward which a great deal of research and development is in progress today [9]. In particular, reducing water, nutrients and energy demands represents a valuable approach to improve system performance and economic viability [2, 10]. Also the use of flue gas as a source of CO_2 and wastewater instead of fresh water for algal cultivation could bring a positive impact on the cost and environmental performance of the biofuel production [11–13].

As the use of flue gas and wastewater may be favored by the co-location of the algae cultivation plant with other industrial facilities, such as a cement plant or a wastewater treatment facility, in this paper a comparative life cycle assessment approach is used to examine two different, realistic scenarios for the co-location of an algae production plant based on an open pond technology and having a capacity of about 120 tons of microalgae per year. In particular, the study seeks to identify the preferred siting option from the perspective of minimizing environmental impacts.

The first scenario examines co-location with the Lafarge cement plant, on the north shore of Lake Ontario, near Bath Ontario. In this case, the algae cultivation foresees the direct injection of a part of the cement plant flue gas and the supply of nutrients from the centrate provided from the Ravensview wastewater treatment plant, east of the city of Kingston on the St. Lawrence River, transported by tank truck (scenario 1a) or by pipe (scenario 1b).

The second scenario considers co-location with the Ravensview wastewater treatment facility. In this case, nutrients are supplied through the centrate produced by the wastewater treatment plant itself, while CO_2 is provided from the Lafarge cement plant flue gas, conveyed to the algae cultivation facility via pipe.

In the following, the analysis of the co-location alternatives considered is presented on the basis of an assumed inventory of biomass and resulting energy balances. Finally, results obtained using the ReCiPe method in the computation of environmental impacts based on these alternatives are discussed.

2. The goal and scope of the analysis

The analysis seeks to identify a preferred co-location solution between two realistic alternatives for an algal cultivation pond with a capacity of approximately 120 tons of dry algal biomass per year. The two sites considered for the co-location, i.e. the Ravensview wastewater treatment plant and the Bath Lafarge cement plant near the city of Kingston (Canada), were selected because they produce waste, i.e. flue gas and centrate, that can be employed as sources of CO_2 and nutrients for algae cultivation and because of their relative proximity (~36 km from each other). The industrial system for the production of biodiesel from microalgae considered in this analysis is shown in Fig. 1. In this study, the LCA adopts a consequential approach, i.e. it is not intended to quantify the whole environmental impact generated by the entire industrial system, but only the differences with respect to the two co-location alternatives, which only occurs at the algal cultivation phase.

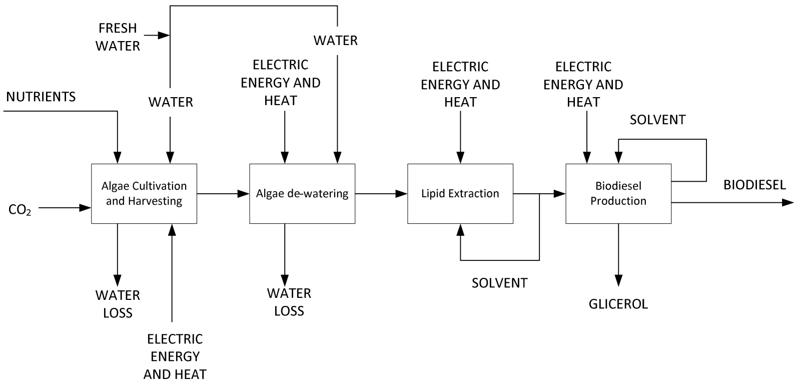

Fig. 1. Biodiesel from microalgae production process with main inputs and outputs.

Table 1 summarizes the main differences among the three scenarios considered, with respect to the supply of CO_2, nutrients and water for the algae cultivation.

Table 1. Scenarios overview.

Scenario	Co-location site	CO_2 supply	Nutrients supply	Water supply
Scenario 1a	Bath Lafarge cement plant	From cement plant flue gas	From centrate coming from wastewater treatment plant, transported to the algae pond with a tank truck	Fresh water
Scenario 1b	Bath Lafarge cement plant	From cement plant flue gas	From centrate coming from wastewater treatment plant, conveyed to the algae pond via pipe	Fresh water
Scenario 2	Ravensview wastewater treatment plant	From cement plant flue gas, conveyed to the algae pond via pipe	From centrate coming from wastewater treatment plant	Wastewater

The functional unit chosen for the study was the production of 1 kg of dry algal biomass. The selected strain, *Chlorella vulgaris,* achieve on average a biomass concentration of 0.1 % dry weight (DW), and was selected as a model species as it has been shown to grow well in wastewater, provide nutrient polishing, and is robust, as well as one of the predominant species in pond systems throughout North America [14]. As the cultivation conditions should be the same in all scenarios considered, the same lipid yield was assumed, regardless of the co-location.

3. Life cycle inventory

As stated above, the LCA analysis adopts a consequential approach and only the resulting differential input and output mass and energy flows were considered, as they concern the supply of CO_2, nutrients and water to the algae cultivation pond. For the selected algal species, *C. vulgaris*, and for open pond technology, the average growth rate of 25 $g/m^2/d$ (91 MT/m2/yr) was assumed [11, 14, 16, 17].

In an algal cultivation, several nutrients are required, as different metals, Calcium, Potassium, Magnesium, Vitamins, etc. Nevertheless, the two most demanded ones are Nitrogen and Phosphorous, and these are usually the growth limiting factors in a cultivation system. The anaerobic digester effluent (centrate) is a rich source of inorganic nutrients for photoautotrophic cultivations [18]. The analysis of the centrate produced at the Ravensview Wastewater Treatment plant revealed that the ratio of N:P was particularly high. Thus, the production capacity of the algal pond was limited in order to avoid additional CO_2 or nutrients supply requirements from external sources. Based on preliminary calculations [19], one of the techno-economic bottlenecks exists in the availability of Phosphate in the centrate produced by the wastewater treatment plant. The nutrient requirement for algal cultivation varies with specific algae species, but most optimizations are expected to be around the recommended Redfield ratio of C:N:P (106:16:1) [19]. The characteristics of the wastewater and centrate discussed in this work are relatively low in phosphate (Table 2). Although the nitrogen starvation is widely used to induce lipid accumulation, the lack of phosphate in a culture does not have the same effect [20]. Hence, this work considered the phosphate availability in the centrate and final effluent of the targeted wastewater plant as the limiting factor for culture scalability. The production capacity of the plant was, thus, limited to 120 tons (DW) of microalgae per year, which would require a pond size of approximately 1 ha, compatible with the land area available at the two co-location sites considered.

In case of scenario 1a, which involves the use of a tank truck to transport the centrate from the wastewater treatment plant to the cement plant, a 74 km route per round trip was assumed. Moreover, considering a tank capacity of 25m^3, this would require about 8 trips/day to transport the necessary centrate volume.

Table 2. Composition final effluent Ravensview wastewater treatment (Data collected from Revensview WWTP).

Ravensview Centrate unfiltered	Value	Ravensview Centrate unfiltered	Value
Daily centrate volume (m^3/d)	216.44	Phosphorus concentration (mg/l)	23.1
Total centrate volume (m^3/y)	48700	Nitrogen concentration (mg/l)	787
Phospate concentration (mg/l)	19.7	Potassium concentration (mg/l)	38

In determining the dimensions of the piping system to convey centrate from the wastewater treatment plant to the cement plant (scenario 1b), a flow rate of 9.53 m^3/h, 14 hours per day, was assumed and a pipe with a diameter of 120 mm with a length of 36.3 km was selected, entailing a dynamic pressure drop of 1.29 kg/cm^2 and requiring a pump absorbing 1.2 kW. A lifetime of 40 years was assumed. In determining the dimensions of the piping system to convey flue gas from the cement plant to the wastewater treatment plant (scenario 2), a CO_2 concentration of 22 % and a need of 1.8 kg of CO_2 per kg of dry algae biomass produced was assumed [15]. For a flue gas flow rate of 110 m^3/h, a pipe with a diameter of 20 cm and a length of 36.3 km was selected, entailing a dynamic pressure drop of 302 mm H2O and requiring an air turbine absorbing about 3,6 kW. A lifetime of 40 years was also assumed in this case. Table 3 summarizes the main inventory data for the selected functional unit, i.e. the production of 1 kg of algae (DW), and to each of the three scenario. Inventory data regarding fresh water refilling, tank truck, electric energy consumption, pipes construction and operations have been taken from the Ecoinvent V.2.2 database [15].

Table 3. Main inventory data for the production of 1 kg (DW) of algae biomass.

Inventory flow	Scenario 1a	Scenario 1b	Scenario 2
Transport by tank truck (tkm)	31.7143	-	-
Electric energy to convey flue gas via pipe (kWh)	-	-	0.0068578
Electric energy to convey centrate via pipe (kWh)	-	0.00228593	-
Pipe construction to convey flue gas (m)	-	-	0.0081
Pipe construction to convey centrate (m)	-	0.0081	-
Fresh water consumption (kg)	7,22	7,22	0

4. Life cycle impact assessment

The life cycle impact assessment quantifies the positive or negative impact of process inventory flows. For this analysis, the ReCiPe impact assessment method was adopted. It considers the following impact categories: climate change human health, ozone depletion, human toxicity, photochemical oxidant formation, particulate matter formation, ionising radiation, climate change ecosystems, terrestrial acidification, freshwater eutrophication, terrestrial ecotoxicity, marine ecotoxicity, agricultural land occupation, urban land occupation, natural land transformation, metal depletion and fossil depletion. All calculations were performed using SimaPro V7.3 software [21].

As previously stated, the objective of this work was to identify the preferable co-location option for an algae production plant between two alternatives sites and among three co- location scenarios. Fig. 2 presents the results of the comparison, trough characterization, between scenario 1a (i.e. co-location with Bath Lafarge cement plant and transport of centrate from Ravensview wastewater treatment plant by tank truck) and scenario 2 (i.e. co-location with the Ravensview wastewater treatment plant and flue gas conveyed from the Bath Lafarge cement plant via pipe). In particular, the red and green bars show the relative impact of the two scenarios compared in each impact category.

Results highlight a strong preference for scenario 2 for all impact categories, which is mainly due to the high environmental impacts associated with the transport of the centrate via tank truck. This is consistent with the fact that after normalization, shown in Fig. 3, the most impacted categories are fossil depletion, human health, human toxicity, particulate matter formation, climate change and natural land transformation.

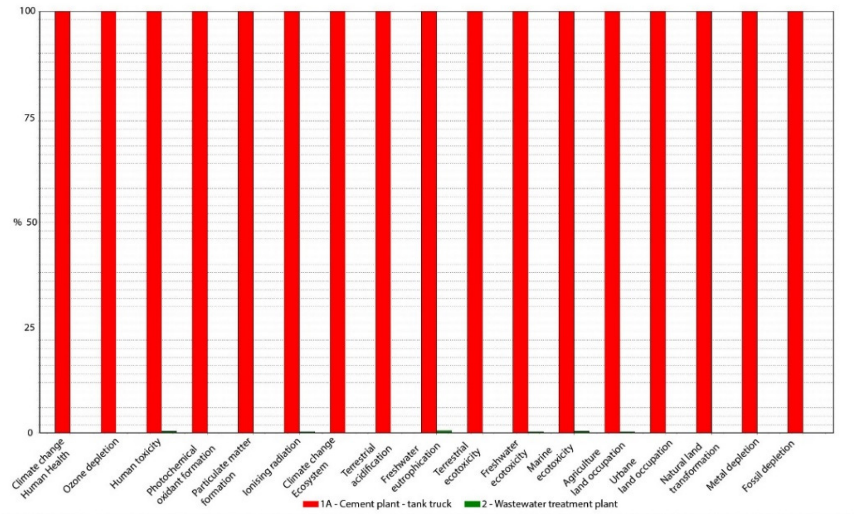

Fig. 2. Comparison between scenario 1a (red bars) and scenario 2 (green bars) after normalization.

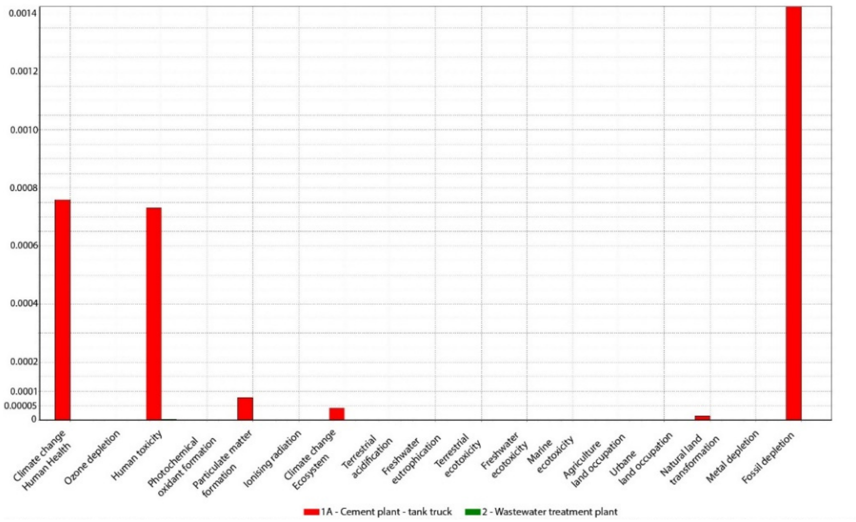

Fig. 3. Comparison between scenario 1a (red bars) and scenario 2 (red bars).

Fig. 4 and Fig. 5, the results obtained from the comparison between scenario 1b (i.e. co-location with Bath Lafarge cement plant and transport of centrate from Ravensview wastewater treatment plant via pipe) and scenario 2 (i.e. co-location with the Ravensview wastewater treatment plant and flue gas conveyed from the Bath Lafarge cement plant via pipe) are shown. For all the impact categories considered by the ReCiPe method, the severity of the impact of scenario 1b was three times higher than that of scenario 2. In this case, the differences between the two scenarios largely depended on the difference between the electric energy consumption of the pump for the transport of centrate containing nutrients and the electric energy consumption of the air turbine to convey the cement plant flue gas containing CO_2.

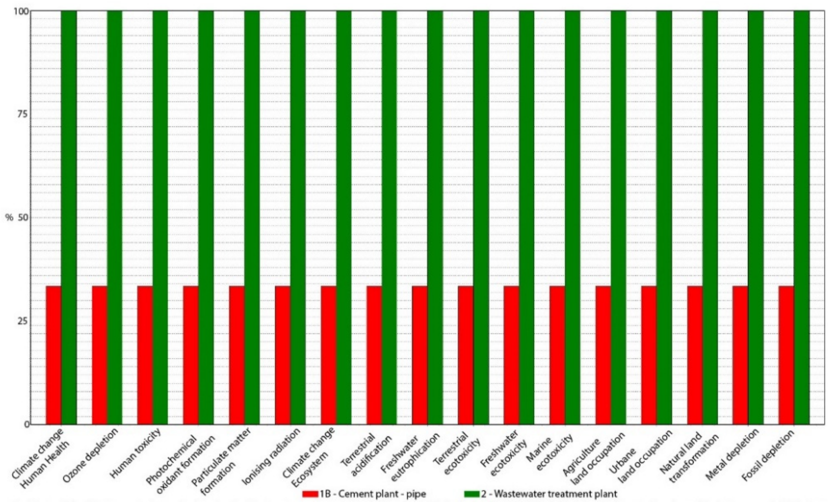

Fig. 4. Comparison between scenario 1b (red bars) and scenario 2 (red bars).

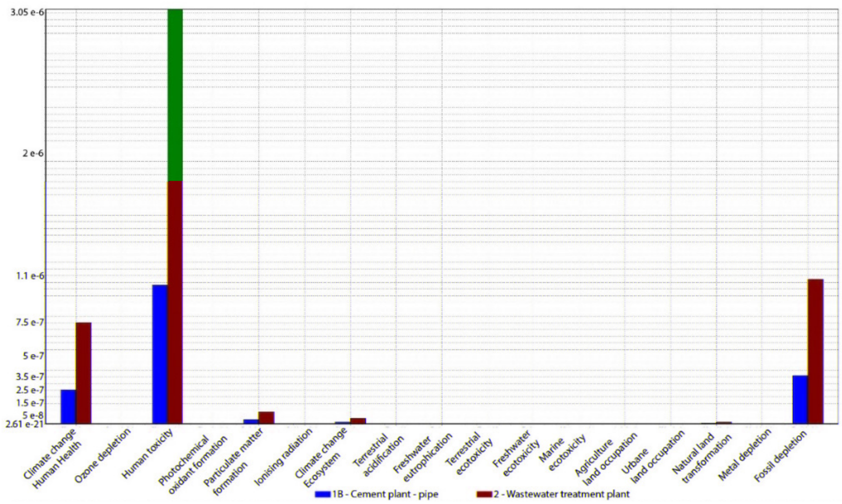

Fig. 5. Comparison between scenario 1b (red bars) and scenario 2 (red bars) after normalization.

5. Conclusion

In this work, a comparative life cycle assessment approach was used to examine two different, realistic alternatives for the co-location of an algal cultivation plant with an existing cement plant or with a wastewater treatment facility, both located near Kingston, Ontario, Canada. In the analysis, a consequential approach was adopted, meaning that only differential mass and energy inputs and outputs were quantified and assessed. The primary aim of co-location would be to make waste streams from these two plants, in particular centrate from WWTP and flue gas from cement plant as sources of nutrients and CO_2, available for the cultivation of algae. In both alternatives, in addition to the availability of centrate or flue gas (depending on the scenario considered), the concomitant transport of flue gas or centrate from each site was considered. With regard to the specific case under consideration, the results demonstrated that the best solution was in the co-location of the algal plant with the cement plant in case the transport of centrate from the wastewater treatment plant is performed via pipeline, while the transport of centrate with tank trucks implies a much higher environmental impact. More generally, it was also seen that, in both cases centrate and flue gas were transported via pipe, the preferred solution essentially depends on the energy consumption required for the transport of the waste streams, which indeed could considerably depend on the specific conditions, particularly the relative distance and the altitudes, of the co-location sites considered.

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