Biological Carbon Sequestration: Algae Biomass Farming

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Abstract

To align with Australia's target of net zero by 2050, the amount of carbon emitted by the energy sector needs to be reduced significantly through altering existing processes and through alternative means, or through the use of verifiable offsets. The client, a natural gas producer and exporter of Liquified Natural Gas (LNG), has been actively investigating innovative opportunities to achieve scope one net emissions by exploring carbon capture and storage options.

This CEED project evaluates the techno-economic feasibility of utilising microalgae biomass farming to aid in lowering carbon intensity of an industrial LNG. This project aims to identify suitable microalgal species for the greatest yield of carbon absorption and to assess the optimal conditions for carbon dioxide to be captured. This project is the first in a series to be conducted by the client. The intended outcomes for this project includes the production of an extensive literature review, case studies specific to the client's circumstances, and recommendations for future student research. Through the desktop study, it was determined that microalgal growth for the purpose of sequestering carbon was not feasible. Recommendations for future projects include investigating a wider range of microalgal strains, exploring the effects of saline water on growth, conducting experimentation, and conducting a more in-depth economic analysis of the system.

1. Introduction

Many Australian energy producers are exploring technologies and approaches to reduce the carbon intensitiy of energy production and achieve scope one net zero greenhouse gas emissions aspirations. Multiple technologies and approaches will be required to reduce global emissions, and geo-sequestration is unlikely to be suitable for all industrial sites. Due to the complex nature of the challenge, there is not an all-encompassing, one-size-fits-all solution, and therefore the client is interested in investigating a range of alternative technologies, approaches, and advances to reduce emissions, such as microalgal farming.

Algae are simple photosynthetic organisms and dependent on the species, have a high tolerance to a range of aquatic environmental factors, including temperature, pH, salinity, water conditions and light intensities (Khan et al., 2018). Algae require sufficient access to light, water and nutrients, however arable land is not required for growth and thus it does not compete with agriculture and the growth of food crops.

Microalgae is a strong candidate for carbon sequestration due to the photosynthetic properties of the organisms. Through photosynthesis, microalgae transforms CO_2 into oxygen and sugars, and along with cyanobacteria, is responsible for the production of approximately half of the atmospheric oxygen (Lehmuskero et al., 2018). The photosynthetic efficiency of microalgae typically ranges between 10-20%, while the majority of terrestrial plants range from 1-2% (Singh & Ahluwalia, 2013). The sequestration and photosynthetic abilities of microalgae plays a vital role in the carbon cycle and thus has great potential for CCS (Lehmuskero et al., 2018).

The literature review for this project had been produced to understand background information, to review the key considerations required for optimal microalgal growth and carbon absorption in the contextualised setting, and to build case studies upon. A section of the literature review that was important to building the case studies was the assessment of microalgal species' tolerance to the client's conditions.

The main objectives of this project were to assess the economic feasibility and carbon sequestration potential of microalgal cultivation, where CO_2 has been redirected from an industrial LNG facility in North Western Australia. Other objectives of the project include understanding the fundamental roadblocks and enablers associated with algal bio-sequestration, identifying suitable microalgal species for the greatest yield of carbon absorption, and assessing the synergistic benefits associated with recycling wastewater.

2. Process

The aims and objectives of this project have been achieved through conducting a literature review and building case studies specific to the client's conditions.

The aim of building case studies was to conduct a high-level techno-economic analysis and assess the feasibility of the project. The case studies were achieved through modelling microalgal growth rates in the client's contextualised setting, accounting for the client's hot weather conditions, quantity of carbon dioxide available, and the feedwater nutrient composition. Wastewater from one of the client's LNG facilities was analysed to assess the composition of nutrients present to indicate if additional nutrients would be required for the microalgal growth systems.

There were three different models trialled when building the case studies, including mathematical models, the SABANA model (SABANA, 2021), and the Greene et al. model (Greene et al., 2021). It was important for the model to be able to simulate a year's worth of growth to understand annual production, the productivity of microalgae, nutrient consumption during growth, and the amount of carbon dioxide consumed.

2.1 Models Investigated

2.1.1 Mathematical Models

Mathematical growth kinetic models were the first type of model explored. Some mathematical models consider a single variable while others consider multiple variables, generally substrate and environment specific. These models were sourced from scientific papers and were input into Microsoft Excel to model algal growth rates. The various mathematical models trialled for this project included the Monod equation, which accounts for a limited number of variables, and the Ketheesan and Nirmalakhandan equation, which accounts for a greater number of variables. Both equations were deemed too simple for the purposes of this project as not enough key growth considerations were included. It is extremely difficult to account for the majority of growth factors in a single equation and thus to fulfil the aims of this project a more complex model was required.

2.1.2 The SABANA Model

The Sustainable Algae Biorefinery for Agriculture and Aquaculture (SABANA) project was funded by the European Union's Horizon 2020 Research and Innovation program with partners from various universities, companies, and research centres (SABANA, 2021). SABANA developed a model which intended to simulate microalgae production in raceway ponds and tubular photobioreactors (PBRs). This model was significantly more intricate than the mathematical growth kinetic models as it required a larger range of parameters, including environmental (i.e., pH, dissolved oxygen, and temperature), biological species specific (i.e., ideal ranges for pH and temperature, form exponent and maximum photosynthesis rate), and pond design (i.e., reactor length, width, height) (Hoyo et al., 2022).

The primary author and creator of the simulation software was contacted to clarify how tubular PBRs could be simulated with the available version of the model, to explain complex parameters, and how to obtain other difficult to find parameters. No reply was received and thus the SABANA model could not be used simulate the growth of microalgal species with the client's conditions. The SABANA model was determined as inadequate for this project.

2.1.3 The Greene et al. Model

The Greene et al. model is able to simulate both raceway pond reactors and vertical flat plate PBRs (Greene et al., 2021). The useful parameters produced by the model include areal productivity in ash free dry weight (a weight measurement for organic material), water demand, CO_2 demand, and nutrient demand. Required input variables include the desired location (to simulate weather conditions), simulation period, pond design parameters, selection of microalgal strain from the included strain library, harvesting parameters, and optional CO_2 and nutrient consumption parameters.

Included in the model's strain library, the three available raceway pond strains are Nannochloropsis oceanica, Chlorella vulgaris and Desmodesmus intermedius, and the two available vertical flat plate PBR strains are Galdieria sulphuraria soos and Galdieria sulphuraria 5587.1. The three raceway pond species are amongst the most popular and widely used for large scale microalgal growth, and the two PBR strains were included in the model due to their wastewater treatment potential and feedstock potential for biofuel production (Greene et al., 2021).

The model's in-built strain library is beneficial as not only are the microalgal strain's temperature, light, concentration, and respiration parameters included, but these parameters have been calibrated using literature and experimental data from various locations (Greene et al., 2021). Conducting experimentation in different climatic conditions to calibrate and validate the model provides a degree of confidence associated with the outputs of the model.

Only towns and cities within America could be selected for the modelled location, thus, the widely used Köppen-Geiger climate classification was utilised to find a representitive climate to the client's conditions. Phoenix was found to be the most representative and was used as the location during modelling as both the North West of Australia and Phoenix, Arizona are considered dry, hot, arid deserts by the climate classification.

The wide range of input parameters required by the user was sufficient and detailed enough to build good case studies. The Greene et al. model was determined as the best fit to assess the feasibility for this project.

2.2 Case Studies and Techno-Economic Analysis

After determining the appropriate model for simulation of microalgal growth and CO_2 consumption, case studies were produced to simulate growth in two different growth systems (raceway pond and photobioreactor). From the five species across the two different growth mediums available on the Greene et al model, the two case studies comprised of the most productive strains of each growth medium type. All three strains available for the raceway pond and both strains for the flat plate PBR were used to simulate growth under the contextualised conditions.

A high-level techno-economic analysis was conducted on both case studies to provide an indication of the feasibility of cultivation for effective carbon sequestration. The analysis was conducted through applying and scaling the cost of a microalgal cultivation plant to the case studies. Norsker et al. (2011) determined the capital and operational costs associated with raceway ponds and vertical flat plate PBRs for a 100 ha plant. The costing of the 100 ha plant was applied to the two case studies to estimate the cost per biomass of dry weight produced, and thus the cost per kilogram of CO_2 sequestered for each growth medium. These values were then compared against the current cost of an Australian Carbon Credit Unit (ACCU) as a basic measure to assess the economics of using microalgal cultivation to aid in lowering carbon intensity of their operations.

3. Results and Discussion

After comparison of the raceway strains with equivalent architecture parameters (3,600 m^2), Chlorella vulgaris was determined as the strain with the highest areal productivity at 9,904.10 kg/year, and the highest average CO_2 demand of 13,908.45 kg/year. The Chlorella vulgaris areal productivity was nearly twice that of Nannochloropsis oceanica and Desmodesmus intermedius. After comparison of the vertical flat plate PBR strains with equivalent architecture parameters, Galdieria sulphuraria soos was determined as the better strain for areal productivity and CO_2 demand, with values of 10,481.93 kg/year and 4,271.30 kg/year, respectively.

It cannot be said with certainty why the CO_2 consumption of the vertical PBR is less than that of the raceway reactors, while the inverse was expected to be true as PBRs generally have a greater efficiency. It is not specified by the Greene et al. article if the entirety of the CO_2 demand is consumed during cultivation, or if it had accounted for quantities of CO_2 to be released into the atmosphere. If the latter is true, there is a greater surface area of raceway ponds open to the atmosphere and thus explains why there is a greater CO_2 demand. This is a hypothesis that should be investigated by a future student by reaching out to the authors of the model and conducting further research.

The 100 ha plant cost estimates from Norsker et al. (2011) were assumed to be applicable for the high-level techno-economic analysis. The client views the capital costs associated with microalgal cultivation as an investment and was not to be included in the final costing of CO_2 sequestered. Thus, the on-going operational costs were used for calculations and found to be $32,212.3 p.a. for Chlorella vulgaris in raceway ponds and $28,160.9 p.a. for Galdieria sulphuraria soos in vertical flat plate PBRs. The sequestration cost for Chlorella vulgaris cultivated in raceway ponds was calculated as $2,316.0/tonne of CO_2 and the cost for Galdieria sulphuraria soos cultivated in vertical flat plate PBRs as $6,593.0/tonne of CO_2.

An ACCU is equivalent to the storage or prevention of one tonne of CO_2-e of a project. The current cost of 1 ACCU is $37.75 (Core Markets, 2023) which is considerably less than the cost to sequester CO_2 with microalgal cultivation through both raceway ponds and vertical flat plate PBRs. With current technology, microalgal cultivation for carbon sequestration is not economically feasible, and it is recommended the client should investigate ways to increase feasibility as well as alternative means to reduce carbon emissions that are more economically viable. The capital and operational costs associated with microalgal cultivation plants of this calibre are significant and heavily contributes to the production cost of biomass and thus the carbon sequestration cost. Technological progress is to be made towards increasing the productivity of growth while decreasing the associated production costs for such a project to be economical.

4. Conclusions and Future Work

Through conducting a literature review, producing case studies and a high-level techno-economic analysis, carbon sequestration through microalgal cultivation attached to an LNG facility in North Western Australia was found to be infeasible with the current conditions and technologies. The client and future students should critically investigate mechanisms to enhance feasibility, the growth of microalgae under the contextualised setting, and alternative economically feasible means of reducing carbon emissions.

This project provides a good foundation for the client and future students to understand the context surrounding the importance of lowering carbon intensity and the potential of sequestration through cultivating microalgae. Future students will be able to use this work as a stable foundation to build research upon. It is recommended that future students investigate a wider range of microalgal strains and implement the strain biological parameters into the Greene et al. model, research the effects of saline water on the growth of specific strains of microalgae, conduct experimentation of microalgal growth on a lab and pilot scale on-site to investigate growth and CO_2 fixation potential in the client's contextualised setting, explore the useful products microalgae biomass can produce, and conduct a more in-depth economic analysis of the system.

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6. References

Core Markets. (2023). Carbon and environmental market price update. Retrieved 9th May 2023 from https://coremarkets.co/resources/market-prices

Greene, J. M., Quiroz, D., Compton, S., Lammers, P. J., & Quinn, J. C. (2021). A validated thermal and biological model for predicting algal productivity in large scale outdoor cultivation systems. Algal research (Amsterdam), 54(C), 102224. https://doi.org/10.1016/j.algal.2021.102224

Hoyo, Á., Rodríguez-Miranda, E., Guzmán, J. L., Acién, F. G., Berenguel, M., & Moreno, J. C. (2022). A computer-based tool to simulate raceway photobioreactors for design, operation and control purposes. Computers & chemical engineering, 156, 107572. https://doi.org/10.1016/j.compchemeng.2021.107572

Khan, M. I., Shin, J. H., & Kim, J. D. (2018). The promising future of microalgae: current status, challenges, and optimization of a sustainable and renewable industry for biofuels, feed, and other products. Microbial Cell Factories, 17, Article 36. https://doi.org/10.1186/s12934-018-0879-x

Lehmuskero, A., Skogen Chauton, M., & Boström, T. (2018). Light and photosynthetic microalgae: A review of cellular- and molecular-scale optical processes. Progress in oceanography, 168, 43-56. https://doi.org/10.1016/j.pocean.2018.09.002

Norsker, N.-H., Barbosa, M. J., Vermuë, M. H., & Wijffels, R. H. (2011). Microalgal production — A close look at the economics. Biotechnology advances, 29(1), 24-27. https://doi.org/10.1016/j.biotechadv.2010.08.005

SABANA. (2021). Project. Retrieved 25th April 2023 from http://www2.ual.es/sabana/project/

Singh, U. B., & Ahluwalia, A. S. (2013). Microalgae: a promising tool for carbon sequestration. Mitigation and Adaptation Strategies for Global Change, 18(1), 73-95. https://doi.org/10.1007/s11027-012-9393-3