Assessment of Environmental and Economic Footprints of Algae Production Systems for Colder Climate

By

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A thesis submitted in partial fulfilment of the requirements for the degree of

Doctor of Philosophy

In

Engineering Management

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University of Alberta

Abstract

Many open pond raceway (OPR) production systems for algae cultivation continue to be developed for moderate and hot climates (e.g., the USA, Europe and Australia). However, there has been very limited research on economic and environmental evaluations to assess whether these systems can be applied in Canadian northern climatic conditions commercially. Nor has a study been conducted to determine either the economic or the environmental impacts of using algae biomass as a feedstock for conversion to diluent and hydrogen for Canadian oil sands.

This thesis evaluates the techno-economics of cultivating algae in Colder climate like Canada via both OPR and photobioreactor (PBR) technology systems. The research focussed on developing a data-intensive analytical model that considered environmental factors to predict algae yields of 2,000 tonnes per day. The results are provided by way of a comparative techno-economic assessment (TEA). Comparisons between OPR and PBR technologies based on TEA reporting provide optimistic insights and recommendations related to the economic sustainability of an algae industry in Canada.

Where the calculated minimum biomass selling price (MBSP) for algae produced by OPR and PBR at present is \$1,288 T^{-1} and \$550 T^{-1} respectively, the techno-economic research provides optimism that biomass production at below \$200 T^{-1} may be achievable, especially where PBR technologies are used.

The study evaluates the environmental impacts of both algae biomass cultivation and downstream thermochemical conversion via four conversion pathways to diluent and hydrogen through life cycle analysis (LCA): hydrothermal liquefaction and pyrolysis for diluent production, and supercritical water gasification (hydrothermal gasification) and thermal gasification hydrogen production hydrogen.

From the results of the research we can conclude that good, net negative LCA outcomes (-1.0 and -0.9 T CO_2 sequestered T^{-1} biomass produced, -41.1 and -35.5 net g CO_{2e} produced MJ^{-1} algae biomass produced) may be achieved during OPR and PBR cultivation respectively.

Preface

This thesis is an original work by Stanley Pankratz under the supervision of Dr. Amit Kumar. The analytical model developed to predict algae cultivation in open ponds found in Chapter 4, economic analysis found in Chapter 5, the life cycle assessment associated with the cultivation of microalgae found in Chapter 6, concluding analysis in Chapter 7 are my original work, as well as the review of microalgae phytology, and literature review of microalgae technologies applicable for the cultivation of algae in Canada found in Chapters 2 and 3.

Chapter 3 of this thesis has been published as S. Pankratz, A Oyedun, X. Zhang, A. Kumar, "Algae production platforms for Canada's northern climate", *Journal of Renewable and Sustainable Energy Reviews*, vol. 80, 109-120, 2017. I was responsible for the data collection and manuscript composition. Post-doctorates X. Zang and A. Oyedun provided primary advisory assistance. Dr. A. Kumar was the supervisory author with involvement with concept formation and manuscript composition.

Chapter 4 of this thesis has been forwarded for publication as "Novel satellite based analytical model to predict microalgae yields in open pond raceway systems and applied to Canadian sites", *Journal of Algal Research*, vol. 39 (101431) 2019. I was responsible for the data collection and manuscript composition. A. Blodget contributed to manuscript edits, Post-doctorate A. Oyedun provided primary advisory assistance. Dr. A. Kumar was the supervisory author with involvement with concept formation and manuscript composition.

Chapter 5 of this thesis has been accepted for publication as S. Pankratz, A. Oyedun, A. Kumar, "Development of cost models of algae production in cold climate using different production systems", *Journal of Biofuels, Bioproducts & Biorefining,* pending publication[1]. I was responsible for the data collection and manuscript composition. A. Blodget contributed to manuscript edits, Post-doctorate A. Oyedun provided primary advisory assistance. Dr. A. Kumar was the supervisory author with involvement with concept formation and manuscript composition.

Chapter 6 of this thesis is being submitted for publication as S. Pankratz, M. Kumar, A. Olyedun, E Gemechu, A. Kumar, "Comparative life cycle assessment of fuel and chemical production from microalgae cultivated in Canadian open raceway ponds and photobioreactors", *Journal of Cleaner Production*, pending submission for publication. I was responsible for the data collection related to the downstream algae cultivation, associated manuscript composition, compilation of combined research results. My colleague M. Kumar was responsible for developing AspenPlus models for microalgae downstream thermochemical processing via four pathways through to the production of hydrogen and diluent, along with associated LCA calculations along with preparation of tables and graphs. A. Blodget contributed to manuscript edits, Post-doctorate A. Oyedun provided primary advisory assistance. Dr. E. Gemechu provided advisory LCA assistance. Dr. A. Kumar was the supervisory author with involvement with concept formation and manuscript composition

Dedication

"All men dream; but not equally;
Those who dream by night in the dusty recesses of their minds
Awake to find that it was vanity;
But the dreamers of day are dangerous men,
That they may act their dreams with open eyes to make it possible."
T.E. Lawrence

The LORD had said to Abram, "Leave your native country, your relatives,
and your father's family and go to the land that I will show you."
Genesis 12:1 New Living Translation (NLT)

Life is not so much about endpoints as it is about the journey.
It is along the journey, in how we process life, that we define who we will yet become,
to leave the fragrance of our interaction with those that we meet, to impact them
and our world, hopefully for good, and to remind them of the Creator that put us here.
Stan Pankratz

Acknowledgements

The journey leading me into my PhD studies are in large measure the direct result of major personal life adversity, which in turn led to assisting a commercial enterprise to advance their algae cultivation technology, in part by promoting not only the company but the algae industry within Alberta to our Provincial Government. The "pitch" to the Government was that algae, if given proper support, had the potential to help mitigate and address the ever-increasing CO_2 emissions associated with oil-sands operations. Where calculations had been made related to the favourable environmental and economic impact that algae could achieve, what we were apparently missing to convince the Government in providing support to this emerging industry was more rigorous academic research related to both the environmental impacts and economic viability. Hence there was a need for a PhD study. It was as a result of "raising my hand" to inquire whether I could become the appointed researcher for this study in 2012, that my journey leading to completing this thesis began.

One might say that my research has been the result of the "butterfly" effect. God placed me on planet earth in time and space, along with an infinite number of events in between to prepare me for this next "blind" step into research. As I complete this phase of studies I will again be stepping toward a yet unknown destination – what I will yet become and accomplish as a result of these studies. However, I have been preparing for the journey.

I am indebted with heart of gratitude to my beloved wife Elsie, for her stalwart encouragement, love and support, and without which, these studies would not have been possible. I am deeply thankful to my children, Kyle and Vanessa (Aaron) who have likewise shown their love and support throughout this period of studies, along with extended family and close friends.

My gratitude goes to Art Deane, President of Symbiotic Envirotek Inc. for his invitation to provide assistance to his algae cultivation initiatives, in part by increasing the awareness of both the company's initiatives and the potential of an algae industry in Alberta to the Provincial Government. My gratitude goes to Dr. Susan Wood-Bohm, who at the time when I approached the Government, was Executive Director of the Biological GHG Management Program funded by the Emissions Reduction Alberta and delivered in partnership with Alberta Innovates. It was as a direct result of her encouragement and introduction to Dr. Amit Kumar, the Head of the Analytical Biomass Modeling Group with the University of Alberta, Mechanical Engineering Faculty that I made application and was accepted into the Mechanical Engineering Program. Dr. Kumar became my PhD Supervisor and I extend my special thanks and gratitude to him in that role and for his ongoing support throughout the course of my Doctoral studies.

Gratitude is given to my supervisory and examination committee members: Dr. Mohtada Sadrzadeh, Dr. Raj Gupta, Dr. Zhigang (Will) Tian and Dr. Bipro Dhar, for their feedback in support of my studies and to my Technical Advisory Committee including: Steve Price, Christine Murray, Susan Wood-Bohm, Alberta Innovates; Art Deane, Symbiotic Envirotek Inc. My gratitude goes to Post Doctoral Fellows in our Biomass Group, Dr. Adetoyese Olajire Oyedun, Dr. Eskinder Gemechu, and Dr. Xiaolei Zhang for their personal contributions to my research, along with Astrid Blodgett for her valuable editorial support. I am grateful to my fellow research colleagues Mayak Kumar and Edson Nogueira Junior who participated with me on this research project. My gratitude also extends to: Dr. Suresh Kumar Jayaraman, Dr. Hecter Dela Hoz Siegler, Dr. Joule Bergerson, Dr. Neil Ross, Dr. Marc Strous, Dr. Christine Sharp, Dr. Michael Lipsett, Dr. Christian Jacob for support, feedback and discussions related to my studies. Beyond this there have been interactions and conversations with a host of researchers, Government leaders, business leaders and fellow life travelers that have each contributed through their interactions to my research, and for which I am grateful.

This research was made possible thanks to the financial support provided by National Science and Engineering Research Council of Canada (NSERC), Emissions Reduction Alberta (ERA), Alberta Innovates, Symbiotic EnviroTek Inc. and the University of Alberta, Department of Mechanical Engineering. I am also thankful for the travel and professional grants awarded by the Faculty of Graduate Studies and Research (FGSR), the Graduate Student Association (GSA), Shell Enhanced Learning Fund (SELF), Canadian Heavy Oil Association (CHOA), and the Algae Biomass Organization (ABO) Mary Rosenthal Travel Grant Award.

The author is grateful to Ms. Astrid Blodget for editing the thesis.

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A	Arrhenius constant	
AFDW	Ash free dry weight	
ATP3	Algae testbed public private partnership	
ARID-HV	Algae raceway integrated design – high velocity	
AzCATI	Arizona Center for Algae Technology and Innovation	
B	Biomass concentration	$g\ L^{-1}$
B_D	Biomass comprised of dead algae cells	
B_L	Biomass comprised of live algae cells	
B_{init}	Biomass initial concentration	$g\ L^{-1}$
BAT	Biomass assessment tool	
CAPEX	Capital expenses	
C_x	Nutrient concentration	$g\ L^{-1}$
CLIGEN	Climate Generator	
CO_2	Carbon dioxide	
d	Day	
D	Depth	$0.25\ m$
DAP	Di-ammonium phosphate	
d_B/d_t	Change in biomass / change in time	$gL^{-1}d^{-1}$
DW	Algae dry weight	$g\ L^{-1}$
E	Activation energy	
GHG	Green house gas	
GHI	Global horizontal irradiance	$kWh\ m^{-2}day^{-1}$
GMAP	Global modeling and assimilation office	
GWP	Global warming potential	
H_2	Hydrogen	

HTL	Hydrothermal liquefaction	
I_{avg}	Average light intensity for period	$W\ m^{-2}$
I_{init}	Incident light intensity	$W\ m^{-2}$
I_{β}	Light intensity transmitted through media	$W\ m^{-2}$
ISO	International Organization for Standardization	
K_a	Algal extinction coefficient for living cells	0.014 +/-0.0003
K_C	Half-velocity constant, concentration @ μ / $\mu_{\max}$ = 0.5	
K_n	Nonalgal turbidity extinction coefficient	0
K_{p}	Biomass production attenuation coefficient	0.00076
K_t	Temperature effect coefficient	0.00001
K_x	Species rate constant	
LCA	Life cycle assessment	
LED	Light emitting diode	
MBSP	Minimum biomass selling price	
MCS	Microalgae cultivation system	
MJ	Megajoule	
N	Nitrogen	
NAABB	National Alliance for Advanced Biofuels and Bio-products	
NASA	National American Space Administration	
NREL	National Renewable Energy Laboratory	
NRC	National Research Council of Canada	
NSERC	Natural Sciences and Engineering Research Council	
OPEX	Operating expenses	
OPR	Open pond raceway	
P	Phosphate	
PAR	Photosynthetically active radiation	
PBR	Photobioreactor	

PY	Pyrolysis	
R	Universal gas constant	8.314 J mol^{-1} K^{-1}
r_x	Rate of consumption of nutrient	
RABR	Rotating algal biofilm reactor	
SATOPR	Satellite open pond raceway	
SCO	Synthetic crude oil	
SCWG	Supercritical water gasification (hydrothermal gasification)	
SRB	Surface radiation budget	
T	tonnes	
T	Media temperature	°C.
T_{amb}	Ambient temperature 2m above surface	°C
T_{opt}	Optimum growth temperature	26.7 °C
T_{min}	Minimum temperature required for growth	-2 °C
T_{max}	Maximum temperature for growth)	33.3 °C
TEA	Techno economic analysis	
TG	Thermal gasification	
U	Growth rate	$gL^{-1}d^{-1}$
U_{opt} (max)	Maximum growth rate	$gL^{-1}d^{-1}$

1. Introduction

Background

The alarming rise of global temperatures and issues with smog have prompted Governments to take action to reduce green house gas (GHG) emissions. In Canada, Alberta's energy sector and particularly the related oil sands operations and downstream petrochemical processing contributes the majority of the Province's GHG emissions[2]. In Alberta, emphasis has been placed on reducing the energy intensity associated with operations through both carbon capture and storage (CCS) and developing a renewable energy program to offset emissions[2, 3].

Fortunately Canada has an abundance of renewable energy sources including wind, solar, hydro, geothermal and biomass[4]. Biomass sources in Canada include forest related plant material[5], agricultural plants[6] and microalgae[7].

Algae have biomass production rates 30 to 100 times higher than most agricultural and forest-based biomass [8]. It is for this reason that large resources are being invested globally in algae research in the anticipation that these microorganisms will become the "silver bullets" that lead to economic bio-renewable fuels, new food sources, and a host of high value products and simultaneously mitigate rising atmospheric CO_2 levels[9, 10].

These single-celled plants are extraordinary in their capacity to more than double biomass within a single day [11]. Research has shown the plant's ability to synthesize a host of highly valued products including bio-oils for energy [12-20], hydrogen and isoprene [21], food, livestock and fish feed [22, 23], and coveted health and nutrition ingredients [24-28] while simultaneously improving water [29-31] and air quality [32-36]. For these reasons, alga is seen to hold enormous potential for meeting a number of our world's pressing challenges.

A great deal of research has been completed on strains of algae with the potential to produce high lipid yields that make the biomass suitable for biofuel production. Many production systems for algae cultivation continue to be developed for moderate and hot climates (e.g., the USA[37, 38], Europe, India[37] and Australia[7, 39]). The largest algae cultivation systems to date use open pond systems [40]. These autotrophic systems, however, have limited applicability for Canada's (northern) climatic conditions. There is general consensus that closed photobioreactor systems would be required to control environmental conditions (i.e., temperature), minimize evaporation and contamination, and augment the limited sunlight available during the winter to generate consistent biomass yields that would enable economically sustainable crops[7, 41]. Several photobioreactor cultivation technologies have been developed for the cold Canadian climate[7]. Given the associated high capital and operating costs, many observers are skeptical that meaningful and economically sustainable algae cultivation can take place in Canada[42]. A detailed literature review is provided in chapter 3.

Given the absence of information related to algae cultivation in Canada, a comprehensive, quantitative analysis related to both the economic sustainability of cultivating algae in Canada and a similar environmental impact study to provide carefully researched answers to these cultivation activities are needed.

Objectives of the research

Fuels and chemicals produced from biomass are gaining much interest as they have a lower greenhouse gas (GHG) footprint over their life cycles than similar conventional fossil fuel based products[43, 44]. In Alberta which is home to one of the world's largest oil sands deposits[45], hydrogen and diluent are two key petrochemicals that are used extensively for upgrading the oil bearing bitumen[46] and subsequent transport of the resulting heavy oil[45].

Hydrogen is required to upgrade bitumen and this use is anticipated to increase significantly in future[47]. Currently most of the required hydrogen is produced from natural gas. Bitumen is mixed with diluent for pipeline transport and this demand will also increase in the future[47]. If hydrogen and diluents were produced from algal biomass, the greenhouse gases (GHG) footprint of oil sands could be significantly reduced.

The overall goal of the current research is to assess algae utilization to produce hydrogen and diluent for applications in the Canadian oil sands.

This research study assesses a range of algal production systems in a cold climate, i.e., the Canadian context, on a comparative basis. The results of this research will provide the petroleum industry and interested government departments with a clearer understanding of the breadth of subject material from multiple scientific and engineering disciplines that are entwined in the algae industry, costs and sustainability of algal-biomass production, as well as associated environmental impacts.

The specific objectives of this research are to:

a. Review current microalgae cultivation technologies that may be applicable to Canada's geography;

b. Evaluate existing analytical models to predict biomass yields in Canada based on open pond raceway (OPR) and photobioreactor (PBR) algae cultivation systems;
c. Construct a unique, data-intensive analytical model based on satellite ambient temperature and irradiance measurements to predict site-specific algae cultivation yields and facilitate rapid comparative evaluation of cultivation systems found in different geographic locations;
d. Develop data-intensive techno-economic assessment models for algae biomass cultivation based on a comparison of Canadian OPR and PBR cultivation systems;
e. Conduct a "cradle-to-gate" life cycle assessment (LCA) based on a comparison of Canadian OPR and PBR cultivation systems producing algae biomass feedstock;

The achievement of these objectives provides insights into the emerging algae industry considering factors that affect production and the state of support for technological development in Canada to cultivate algae given its geographic and climatic context. The research therefore, offers insights and considerations necessary to make recommendations related to the application of algae cultivation systems to produce biomass to be used downstream for diluent and hydrogen in Alberta oil sands operations.

Scope and limitation

a. The study focuses primarily on a conventional OPR and a unique PBR algae cultivation system, both modelled as constructed in Canada.
b. This study considers the production of 2000 T d^{-1} as commercial scale production with a representative production minimum biomass selling price (MBSP) of \$(USD) T^{-1} algae biomass produced (20% solids).
c. Downstream processing and conversion of algae biomass for production of diluent and hydrogen for oil sands operations is addressed by others.

Organization of the report

This thesis has six chapters. Chapter 1 is a general introduction. This chapter provides an overview of the thesis beginning with a discussion related to the knowledge gap that the research sets out to address. A discussion of the problem and objectives that that the research attempts to achieve will follow to provide the reader with an understanding of the structure of the thesis. Chapter 2 reviews the topic of microalgae, its phytology, photosynthesis, and cultivation techniques, as well as algae's potential use as a biomass feedstock for downstream processing to energy-related products. Chapter 3 focuses on algae cultivation technologies with potential application in Canada. Chapter 4 discusses the development of SATOPR (SATellite Open Pond Raceway), a unique data-intensive analytical model that uses satellite data to predict algae cultivation yields at site-specific locations in Canada and around the globe. Both a conventional open pond raceway and a unique photobioreactor system are presented. Chapter 5 presents a techno-economic analysis of algae cultivation through both OPR and PBR technologies, with consideration for the effects of geography. Chapter 6 provides a life cycle assessment of the cultivation of algae biomass, again comparing OPR and PBR cultivation system performance. Conclusions related to this research are provided in Chapter 7 along with a series of recommendations for future research. References throughout this work may be found at the end of the report.

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2. Algae cultivation in Canada[1]

Much of commercial algae cultivation to date has taken place in geographic regions where the energy of sunlight is prevalent, temperatures are moderate and there is a ready source of water and low-cost nutrients. The most prevalent commercial scale algae cultivation operations have chosen to use open ponds raceway (OPR) systems. It is relatively "low tech" and is considered to be the most cost-effective approach from an initial capital outlay perspective. Therefore, it offers a good potential to achieve a viable and economically sustainable operation. However, the system also has significant drawbacks and vulnerabilities.

From a geographic climatic perspective, OPR systems are viewed as a less than ideal algae growth platform for a Canadian context. They would only be operational for four to eight months annually. Due to this seasonal challenge, pond systems are not seen to be an economically viable algae growth model for this region. Although

[1] A version of this chapter has been published as a peer-reviewed journal. Pankratz S, Oyedun AO, Zhang X, Kumar A. Algae production platforms for Canada's northern climate, *Renewable & Sustainable Energy Reviews*, 2017, 80: 109–120.

conventional thinking persists, there are no known research attempts to experimentally quantify or model open pond systems in Canada.

To bridge the climatic challenge, a number of alternative controlled environmental algae growth technologies have been developed. These include photo-bio-reactor (PBR) systems for cultivating algae under phototrophic/autotrophic conditions, flat plate and membrane systems, plastic tube systems, as well as fermenters that take advantage of algae's unique capability to grow in heterotrophic conditions in the absence of light and rely on other carbon sources rather than sunlight for the energy used in their growth. Other algae cultivation systems utilize both autotrophic and heterotrophic conditions (mixotrophic) to achieve their growth objectives.

There have been a number of commercial attempts to develop algae cultivation technologies that achieve economic sustainable production levels. Most of these commercial attempts have failed to achieve sustainability and have withdrawn from active commercial / research and development activities. Companies that were formerly involved include: SFN Biosystems Inc. (Calgary), International Energy Inc. (Vancouver); Centurion BioFuels Corp. (Hamilton) and recently renamed to Algaeneers Inc. which is looking to convert glycerin to n-butanol; Algae Fuel Systems (Saskatoon).

The National Resources Canada – National Research Council of Canada (NRC) provides a context for algae technology development within Canada.

The NRC Institute for Marine Biosciences in Halifax has a history spanning more than 50 years of cultivating algae. Since prior to 2010 the Government of Canada [48] put together a multiparty research and development (R&D) program, linking both the Agricultural and Agrifood Canada with National Resources Canada (AAFC) – National Research Council of Canada (NRC) to set in place a National Bioproducts Program (NBP) with the objectives to address Canadian priorities for: Sustainable Energy; Environment; Rural Revitalization. It was proposed that this would provide the means to bring together stakeholders and expertise from Government, academia and industry to tackle this large scale multi-dimensional project.

NBP identified microalgae biomass as holding the greatest potential to meet the stated objectives and set out to develop and support Canadian industries focused on the production of renewable fuels from microalgae biomass for electrical generation, land transportation and aerospace applications. NBP's threefold goals were to be able to achieve biomass production capability that would be cost effective and competitive with other conventional energy sources; provide a positive impact on the environment and sustainable energy; and contribute to the economic vitality of the Canadian energy sector.

To achieve the desired outcomes a number of significant barriers would need to be overcome. One major barrier is the identification of algae strains that demonstrate the best potential for producing biofuels. Efficient and scalable cultivation technologies for Canadian climatic conditions would have to be developed. Furthermore, cost effective industrial scale processing technologies would need to be developed, and these would need to be compatible with end-use applications.

It was against this background that NRC came up with four sub-projects. First, it would screen algae species for biofuel applications. Second, it would develop supporting commercial scale photobioreactor cultivation technologies looking to concentrate solar energy for algae production, heat and power. Step three focused on the development and evaluation of processing and conversion technologies. The gross steps leading from the production of algae through to its conversion to biofuel were mapped out. Process limitations were identified pointing to specific areas where research activities would be required to provide cost effective solutions leading to successfully achievement of overarching objectives. The fourth and final step would be to evaluate the algae-derived fuels and lubricants for the aerospace industry [48].

The NBP links Canada and the US under the collaborative Clean Energy Dialogue, partnering with the US-DOE- National Renewable Energy Laboratory (NREL), Sandia National Laboratories (SNL) and the Pacific Northwest National Laboratory (PNNL).

Where progress continues to be made on all four steps outlined above, of interest within the context of this review paper has been the development of the NRC's "Brite-Box" algae cultivation photobioreactor (PBR).

Algae cultivation technologies suitable for the Canadian climate

The following section provides a brief introduction to nine scalable PBR algae cultivation technologies with potential application to Canadian northern climates including NRC's "Brite-Box" technology. Table 1 provides relevant patent information [49-69] on PBR technologies being employed by the companies discussed in this study.

Open Pond Raceways (OPR) and Algae Raceway Integrated Design (ARID)

Open pond raceways (OPR) are mentioned since they are the prevailing most cost-effective means of cultivating algae. These technologies are typified by research ponds found at the University of Arizona. Although not currently considered as a viable or sustainable algae production platform in Canada no known research has attempted to quantify the extent to which this technology could be employed. The two greatest barriers to implementation are temperature and access to ambient light during the unfavorable winter months.

Open pond raceways require large water surface area to allow for light penetration, especially as the algae culture becomes increasingly dense. For this reason, ponds are generally less than a half meter deep. The large surface area enables higher utilization of solar photons, the energy that enables the microalgae plants to grow, but during colder periods also contributes to the rapid cooling of these ponds, thereby limiting metabolic activity associated with their growth.

Given the energy intensive industrial processes throughout the Province of Alberta, there may be an opportunity to harvest the associated low-grade heat for maintaining more favorable pond temperatures to increase their productivity.

To counteract the fluctuating temperatures associated with OPRs, and algae raceway integrated design (ARID) has been developed and continues to undergo testing, with early results showing good promise.

Table 1: List of Patents on PBR Technologies

Company Name	Patent Number	Date	Patents/Comments	Ref.
Algae Aqua Culture Technology	WO2014015184	1/23/2014	Biorefinery system, components therefor, methods of use and products derived therefrom	[68]
	WO2014018785	3/20/2014	Biorefinery control system, components therefor, methods of use	[67]
	WO2012100093	10/26/2012	Biorefinery system, components therefor, methods of use and products derived therefrom	[69]
AlgaBloom Technologies	20140315290	10/22/2012	Low-Cost Photobioreactor	[65]
Industrial Plankton	WO2014006551A	1/9/2014	Photobioreactor for liquid cultures	[66]
National Research Council of Canada	CA 2394518A1	1/23/2003	Photobioreactor	[49]
Pond Biofuels, Inc.	20140199639	7/17/2014	Process for managing photobioreactor exhaust	[59]
	20140186931	7/3/2014	Process for operating a plurality of photobioreactors	[64]
	20140113275	4/24/2014	Recovering off-gas from photobioreactors	[60]
	20130316439	11/28/2013	Biomass production	[63]
	20130183744	7/18/2013	Producing biomass using pressurized exhaust gas	[58]
	20120276633	11/1/2012	Supplying treated exhaust gases for effecting growth of phototrophic biomass	[56]
	20120202281	8/9/2012	Light energy supply for photobioreactor system	[70]
	20120156669	6/21/2012	Biomass production	[62]

Company Name	Patent Number	Date	Patents/Comments	Ref.
	20110283618	11/24/2011	Supplying bioreactor gaseous effluent to combustion process	[51]
	20110287405	11/24/2011	Biomass production	[61]
	20110287507	11/24/2011	Process for growing biomass by modulating supply of gas to reaction zone	[52]
	20110287522	11/24/2011	Producing biomass using pressurized exhaust gas	[53]
	20110287523	11/24/2011	Recovering make-up water during biomass production	[54]
	20110287525	11/24/2011	Diluting exhaust gas being supplied to bioreactor	[55]
Symbiotic EnviroTek Inc.	WO2011050472A1	5/5/2011	apparatus, method and system for algae growth	[50]

The concept is based on draining the ponds for night into a much deeper holding area. In the morning after the sun has opportunity to heat the greater pond area, media is recirculated into the cultivation ponds. The deep pond retains the heat from the day to a much greater extent, resulting in a more favorable cultivation temperature. More research specific to the Canadian context is warranted.

Algae Aqua-Culture Technology (2010) MT

The Algae Aqua-Culture Technology (AACT) PBR for cultivation of algae is designed for challenging climatic conditions and is part of a fully integrated production bio-cluster or closed-loop biorefinery platform. The system includes: photobioreactors for the cultivation of the algae; anaerobic bioreactors that digest the algae using benign digestive bacteria: an Organic Carbon Engine (OCE), generating syngas from waste wood from a neighboring lumber mill to produce bio-oil and biocarbon (biochar).

The 465 m^2 facility run by a staff of 4 can convert 6 T of waste wood to 2 T of soil amendment daily plus 2.1 GJ hr^{-1} and the potential to create 250 kW of continuous power. The associated CO_2 and nitrous oxide fuel algae growth. A patented automated computer control system, ANT (Autonomous Networked Technology), keeps all of the operation components in balance and adapting to environmental changes [71].

Algae produced in a serial batch process with daily harvesting goes into to the bio-digester to produce methane used in the OCE. The nutrient rich digestate is combined with biochar to produce a dry saleable fertilizer. The approximate 370 m^2 of algae ponds represents some 50 m^3 of growth media and utilizes carbon dioxide from the pyrolysis of the waste woody residue from the adjoining lumber mill [72, 73]. The system, an integrated biorefinery, has the capacity to provide a five-year payback in isolated regions where energy prices are high. Research continues on extraction of other high value products from the algae biomass. AACT has received funding in part for their research project from the State of Montana.

Table 2: Algae Cultivation Technologies Suitable for Canada's Northern Climate

Technology Supplier	Type	Size	Process	Associated Processes	CO_2 source	N_2O	Output Products	Algae Species	Density Achieved	Energy Required	Patent & Refs
Generic ATP3 Demonstration	OPR	125 m^3			air		research facility				
ASCATI ATP3 Demonstration	ARID	30 m^3			air		research facility				[74]
Algae Aqua-Culture Technology (2009), MT	EPR	370 m^2	coupled serial batch with waste wood pyrolysis	AD, pyrolysis	Pyrolysis	Pyrolysis	6 T/d wood waste to 2 T/d soil amendment fertilizer with biochar, biofuels				[67]
Algae Tec Limited (2007), Australia	PBR				atmosphere, stack gases		ethanol, biodiesel, jet fuel, EPA/DHA nutraceuticals				
AlgaBloom Technologies (2009)	PBR	400 m^2					food, omega 3	spirulina / synechococcus			[65]
Algaecan Biotech Ltd (2009)	PBR	7.5 m^3	batch multi-phase approach				astaxanthin	haematococcu s pluvialis	30 g/L		
Hy-Tek Bio LLC (2008)	PBR	6.8 m^3	batch / continuous flow	HTL, enzyme conversion to biodiesel	natural gas engine exhaust	exhaust, chicken manure	methane, biodiesel, jet fuel	HTB1	3-5 g/L	1.68 kW	
Industrial Plankton (2010)	PBR	1.25 m^3	batch / continuous flow				algae biomass	Nannochlorop sis	210 m cells/ml, 2.5 g/L	1.6 kW	[66]
National Research Council	PBR	1 m^3	batch / continuous flow	HTL			research facility, algae biomass, biodiesel	Isochrysis	0.6 g/L/d		[49]
Pond Biofuels Inc. (2007)	PBR	10 m^3	batch / continuous flow	HTL	natural gas engine exhaust, cement production gas emissions	chemical processes	algae biomass, bio-fuels				[61]
Symbiotic EnviroTek Inc (2008)	PBR	103 m^3	batch / continuous flow	HTL	bottled gas	waste streams	algae biomass, bio-fuels				[50]

EPR - Enclosed Pond Raceway, OPR - Open Pond Raceway, ARID - Algae Raceway Integrated Design, PBR - Photo Bio-Reactor
*Information provided from Patent references, web sites and other open information sources

Algae Tec Limited. (2007) - Australia

Algae Tec Limited (ASX:AEB), has developed a proprietary McConchie-Stroud algae cultivation system. This publicly traded company has conducted hundreds of its own research trials from laboratory scale, to bench-top and pilot tests, and conducted detailed engineering evaluations of a commercial scale plant operation. The company, reporting revenues of $4.5 million AUD in 2014 [75] claims significant advances in product yield, productivity, CO_2 sequestration and reduced capital cost savings. It is commencing a joint commercial scale algae plant project in India consisting of a high-yield modular PBR and harvesting system. An industrial scale plant is also underway near Sydney to convert CO_2 from the Macquarie coal-fired power plant into valuable bio-oil. The facility is targeted to produce 50 million L (50,000 T) of algal oil per year. Production to begin producing oil has been scheduled for the end of 2014.

AlgaBloom Technologies (2009) BC

The focus of AlgaBloom Technologies is to develop large scale microalgae farming solutions. The company has developed a suite of PBRs from the land-based "AlgaBioReactor", to a roof-based "AlgaRoof", to "AlgaBag" a large-scale bioreactor bag with an integrated sparging and agitation system, and the "AlgaBox" a compact multi-level bioreactor. The modular multi-layer matrix design consisting of both thin-film and suspended components enables control over both environmental and nutritional factors. 400 m^2 of growth media surface area is achieved within a 30 m^2 footprint.

AlgaBloom is also working to develop associated oil extraction, harvesting and monitoring capabilities. One of the strains of algae being focused on is Synechococcus PCC 7002.

The company has been the recipient of two NSERC research grants in conjunction with both the University of British Columbia and University of Victoria. It has established a commercial partnership with Qponics Limited based in Australia on an omega-3 oil production project.

AlgaeCan Biotech Ltd. (2009) BC

AlgaeCan Biotech Ltd. is currently working on financing a demonstration plant with PBRs of a scalable commercial biorefinery which includes both the cultivation and subsequent processing of the algae through to saleable products. An initial key market with the production of astaxanthin from *haematococcus pluvailis* continues to be the primary focus of research activities. Ongoing work looks to reduce energy inputs. Key production achievements include:

- attaining >3% yield (wt) of dried algae biomass where open pond producers only achieve 1.5%;
- establishing key optimization parameters:
  - light frequency, intensity, saturation, low energy
  - consistent, non-shearing low energy flow
  - dependable, simple, low cost sterilization
  - monitoring and control capability of 5 crucial bioreactor factors
- Nutrient formulation JAG, to ensure cost effective yields specific to their algae strain
- Establishing production protocols to efficiently transition the algae from the vegetative growth phase through the induction of astaxanthin production and extraction of this product into an oleoresin without the use of solvents.
- Production of 4mg softgels using a toll processor technology.

The work of the company has progressed from lab scale trials, to bench-top, to 1000 L and 7,000 L PBRs. They are currently building a 14,000 L PBR.

HyTek Bio LLC (2008) MD

HyTek Bio has developed a PBR based on cylindrical PVC (poly-vinyl chloride) bags (a mylar-like material with carbon fiber and Kevlar structural support) providing a column of growth media of approximately 1 m diameter and 6-7m high with a total growth volume of 6.8 m^3. The system is housed in a protective building environment which helps to control environmental temperatures. The system has been developed to include monitor and control capability. Their business model is to take down stack gas emissions from industrial processes, specifically oil and gas refining processes and having the algae absorb not only the CO_2 but also the other potent greenhouse gases like SO_x and NO_x. Carbon credits as well as offsets from not having to deploy other costly gas scrubbers and their associated maintenance are anticipated. The company is achieving algae culture densities which support relatively high production yields.

Together with the University of Maryland the company has isolated a proprietary HTB-1 strain of algae that shows the greatest promise for the commercial objectives of the company showing a 42-47% lipid content and able to survive environments with 100% CO_2. It can also withstand high variability in pH from acidic to basic, and temperature swings from 15ºC – 43ºC. In nature the algae will double mass in 22 hr. In research trials it has been shown to double every 12 hr.

Significant research headway has been made on monitor and control of nutrients and lighting to optimize algae growth. Lighting regimes that are used have enabled a 90% reduction of energy use from traditional LED lighting systems.

Moving from 3m high column PBRs, the 6-7m height second generation algae tanks are being constructed to hold 6.8 m^3 of growth media. Cost for these light weight 30 kg tanks cost approximately 25% of the cost of a similar volume stainless-steel tank. The development plan is to construct a commercial scale tank holding $18m^3$ of growth media.

Other key data include:

- Flue gas – 100 scfm/PBR @ 11.8%CO_2 and 130 ppm NO_x
- Flue gas temperature - 425ºC stack T and 27ºC PBR T
- Nutrient requirement – 375L proprietary nutrient / PBR / day based on waste chicken manure.
- 5% water loss due to photosynthesis
- Power: 180W lighting / PBR and 1.5kW air injection
- Gas injection / media mixing via micro-bubble full-floor sparging system
- Algae: HTB1

- Culture density: 3-5 gL^{-1}
- Production: 23 – 34 kgd^{-1} or 3.4 – 5 $gL^{-1}d^{-1}$
- O_2 Production: 8.5 cfm 90% O_2
- Harvesting: 10% of media is harvested when optical density reaches upper threshold.
- Dewatering: using bacterial aggregation agent. Removed water is filtered and replenished with nutrients, then returned to PBR
- Drying / packaging: remaining slurry spray dried and vacuum packaged for shipping
- Cycle repeated every 1.5 hr
- Automated control system

Industrial Plankton Inc. (2011) BC

Industrial Plankton is a more recent algae cultivation technology developed in Victoria, BC. They have developed a patented fully automated, monitor and control PBR that enables them to achieve significant production yields, having recorded up to 210 million cells per ml (*nanochloropsis),* 25 million cells ml^{-1} *isochrysis)*, 18 million cells ml^{-1} (*thalassiosira weissflogii*), 20 million cells ml^{-1} (*skeletonema costatum*) and 4.5 million cells ml^{-1} (*tetraselmis)*. To date they have developed a 100 L research scale, 500, 1,000 and 1,250 L automated PBR system complete with sterilization. Air and water is micro-filtered and includes a UV sterilization cycle. The control system covers a variety of parameters including scale up density, nutrient addition, light levels, harvest density, etc complete with data-logging for analytical research. Scale up from 20 L to 1,000 L will require 7-10 days depending on the algae species. Harvesting can take place automatically and replacing removed media with fresh water and nutrients. PBRs utilize LED lighting system. The 75 L unit uses an average of 900W and the 1,000 L unit uses an average of 1,600W. A growing number of their PBRs have been installed for commercial projects.

National Research Council of Canada (NRC) NS

The Brite Box is a proprietary technology owned by the NRC [76] and developed at 250, 500 and 1,000 L sizes. Each unit is comprised of a cooling loop, fluorescent lights, pH probe coupled to CO_2 solenoid for sparging this gas into the growth media for pH control. A 50,000 L cultivation pilot plant is being planned.

2010 published data indicated that production yields based on *chaetoceros mulleri* or *isochrysis galbana* cultivated at 20 ºC in seawater reached 0.6 gm $L^{-1}d^{-1}$ over a 21 day trial cycle [77, 78]. The technology has been used to conduct algae cultivation studies on numerous algae strains [79].

From data that has been collected from cultivating algae using this technology, valuable information has been accumulated benchmarking the current state-of-the art systems. From the R&D activities, the NRC has been able to document yield data of algae biomass and extract a variety of unique algae strains. The information has also been used to evaluate the potential for scalability of the cultivation processes and determine carbon / energy balances for the biomass-to-fuel conversions. This empirical data has also been valuable for developing meaningful Life Cycle Assessments (LCA) and conducting Techno-Economic Analysis (TEA).

The development of the “Brite-Box” PBR was done in collaboration with Carbon2Algae Solutions and Menova Energy Inc. and the biomass production capability was done in conjunction with Ocean Nutrition Canada.

The NRC collaborates with industrial / commercial partners including several of the companies mentioned below to conduct research advancing scientific knowledge and related technology development to support the evolution of the algae industry in Canada.

Pond Biofuels (2007) ON

Pond Biofuels came into existence in May 2007 and since its inception has filed 17 patents related to the cultivation of algae. The patents are related to algae cultivation technology processes including factors related to scalability, handling of both input and output gases, and recycling processed water [80].

This Canadian company has been successful in scaling their PBR technology to two 12.5 m^3 tanks (2013) working in conjunction with St. Mary's Cement and utilizing pulsed red LED lighting systems. The lighting system has the capacity to inject more than 1kW of light energy per m3 of growth media. The company claims achieving between 4 and 6 generations of algae daily [81].

The company is Canada's largest and most publicized algae biomass company. They were recently awarded a $19 million for a demonstration plant in cooperation with the Government of Canada and Canada Natural Resources Ltd. (CNRL) [82].

Their re-developed PBR system is based on injecting high intensity light into large 10,000 L plastic vessels with monitor and control capability utilizing CO_2 from industry.

Energy and CO_2 is provided by a natural gas fired 4MW generation system in Bonnyville AB. Nutrients including N, P and trace elements are provided from chemical processes.

Symbiotic EnviroTek Inc (2008) AB

Symbiotic EnviroTek Inc. was established in 2008 with its primary goal to develop a commercial scale photobioreactor (PBR) that would cost effectively cultivate algae for commercial purposes in adverse (Canadian) climatic conditions. The first test PBR fabricated by the company holds 106,000 L. Testing in 2010 and 2011 demonstrated that algae could be successfully grown at this commercial scale. The company's initial focus was on the development of the mechanical technology including proprietary controllable, submersible LED lighting, mixing of the algae media, appropriate aeration for efficient CO_2 infusion, nutrient mixing and delivery. It has expanded the scope of its research to include the entire spectrum of technologies and capabilities to take strains of algae, customize their associated growth parameters and adjust the associated monitoring and control capabilities to effectively optimize the growth of multiple different algae strains.

In 2012, 2013 R&D activities included developing protocols for specific algae strains for optimized growth based on utilizing waste agricultural waste nutrient sources, testing of specific light frequencies and pulsed photon delivery to optimize yields and minimize energy/cost of inputs. The company anticipates demonstration of sustained growth at levels in excess of 4 gm/L/d over the course of the next year.

The Symbiotic system has been designed to be scalable for deployment and integration / co-location at existing waste industrial / agricultural waste streams at source to minimize the GHG footprint associated with an overall bio-cluster operation. An envisioned bio-field consisting of 64 modules each having 106 m^3 of growth media situated on 2 acres is estimated to utilize over 45 TT of CO_2 daily and produce some 25 TT of algae biomass.

Symbiotic has been the recipient of AITF, CAAP, IRAP, GF2, SR&ED and NSERC research funding.

Technology Assessment

Given the limited amount of information related to each of the technologies highlighted in the public domain it is difficult to predict a technology best suited for the Canadian context. Table 2 provides comparative data between technologies that have been discussed. From an economic perspective, success will be achieved in part by minimizing the sum costs of several key factors including the aggregation of a suite of related technologies that comprise the algae biomass production platform. These decisions will be reflected in capital costs, down-time, operating, nutrient, media (including water) and maintenance costs. Economic success is also coupled directly to species specific optimized biomass yields both in quantity and composition. Only with the release of reliable and accurate algae production platform data from respective technological approaches will a meaningful economic comparison and assessment be possible.

Factors Affecting Economic Viability of Photobioreactors

Interestingly, all of the PBR designs are the result of unique perspectives, with each company choosing to focus on specific aspects of their PBR design which they believe to be most crucial. Studies on the optimization of PBR design have been conducted, providing useful reference data and criteria to be considered in achieving production yield objectives [83].

Isolation of algae strains that show high concentrations of desired compounds of commercial interest continues at Canada's National Research Council, academic colleges and universities across the country and at independent commercial laboratories. A few noteworthy strains include *Chlorella Protothecoides* and *Scenedesmus Obliquus* (51% lipid concentration) [84, 85] for biofuel production, and *Haematecoccus pluvialis* for astaxanthin production [86, 87].

Chlorella Protothecoides has been demonstrated to grow at densities of up to 17 g L^{-1} in heterotrophc conditions compared with 0.87 g L^{-1} in autotrophic conditions under 12:12 hour Light:Dark cycles [88]. For *Scenedesmus sp.* recent growth trials achieved 1.3 g L^{-1} dry biomass at a density of 1.5 million cells L^{-1} and growth rate of 0.62 div. d^{-1} under 12:12 hour light:dark cycles [89].

Haematococcus pluvialis, known to synthesize high value astaxanthin, has been documented (2003) to grow at a rate of 0.7 div. d^{-1}, 0.228-258 mg L^{-1} at cell densities between 200 and 250 thousand cells ml^{-1} [86]. A more recent study achieved astaxanthin accumulation of 18.21 g m^{-3} (3.63% by dry weight) achieving a growth rate of 0.52 div. d^{-1} with cell density at 330,000 cells ml^{-1} with an estimated production cost of \$1000 kg^{-1} astaxanthin [90]. A 2009 study demonstrates the complexity of interactions within an algae growth platform based on the effects of light and pH [87].

A 2011 conceptual model comparing commercial scale (100 ha plant) open pond raceways, tubular PBRs and flat panel PBRs based on current exchanges rate placed a cost of \$6.96, \$5.85 and \$8.38 per kg of dewatered algae biomass. When optimized for location, irradiation, zero costs for CO_2 and nutrients, with increased photosynthetic efficiency, these costs dropped to \$1.80, \$0.98 and \$0.96 per kg [91]. A recent review of bio-oil production from fifteen algae research reports provided a range of estimated costs from various researchers from between \$0.82 and \$10.93 L^{-1} of oil produced [92].

In 2008, over \$350 million was invested in algae projects [93] with more than \$1.1 billion having been invested cumulatively in the US[94]. In 2009 Exxon Mobil Corp had planned to invest some \$700 million anticipating the development of algae fuels within 10 years. In 2013, after spending \$120 million the company had determined that it was unsuccessful in achieving commercial viability and that it would likely take at least another 15 years to reach its objective [95]. All the reports point to the significant challenges to be overcome within the industry to achieve commercial viability [20, 96].

These figures however, provide useful reference points to the technologies introduced above and the economic viability of their operations. Minimal information on their operational performance is available in the public domain.

The production of algae requires the monitoring and control of a large number of variables. Different algae strains have different growth rates and the composition of the resulting biomass varies significantly, which in turn determines the value of the saleable product. Each company is focused on different product outputs. In some cases there is a single relatively low value, high volume market that is being targeted (biofuels). In other cases high value nutraceuticals are the focus (astaxanthin).

Although each company will focus on a primary output product, in every case, consideration is given to a biorefinery approach to derive economic benefits from one hundred percent of output products to create a more favorable economic output [97]. Each company has come up with independent approaches to source of CO_2 and infusion, light source, wavelengths, light-dark cycles and intensity regimes. Sourcing lower cost nutrients and more energy efficient dewatering processes will all help to establish improved profitability.

The algae biorefinery concept is a relatively new topic having first appeared in technical journals (Scopus search) in 2008. Of the 175 articles on the subject, more than 100 have been written in the past three years. Because of the complexity of multiple pathways including technologies and processes leading from cultivation through to oil upgrading, there is a body of analytical research and simulation modelling beginning to take place to compare these options and provide recommendations for large-scale algae biofuel production. A recent study begins to explore the development of a process "superstructure" of carbon capture for the utilization of wet biomass. Four out of a wide range of technology alternatives are considered in off-gas purification, algae cultivation, harvesting, dewatering, lipid extraction, remnant treatment, biogas and algal oil utilization [97, 98].A topic not currently integrated into many of the studies is the impact of environmental parameters like light intensity, wavelengths and photoperiods. Lighting regime and photoperiod are viewed to be key factors related to algae growth rates and biomass production [99, 100]. A recent study on the topic using *scenedesmus obliquus* achieved cell concentrations up to 114 million cells ml^{-1}, a growth rate of 0.86 and density of 3.3 gm L^{-1} [101] under a specific pulsed fluorescent lighting regime. Another area requiring further research is the correlation between cell weight and algae biomass composition to parameters like temperature, dissolved oxygen, dissolved carbon dioxide, electrical conductivity, specific nutrient concentrations, pH, and light intensity. Findings to this point appear inconclusive [101].

In large measure successful commercialization of the technology platform will depend on adherence to regimented operational protocols and ongoing research and development activities that will continue to optimize production.

Table 3: Comparative and Competitive Algae Production Pricing (96)

Feedstocks	Production Cost ($/T)	Algae Required Equivalent ($/T)
Palm oil	603	164
Soybean oil	623	169
Crude oil	752	204

The cost of delivery of algae biomass to industry in Canada

In order for the algae industry globally to become a meaningful and potentially dominant economic force, the costs associated with cultivating, harvesting and processing of the associated biomass must be significantly lower than the current market prices for the final products that may be extracted from the biomass.

To date, relatively little research has been conducted on both Life Cycle Assessments (LCA) [102, 103] and techno-economic analysis of the inclusion of technologies and processes leading from algae cultivation through to the production of valued end products. There is also skepticism among certain authors as to whether the environmental impact of producing end products is less than using conventional feedstocks and petroleum resources. Research is required to provide better information. From a sustainability perspective, research must also include water utilization as part of the environmental impact analysis.

How algae cultivation platforms are operated and potentially integrated with other industries will have significant impacts on not only commercial outcomes but also environmental outcomes. By way of examples, algae cultivation could be co-located with municipal waste water treatment facilities, landfill operations, agricultural effluent streams including: feedlots; breweries; sugar beet, corn, potato processors; conventional energy extraction/refineries; co-generation facilities, etc. Association with these kinds of existing operations could result in favorable symbiotic commercial and environmental outcomes. (See Table 3). With existing algae cultivation systems there are challenges associated with access to accurate costing information. This is made more difficult given that the process of the algae cultivation leading to the delivery of dry biomass to industry generally involves multiple steps.

Given that this is an emerging industry requiring significant resources, the developers of algae related technologies generally focus on single steps within the overall production platform. Currently it is the coupling of technologies throughout the platform that together will provide a complete and integrated solution. There are very few of these integrated algae production platforms in existence in Canada and even less that represent plausible scalability for industrial purposes. What may work as a prototype may not work meaningfully at a larger scale.

For certain companies the production of the algae biomass has been focused on delivering high value compounds rather than simply generating biomass. Operation and production data is confidential. Because of the high value of the end product, meaningful revenues can be achieved even with very modest amounts of biomass produced. Costs for the production of the biomass for astaxanthin which may have a street value of \$2,500 kg^{-1} [104] although important, is a much less of a factor than where the goal is to produce a million tonnes of biomass for the extraction of algal oil for biofuels (i.e. biodiesel at \$1 L^{-1}(kg)).

From a production perspective, comparative costing is meaningful. Palm oil, viewed to yield the lowest cost bio-oil has a reference production cost of \$603 T^{-1} (~\$0.61 L^{-1}). To be competitive, algae biomass (with 30% lipid content) through to oil extraction would need to be priced at or below \$164 T^{-1}. If the reference is soybean which in the US is the dominant source for biofuel production, with a commodity price of \$623 T^{-1} (based on 20% lipid content), then algae biomass through to extracted oil would need to be priced at or below \$169 T^{-1}. Where the reference is crude oil priced at \$118 bbl^{-1}, the same algae biomass would need to have a cost at or below \$204 T^{-1} [103]. See Table 3 for a summary of equivalent required pricing for algae to compete with other feedstocks.

Table 4: Cost to Produce Algae Biomass

Technology	For Biofuels (\$/T)	For High Value Products (\$/T)	Literature Variability in Pricing (\$/T)		100 T/yr Scaling (\$/T)
			Minimum	Maximum	
OPR	233	30,704	3,118	19,486	4,830
PBR	17,292	40,895	3,774	94,430	3,828

It has been estimated that current costs for algae biomass as a feedstock for electricity generation are at \$233 T^{-1} for open algae systems and \$17,292 T^{-1} for closed environmentally controlled production platforms for health foods. For high value products, production costs increase to \$30,704 T^{-1} in open systems and \$40,895 T^{-1} in closed systems. There is a tremendous variability in reported production costs ranging from \$3,118 to \$19,486 T^{-1} for open systems based on raceway ponds and \$3,774 to \$94,430 T^{-1} for closed systems. Interestingly, numbers reported for 100 $T^{-1}yr^{-1}$ algae biomass operations, open systems had production costs of \$4,930 T^{-1} and closed systems were at \$3,828 T^{-1}. Furthermore, for algae production platforms economies of scale do not appear to work well when going from 50 ha to 500 ha to a 5,000 ha production facility with very little cost reduction being possible [103]. See Table 4 for a summary of production cost variability between OPR and PBR technologies found in literature.

Table 5: Factors affecting algae biomass production

Climate
Solar irradiance
Nutrient source and cost
Capital costs
Algae species / composition
Energy Costs
Operating Costs
Colocation with symbiotic industry partners
Ability to control production factors
Optimization of biomass yield
SCADA / Automation
Active research and development – access to highly qualified multi-disciplinary scientific community
Scalability

In the context of Canada, given a relatively short growing season, open systems have not been considered as a viable commercial option and therefore only closed systems need be considered.

For many algae production platforms there remains a large negative gap between actual production costs and pricing for commercial products derived from the biomass. In an attempt to bridge this, a number of companies that were initially focused on a single, large and subsidized biofuel commodity market were now shifting production to focus primarily on high value by-products with residual oils going to biofuel production. This shift leads to operational changes including a potential shift in algae strain being used, cultivation practices including nutritional and environmental factors, adding production steps that enhance the expression of desired compounds.

Other opportunities for overcoming the costing challenge include research to lower energy input, incorporating existing “waste” streams that can offset fertilizer costs and potentially provide an add-back value from the deferral waste disposal transportation and landfill costs, the uptake of amines to significantly reduce operating costs in these industrial applications, as well as the potential for CO_2 mitigation credits.

Research may provide techno-economic data on processes leading to biomass at a laboratory scale, but this may have little relevance to costing at commercial scale. Other research has utilized powerful software modeling capability (i.e. ASPEN) but results are scrutinized and questioned because of the tremendous numbers of assumptions and parameters needing to be considered. Similar to challenges related to economies of scale, these modelling tools may have value for thoroughly understood commercial operations currently found in industry but may prove inadequate for the meaningful evaluation of processes related to the operations of an algae production platform. The algae industry is evolving and involves complex micro-biological, physical, botanical, marine, biochemical and environmental interactions, spanning multiple thousands of strains. Cultivating, harvesting and processing these single cell organisms introduce other technological challenges.

There have been numerous approaches attempted to increase algae biomass yield and reduce costs. There remains a vast opportunity to discover other new and innovative approaches which will undoubtedly lead to breakthroughs in cost effective algae production strategies.

Distracting to these research initiatives are vocal commercial, environmental and political interest groups that ask daunting questions related to energy and carbon balances. Environmentalists and politicians are looking for meaningful solutions to climate change and reducing airborne greenhouse gas (GHG) emissions. What is well understood is that algae, being one of the world's fastest growing plants, have the capability to more than double its mass within a single 24-hour period. Every tonne of biomass created will take down 1.8 tonnes of CO_2 [11, 105]. Hence significantly scaling up algae biomass production to offset GHG emissions is more than plausible. The "fly in the ointment" is what do you plan to do with the biomass? Taking biomass to biochar is seen to be a great CO_2 mitigation strategy, locking up carbon in one of its most stable forms. Any positive net difference between GHGs produced and GHGs sequestered in the cultivation and processing of algae would qualify for carbon credits. However, this in itself would ignore economic considerations. Furthermore, to be awarded carbon credits, a quantitative Life Cycle Assessment (LCA) meeting the International Standards Organization (ISO) guidelines would have to be conducted that would validate results. Currently, there are concerns that the LCA results may be misleading because rarely are parameters within the LCA calculation identical [102].

Related to the bio-fuel production use for algae, the same interest groups ask a similar probing question. What is the net energy ratio? Is more energy produced than is consumed using non-renewable sources through inputs required to cultivate the algae along with processes leading to the bio-oil into the system? Numerous arguments are forwarded stating that in many cases more input energy is required than is produced. The same argument would hold true for CO_2 emissions.

Strategies and opportunities for sustainable algae cultivation in Canada

Algae companies have recently shifted focus to producing high value products that can be derived from the biomass since this strategy shows the greatest promise of economic sustainability and that, in the absence of Government subsidies. Having made a determination on primary product, these companies have selected algae strains that are known to synthesize meaningful amounts of the desired compound. Research has followed to optimize axenic algae growth by carefully conducting multiple tests to determine a combination of best nutritional, environmental conditions and processes at lab scale. Once an optimized regime has been documented, stringent protocols are established. Rigorous data logs are maintained for analysis and become part of the development of a company's intellectual property. Based on favorable yield results an economic model for scaling the production platform to the next stage is constructed [12]. This is essential for attracting investment funding to build the platform to each successively larger scale production platform [106].

Scalability poses a further challenge [107]. Shifting from a laboratory setting to a series of increasingly larger demonstration and production platforms requires a multi-disciplinary design team to ensure that axenic conditions are maintained and that the multi-variant conditions associated with growth through each production phase may be controlled, thus eliminating many adverse operating effects. All of these conditions point to the development of a carefully controlled growth environment (PBRs) rather than open cultivation systems. (See production factors Table 5)

As noted in this paper, there are companies and research institutions conducting primary research related to algae cultivation. Some entities are comparing algae composition data while others are focused on optimizing growth parameters for specific strains of algae. Yet others focus on technologies that will support the algae cultivation platform. Because of the challenges associated with each of the individual steps within an algae cultivation platform, each research group tends to focus narrowly on a specific aspect. It is therefore prudent for research teams to find collaborative strategies for integrating and coupling strains, cultivation regimes and associated technologies with other research groups to find more cost effective and efficient technologies and processes to apply to their own work. This would lead to achieving meaningful production volumes that result in attaining early incomes of high value products. Embracing a business model to supply a specific product will enable commercial transactions to be completed with relative ease.

Once a successful and profitable algae business is established and operating, there is opportunity then to consider complimenting the business revenues with other sources of value derived from the residual components of the algae biomass, including but not limited to biofuels and carbon credits.

It will be through learning the mechanics and processes of algae cultivation in a specific, profitable niche that will over time open the doors of innovation to cost effective production of algae feedstock for commodities like biofuels, as well as carbon credits.

There are scientific engineering advances that may also be incorporated to provide enhanced yields of specific end products including biofuels [108]. Photosynthetic research may provide important clues to maximizing yield by taking advantage of maximal irradiance [109-111]. In general algae growth has been associated with C3 photosynthesis. More recent studies suggest that C4 photosynthesis may also be taking place and have implications for improving growth yields in the future [112].

A recommendation offered is for Governments to set in place integrated algae cultivation and biomass production / processing platforms similar to / or in association with ATP3 (Algae Testbed Public Private Partnership) leading to multiple valued commercial products and establishing production benchmarks. In facilities like AzCATI (Arizona Center for Algae Technology and Innovation) innovators and companies are able to integrate their specific technologies and test their systems against the existing benchmarks. Where new technologies prove more efficient and effective, these systems will set new production standards and thereby assist in elevating the efficiency of the overall production platform.

Conclusions

Much of the impetus for the recent renewed interest in algae biomass is related to both the acknowledgement that algae biomass has the potential to address pressing global challenges: reducing atmospheric CO_2, reducing national energy reliance on conventional fossil fuels, food and cleaner water. Climate change is and will continue to affect the entire global community. Access to energy is fundamental to maintaining a productive and healthy economy. In the first instance, no economic benefit is necessarily derived from withdrawing CO_2 from the atmosphere. Energy is a commodity and therefore cost will always be a factor and generally shift to lowest price producers. Government incentives in the form of subsidies for renewable energy are important in signaling to industry that change is required and promotes the adoption of alternative energy forms.

In the case of algae biomass, Government subsidies created a frenzy of commercial activity given the implications of legislation demanding that increasing percentages of petroleum fuels be from renewable sources. Over the past 20 years, over a billion dollars have been spent attempting to cultivate algae biomass that would deliver a more cost effective feedstock from which to produce renewable fuels. To date the singular focus on delivering cheap biofuels has been an elusive objective. A more recent shift to cultivate algae for delivering high value products to established markets and / or developing a bio-refining model to deliver multiple products that are possible to be extracted from the algae provides a more pragmatic approach to launching the algae industry into a sustainable and economically viable way.

Future Government incentives should factor in not only the development and delivery of cheap biofuel feedstocks but also the capability to mitigate GHG emissions. Furthermore, given the dearth of meaningful production data related to technologies, it is recommended that any Government subsidies be tied to the release of operating and production data. Given the multi-disciplinary complexities associated with the algae production platform, access to quality data is imperative for overcoming multiple formidable challenges associated with the cultivation of algae. There are numerous data sets that companies withhold, claiming IP interests, which in fact would not be upheld under legal contest. Open access to these data sets would enable researchers to advance the overall knowledge base for the benefit of the greater community, enabling a much faster transition into commercial viability for the entire industry. Evaluation of technologies and associated commercial decisions are extremely difficult to make in the absence of good information.

For the Canadian context, the reviewed algae cultivation technologies provide tangible demonstration of progress that is being achieved to deliver cost effective algae biomass for downstream bio-refining applications. In order to achieve this desired outcome along with the national objective of GHG mitigation, research will need to demonstrate: capability to improve crop yields; improve the percentage of desired compounds within the biomass; sustained and consistent growth; more efficient dewatering, processing, extraction and refining capability; cost effective scalability of related technologies; and reduce energy inputs throughout the algae production platform.

Future research work that will correspond with the current work will look at creating an analytical model to evaluate the utilization of OPRs within Canada and to enable the evaluation of impacts of adjusting media temperature and other growth parameters. It is anticipated that results from the analytical model will enable the development of an associated and meaningful life cycle assessment (LCA) as well as techno-economic analysis (TEA).

3

3. Novel satellite based analytical model developed to predict microalgae yields in open pond raceway systems and applied to Canadian sites[2]

Abstract

Interest in microalgae cultivation continues to increase based on its potential commercial value. Algae converts CO_2, nitrates, phosphates and other nutrients into a biomass that can be processed into biofuels, pharmaceuticals, nutraceuticals, food, fertilizers, and other active compounds. Solar irradiance and media temperatures are key parameters in determining microalgae cultivation yield and hence these parameters are fundamental in existing models that have been

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[2] A version of this chapter has been published as a peer-reviewed journal. Pankratz S, Oyedun AO, Kumar A. Novel satellite based analytical model developed to predict microalgae yields in open pond raceway systems and applied to Canadian sites. *Algal Research*, 2019, 39:101431.

constructed to predict yields in different locations for open pond raceway (OPR) cultivation systems. The challenge in estimating OPR yields in higher and lower latitudes (colder climates) is that there are no known attempts to cultivate algae at any scale in these regions, nor are there data sets that include shallow pond site-specific daily water temperature measurements, from which to construct algae cultivation models. To address these challenges, our research introduces a new data-intensive analytical SATOPR (SATellite Open Pond Raceway) model, relying on ubiquitous historical satellite data. Local solar irradiance and ambient temperature values which are used to predict microalgae production yields at any geographic location including the colder latitudes of central Alberta and the Northwest Territories in Canada. The model predicts that annual open pond algae cultivation to produce 1000 T biomass would require 17-20 ha at Mesa, AZ, 45-56 ha at Medicine Hat, AB, 57-68 ha at Fort Saskatchewan, AB and 71-80 ha at Great Slave Lake, NWT. The Mesa, AZ results are more conservative than forecast by a NREL model predicting 12 ha to produce 1000 T biomass. Modeled land area information provides the basis for life cycle assessments (LCAs), techno-economic analyses (TEAs), and photobioreactor (PBR) versus OPR performance studies, yields simulations based on various parameters, and can assist with algae production platform optimization.

Introduction

Significant micro-algae research continues to be pursued globally based on the potential for these single cell plants to meaningfully address growing global challenges related to clean air, clean water, food, and energy. Algae is the fastest growing plant on the planet [113] and can double its mass in a single 24 h period [114]. The autotrophic production of a tonne of biomass requires 1.8 tonnes of CO_2 [11, 105]. Cultivating these plants using municipal, agricultural, industrial, and other wastewater with high loads of nitrogen and phosphates, two essential nutrient sources for the plant's growth, is similar to running this same wastewater through wetlands [115-122] in the sense that the water released is much cleaner than the water entering. The composition of the algae biomass includes fractions of proteins, carbohydrates, and lipids that can be used as a source of food and energy [123, 124]. The use of algae biomass extends to fertilizers, nutraceuticals, and numerous other high value compounds [125]. An estimated one hundred thousand species of algae exist across the globe and in every conceivable environment [125].

Apart from an adequate supply of nutrients including carbon dioxide (CO_2), nitrogen, and phosphate, environmental factors such as light and temperature play key roles in supporting algal growth [35, 126-130]. In nutrient-replete algae cultivation media, light and temperature are the most important growth factors [131]. Receptors in the algae cell's photosystem II thylakoid structures capture photons of light and trigger the production of electrons, which cascade down the electron transport chain to ultimately effect the capture of carbon from CO_2 and fracturing of water molecules to release hydrogen ions and O_2 gas [132-135].

The growth rate of algae is directly correlated to light intensity. This relationship is species-dependant but generally continues linearly from 0 through 30 µmoles m^{-2} s^{-1} and gradually tapers off to a maximum growth rate at approximately 250 µmoles $m^{-2}s^{-1}$ [129]. Similarly, growth rate is directly correlated to temperature and governed by the Arrhenius equation, Eqn. 1:

$$\mu = Ae^{-E/RT} \tag{1}$$

where µ (specific growth rate) is dependent on A (the Arrhenius constant), E (activation energy), R (universal gas constant), and T (temperature).

The impacts of temperature changes are also species-dependant. However, with many species, growth will occur from approximately 0 ºC and maximum grow rate will be achieved at between 25 and 35 ºC. Increasing the media temperature by only a few degrees above the species maximal rate can trigger the rapid decline of growth and onset of algae cell death [35, 126-130, 136-147].

The preponderance of literature to date suggests that the most economical way to conduct autotrophic algae cultivation is to use open pond raceways (OPR) [39, 113, 125, 148, 149]. There are variations in the construction of these systems. They are generally constructed as flat, shallow (0.2 to 0.5m deep), oval, closed loop raceways

[39, 114, 149]. Many use earthen berms to minimize construction costs, using clay as a sealant to prevent leakage. Other designs include the installation of more costly membranes that help to reflect internal light back to the algae from the bottom. Media in the ponds are kept flowing with paddle wheels and/or pumps. Paddle wheels provide an energy-efficient means to propel the media around the circuit [150].

Given the sensitivity of cultivating algae in OPR systems to both light and temperature, geographic siting becomes critical to achieve economic viability [151-153]. Of particular interest to our research group is the ability to investigate and predict algae biomass yields for OPR systems in colder climates like Canada. Although a number of algae cultivation technologies have been identified that may have application to colder climates [7] there are no known data sets available within Canada that include site-specific, shallow pond, daily water temperature measurements that would enable predictive, analytical modeling. A further weakness in existing predictive models is that yield flux occurs on a daily basis. However, current models tend to consider quarterly changes as reflected in earlier studies on algae cultivation. These predictions rely on seasonal productivity variations in yield values (gL^{-1}) (i.e., summer, fall, winter, spring) [154, 155].

The National Alliance for Advanced Biofuels and Bio-products (NAABB) conducted a comprehensive algae research project from 2010 to 2014 [156]. An attempt was made to draw "best-in-class" technical expertise, soliciting engagement from industry, academia, government and non-government laboratories, and foreign entities to focus on challenges related to algae feedstock supply (strain development and cultivation), feedstock logistics (harvesting and extractions), and conversion/production (accumulation of intermediates and synthesis of fuels and coproducts). A key component of this strategy was to develop a microalgae growth model to identify the best algae strains and pair them with the most favorable climates to optimize production. The resulting simulated growth model, in conjunction with a biomass assessment tool (BAT), is able to predict hourly, monthly, and annual biomass production for OPR systems [157]. An impressive 64000 sites across the coterminous US (primarily located in the south) have been evaluated as potential OPR locations [158]. The original BAT tool selected discretized 485 ha land plots from randomized points generated to assess the costs and availability of various sources of water for biofuel production [159]. Water demand and algae growth rates were determined using Cligen a stochastic model that generates climatic data for specific geographical locations. Cligen was originally developed to predict water erosion in the US, and it evaluated data from some 1100 weather stations across the country, providing stochastic corrections for missing and spurious data. Daily logged data included solar radiation, temperatures, precipitation, and wind, all factors known to effect OPR productivity [160]. Applying these and other evaluative tools proved valuable in the complex task of selecting optimized locations to construct OPR algae cultivation operations. This particular model however falls short with respect to evaluating potential sites in Canada.

Recent literature related to algae growth models using satellite remote sensory photogrammetry revealed that approximately 80% of 54 published works on the topic took place in the last ten years. While a number of papers discuss the monitoring, analysis, and forecasting of open water algae blooms [161-168], there have been no documented attempts to use satellite data to predict algae growth in open pond raceway systems. Therefore, the development of such a model would be valuable and unique.

Given the noted current model shortcomings, the primary objective of this study is to develop a data-intensive analytical model to predict the cultivation of algae biomass at a scale of 2,000 tonnes dry biomass per day in OPR systems applicable to Canada's cold climate regions. The key specific objectives of this study are:

- To analyze Canadian site specific climate data to determine the different model parameters in an OPR system applicable to Canada's cold climate regions.
- To develop a bottom-up analytical model to predict the cultivation of algae biomass in OPR systems located in different sites,

- To conduct the comparative analysis of algae biomass yields between selected OPR sites,
- To perform the sensitivity analyses of the various parameters such as; thermal energy, harvesting period, inoculum concentration on the predicted biomass yield,
- To estimate the impact of supplementing solar light with artificial light on the predicted biomass yield.

Methodology

A flowchart for the development of the SATOPR (SATellite Open Pond Raceway) algae cultivation model can be seen in Figure 1.

Satellite meteorological data is available for geographical locations in Canada, as well as other regions around the globe [169]. The two key parameters required by the model include solar irradiance and media temperature [170]. These parameters are discussed in more detail below.

Because of our interest to be able to evaluate and compare yield results between various locations to cultivate algae and our need to also validate our model, we selected 2014 as the year for which we would calculate the annual yields of our OPR systems. This period coincided with experimental data sets from different locations that we would use for validation.

Algae species - Nannochloropsis oceanica

The analytical model was created with the intention to fix certain key variables including the algae species to be cultivated. Since the experimental data sets involved the cultivation of the algae species, *Nannochloropsis oceanica,* this is the species cultivated in our modeled cases. In a study by Singh et al. [145], the maximum growth rate achieved under varying light wavelengths and intensities was 0.64 d^{-1} under phototrophic and 0.66 d^{-1} in mixotrophic conditions. Sandnes et al. [127], in agreement with Singh et al., found that specific growth rates increase with temperature, peaking at between 25-29 ºC, with growth quickly destabilizing

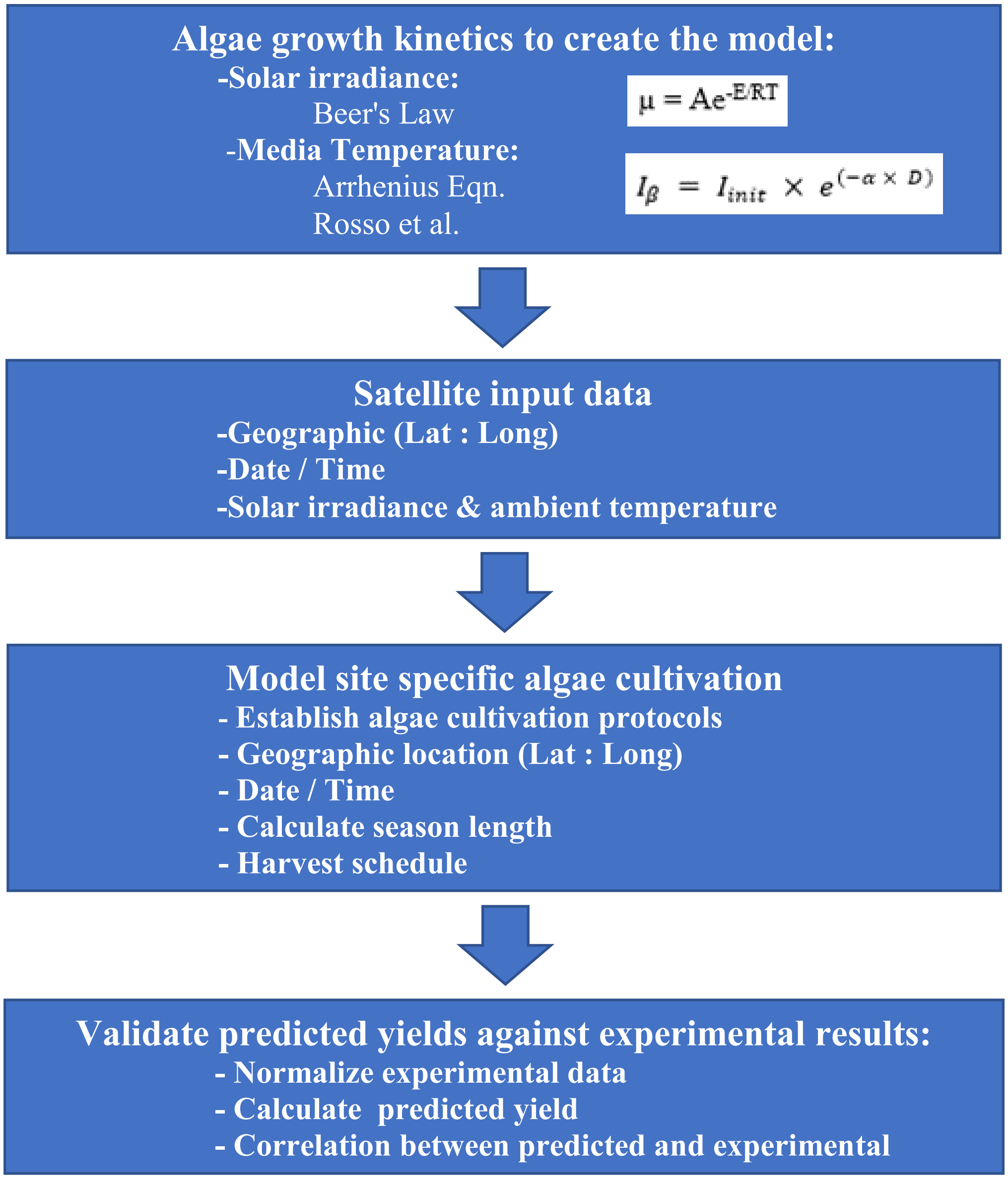


Figure 1: Flowchart for the SATOPR algae cultivation model

beyond 30℃. Likewise, the optimal temperature would increase as light intensity increases up to 28 ºC at 80 μmol photons m^{-2} s^{-1} with a recorded growth rate of 2.3 d^{-1}. Maximal specific growth rate achieved in the study was 1.6 d^{-1}, the culture density at which the cell mass reaches its highest output rate of biomass for specific culture conditions.

Algae growth kinetics

The accumulation of autotrophic algae biomass is a function of the growth rate of live algae cells, a corresponding rate at which algae cells die, which in turn is directly influenced by metabolic activity determined by media temperature and access to energy (light) and nutrients. The associated kinetics can be represented mathematically by the following Eqn. 2 provided by Jayaraman [171]:

$$B = B_L + B_D \tag{2}$$

The total biomass (B (gL^{-1})) is the sum of live (B_L) and dead algae cells (B_D). Given the relatively brief period between harvesting periods in OPR systems, the quantity of dead cells relative to live ones is assumed to be negligible ($B_D = 0$). Thus, the growth rate (μ) of the algae biomass would equal the change in biomass related to the change in time (dB_L/dt), which is normally recorded as grams per liter per day ($gL^{-1}d^{-1}$) in Eqn. 3.

$$\mu = \mathrm{d}B_L/\mathrm{dt} \tag{3}$$

Or, the increase (change) in biomass that occurs over a change in time is represented as Eqn. 4:

$$\mathrm{d}B_L = \mu\,(\mathrm{dt}) \tag{4}$$

However, the growth rate (μ) is attenuated by a biomass production attenuation coefficient (K_P), Eqn. 5,

$$\mathrm{d}B_L = K_P\mu\,(\mathrm{dt}), \tag{5}$$

which is the product of multiple functions that control the metabolic activity of the algae cells including light intensity ($f[I]$), media temperature ($f[T]$), and the availability of nutrients, particularly carbon, in the form of CO_2 ($f[C]$), nitrogen in the form nitrates ($f\,[N]$), and phosphates ($f\,[P]$) seen in Eqn. 6.

$$K_P = f(I)f(T)f(C)f(N)f(P) \tag{6}$$

Light intensity

Light provides the energy for autotrophic algae growth and varies with depth, wavelength, suspended particles (other algae cells), light intensity, and incident angle. The amount of light (intensity) entering the media is affected by diurnal and seasonal variations. Li et al. [172] provide a mathematical analysis of the stoichiometrically derived algal growth model. For our model, we assumed uniform mixing within the system with light penetration being reduced (extinguished) as depth increases. According to the Beer-Lambert Law for liquids, we can calculate light intensity at any depth in a pond based on algae biomass concentration [149, 171, 173-175]. Light intensity (I_β) (also percentage of light), recorded as Wm^{-2}, transmitted through the absorbing media is equal to the impinging light intensity (I_{init}) multiplied by the exponent of the negative total pond extinction coefficient (α) multiplied by the depth of the pond (D) in Eqn. 7.

$$I_\beta = I_{init} \times e^{(-\alpha \times D)} \tag{7}$$

The total pond turbidity extinction coefficient (α) is equal to the sum of the nonalgal turbidity extinction coefficient (K_n) and the algae turbidity extinction coefficient (K_a) multiplied by the associated initial algae biomass concentration (B_{init}) seen in Eqn. 8:

$$\alpha = (K_n) + (K_a)\, B_{init} \tag{8}$$

where the extinction coefficient for nonalgal turbidity (K_n) is assumed to equal zero for clear water, and (K_a) has been estimated by others as 0.014 [176]. Therefore, Eqn. 9 for (I_β) becomes:

$$I_\beta = I_{init} \times e^{(-K_a \times B_{init} \times D)} \tag{9}$$

To calculate the average light intensity throughout the water column, we altered our formula to Eqn. 10 [171]:

$$I_{avg} = \left(\frac{I_\beta}{(K_a \times B_{init} \times D)}\right) \left(1 - e^{(-K_a \times B_{init} \times D)}\right) \tag{10}$$

To complete the calculation that determines the influence of the photosynthetic light response rate *f*(*I*) on the biomass production attenuation coefficient (K_P), we used Jayaraman and Rhinehart's Eqn. 11 [171]:

$$f(I) = 9.34 \times (1 - e^{(-0.0044 \times I_{avg})}) - 1.60 \quad (11)$$

Media temperature

In an analogous way to determining the influence of light intensity on algae growth, we are able to account for the effect of media temperature. In our research study, we considered two alternative approaches to these calculations. In our first model [f (T_1)], we applied the temperature dependence f (T_1) forwarded by James and Boriah, and Jayaraman and Rhinehart [114, 171] in Eqn. 12:

$$f(T_1) = e^{(-K_t \times (T_m - T_{opt})^2)} \quad (12)$$

Temperatures are recorded in kelvins (-273.16 ºC) and matched with species-specific growth rate data, where K_t is the temperature extinction coefficient, which is equal to T_{opt}^{-2}, T_m is the pond temperature, and T_{opt} is the optimal growth temperature. For *Nannochloropsis oceanica*, K_t was determined to be 0.00001. When we apply the pond water temperature dependence on algae, we can predict an increase in growth rate up to the optimal temperature followed by a gradual decline.

In a second model [f (T_2)], temperature dependence follows the kinetics proposed by Rosso [177] and later supported by Bechet [143], Chen [128], and Ras [144] in Eqn. 13:

$$f(T_{2)} = \frac{U_{opt} \times (T - T_{max})\ ((T - T_{min})^2)}{(T_{opt} - T_{min})\Big((T_{opt} - T_{min})(T - T_{opt}) - (T_{opt} - T_{max}\ )\ \big(T_{opt} + T_{min} - (2\ T)\big)\Big)} \quad (13)$$

Rosso postulates in his model that a more accurate approximation of the effects of changes in temperature (f [T_2]) may be achieved by including cardinal or important species-specific temperatures, T_{min} and T_{max}, along with a specific optimum growth rate (U_{opt}) achieved at the optimal temperature (T_{opt}). T_{min} is the temperature below which no growth is observed. T_{max} is the temperature above which no growth is observed.

Our research compared these two models to evaluate the concurrence of predicted results with experimental ones.

Fluctuations in pond temperatures have been extensively studied and show that solar radiation can effect thermal changes that could be harvested for energy. Processes that govern heat transfer in ponds involve complex, inter-related parameters including wavelength-specific angular incident solar radiation, particulate matter, salt concentrations, reflectivity, heat capacity, density, air temperature, water transparency, composition of the pond bottom ground properties, wind, evaporation, convection, long-wave radiation to the sky, conduction, light and heat transmission through water, annual periodic sinusoidal flux, and underground water movement [178, 179]. In all of the associated calculations, to arrive at a predictive result, each variable introduces the potential for errors and relatively large standard deviations, the sum of which may be very significant.

Even if site-specific surface water temperatures were available, significant assumptions are still made. OPR systems have a significantly different limnology and thermal properties than large open lakes and streams. Available government data sets are often linked to larger bodies of water where complex environmental factors interact to govern actual temperatures.

Given the complex science involved in surface water temperature, our model needed a good proxy for surface media temperature in shallow ponds. Our hypothesis was that ambient air temperature would provide such a proxy. To test this theory, we analyzed the NREL experimental data set we had selected, where pond media and ambient temperatures were logged every 15 minutes. We correlated this information to daily mean temperatures and determined that the average media temperature was approximately 4.5 degrees cooler than the daily ambient mean temperature, with a standard deviation of 1.99. This finding concurs with experimental cultivation results by Dahmani et al. [180] on *Chlorella pyrenoidosa* in a small OPR system 0.4 m deep.

We also assumed that average media temperature had to consistently be above -2 ºC, the minimum growth temperature (T_{min}) for *Nannochloropsis oceanica* [127, 144] to commence algae cultivation. Optimum growth temperature (T_{opt}) has been established at 26.7 ºC, maximal growth temperature (T_{max}) at 33.3 ºC, and optimal growth rate at 1.8 d^{-1}.

Nutrient availability (C, N, P)

The consumption of nutrients by the growing algae, represented by $f(C)$, $f(N)$, and $f(P)$, can be modeled kinetically using the Monod equation [181] where $f(C_x)$ represents each nutrient: carbon from CO_2 (C), nitrogen from nitrates (N) and phosphate (P). The change in nutrient concentration (C_x) recorded in gL^{-1} over time (t) can be represented by Eqn. 14:

$$\frac{\mathrm{d}C_x}{\mathrm{dt}} = -K_x\, r_x\, K_p\, B_{init} \tag{14}$$

where K_x is the species-rate constant, r_x is the rate of nutrient consumption, K_p is the biomass production attenuation coefficient and calculated to minimize the standard deviation between modeled and experimental results using Excel solver (sum of squares standard deviation), and B_{init} is the initial biomass concentration. The influence of each nutrient can then be expressed as Eqn. 15:

$$f(C_x) = \frac{C_x}{K_x^h + C_x} \tag{15}$$

where K_x^h represents the half concentration of a specific nutrient species (x) and plays a key role in contexts where nutrients are added only at the beginning of a growth period. As nutrients are used up, the algae eventually shift into a deprived nutrient state. For our research, we maintain that each nutrient will be maintained in surplus concentrations throughout the cultivation period and therefore no values are provided for K_x and r_x. Although production protocols with respect to maintaining these conditions will vary among researchers, they will be consistently adhered to between production platforms. Where N and P concentrations may be readily adjusted using ammonia (NH_3) and di-ammonium phosphate (DAP or $(NH_4)_2HPO_4$), C is generally maintained by the infusion of CO_2 by sparging this gas into the media. However, this could also be effected through the addition of bicarbonate. Interestingly, the addition of CO_2 affects the OPR system pH. For simplicity, we assumed that the pH was maintained by controlling the infusion of CO_2. The effect of this nutrient is expressed as Eqn. 16:

$$f(CO_2) = \frac{1}{(1+e^{\lambda\left(pH-pH_{opt}\right)})} \tag{16}$$

Since our assumption for this research project is that nutrients will be kept in surplus, each function related to these nutrients will equal 1. Therefore Eqn. 6 above, becomes Eqn. 17:

$$K_P = f(I)f(T) \tag{17}$$

Given the foregoing, to predict change in biomass over time we calculate the following using Eqn. 18 from Jayaraman and Rhinehart [171]:

$$\frac{d_B}{d_t} = K_p \times B_{init} \times f(I) \times f(T) \tag{18}$$

To calculate the production of biomass, we rearrange the formula:

$$B = B_{init} + \left(K_p \times \left(B_{init} \times f(I) \times f(T)\right)\right) \times d_t \tag{19}$$

The SATOPR model involved using daily mean photosynthetically-active radiation (PAR) and ambient near surface satellite data for our selected site. Given the daily flux in both parameters during any given day and our assumption that there would be a suitable correlation between ambient temperatures and our OPR media temperature there was uncertainty that we would be able to draw a meaningful correlation between modeled results and experimental results. Where satellite data was provided daily, experimental results provided flux at 15 minute intervals.

Once constructed we applied the SATOPR model for an entire year's growing period (330 days). Predicted algae production was measured based on a weekly harvesting regime with the initial inoculum cell concentration set at 0.2 gL^{-1}.

Results and discussion

This paper reports on the development of a novel, data-intensive analytical model to meet the need to be able to predict algae OPR productivity in Canada. Although day-to-day conditions may be difficult to predict, we can consider historical weather data at specific sites to construct site-specific models. The SATOPR model is based on satellite site-specific irradiance and temperature data, then validated and benchmarked against species-specific/operating protocol-specific experimental OPR data.

Validation

Validation of our model involved testing it using the much more granular experimental data. The validation experimental data set was accessed from the ATP3 (Algae Testbed Public-Private-Partnership) Program conducted at the ASCATI (Arizona Center for Algae Technology and Innovation) / NREL (National Renewable Energy Laboratory), located in Mesa, AZ [182], from June 20 through July 26, 2014. The analysis provided us with 2772 data points. Since the first week of data was based on a three-day cultivation cycle and started at a higher initial concentration, it was not included in our model.

The SATOPR adjusted K_{p} (Biomass production attenuation coefficient) achieves a statistically closer correlation between the modeled and experimental results for different locations. We theorized that this accounts for variance in respiration and photosynthetic flux between sites.

Under the summer 2014 UFS protocol from which the experimental data was taken, *Nannochloropsis oceanica* ASU algae strain KA32 Pond 2 was studied. The algae were cultivated in a 1 m^3 OPR system with a nominal pond depth of 25 cm, media circulated by paddlewheel. Algae were harvested weekly. Data logging took place using a YSI 5200 monitor and control system. Pond variables included pH, temperature, oxidative reduction potential (ORP), dissolved oxygen, conductivity/salinity, and PAR from a local LI-COR sensor. PH was set at 8.0 and salinity at 0 ppt [183].

Research studies have determined that to cultivate algae in OPR systems, a minimum solar irradiance of 4.65 kWh m^{-2} is required [39, 184]. Radiation source information was accessed from the NASA/GEWEX Surface Radiation Budget (SRB) Project. The Global Modeling and Assimilation Office (GMAO) provided the meteorology source information. Canadian sunrise / sunset calculations were obtained from the National Research Council Canada (NRC) and SunEarth Tools.

Validating the model necessitated bringing together several sets of experimental raw data [185] into a single data source file synchronized in time. The data set selected included PAR solar data that was correlated to the rest of the data sets. The data sets included instantaneous (5 min and 15 min intervals), harvesting (weekly), weather (15 min), and operating data (twice d^{-1}, 5 days wk^{-1}). A relatively contiguous set of records for the key variables of interest included date, time, pH, media temperature, dissolved oxygen, algae strain, pond ID, and algae dry weight. Although rigorous experimental protocols were in place, gaps were observed in some of the data streams.

For the selected study period, biomass concentration (g L^{-1}) was plotted against time (days) for each week. From the slope of this graph, we obtained the experimental growth rate for each week of cultivation over a four-week period. Where experimental parameters such as solar irradiance, media temperature, pH, and dissolved oxygen were measured and logged every 15 minutes during a weekly cultivation and harvesting regime (representing some 672 data points), only 4 or 5 data points represent biomass concentration during the same seven-day cultivation period between harvests.

Experimental data was used to determine a level of concurrence and validation with formulas that predict algae growth and to establish values for species-specific constants as discussed above. As Figure 2 shows, there is good correlation between experimental and predicted algae productivity.

The experimental data was correlated to the predicted results, with the values for K_t and K_p adjusted in the analytical formulas to minimize the standard deviations between modeled and experimental data sets and to provide agreement with an experimental yield of 2.14 g. Recorded standard deviations for models T_1 and T_2

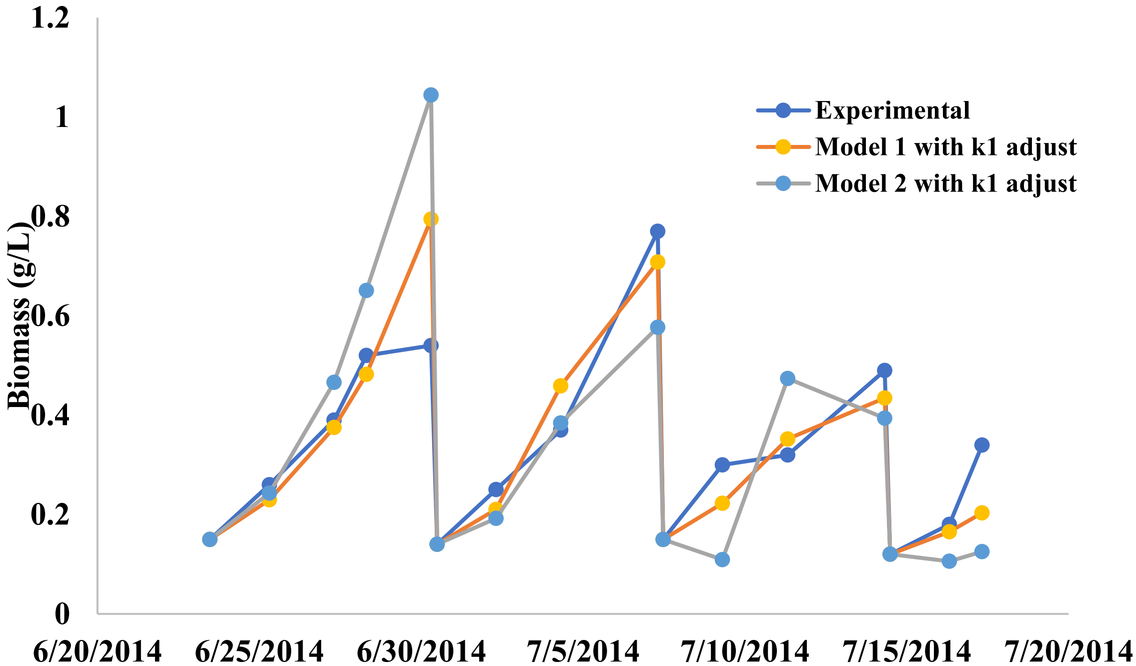


Figure 2: Algae growth – experimental vs. modeled data (Mesa, AZ Jun 23 – Jul 17, 2014)

were 0.1017 and 0.4389 for K_p values 0.000755 and 0.000647, respectively (see Table 6). K_t was set at 0.000011. The findings for K_p are consistent with the acknowledged greater sensitivity of $f(T_2)$ to temperature changes compared with $f(T_1)$.

Table 6: Model coefficients for the case where biomass yield equals experimental yield (2.14 g)

Model	K_t	K_p	Standard Deviation	Experimental (g)	Model 1 (g)	Model 2 (g)
$f(T_1)$	0.000011	0.000755	0.1017	2.14	2.14	
$f(T_2)$	0.000011	0.000647	0.4389	2.14		2.14

With the functional model development completed, work focused on correlating the model's results using NASA satellite data sets for the same location and time for both solar irradiance and local ambient climatic conditions. The next step in our analysis was to determine a similar correlation between experimental results with NASA satellite solar irradiance and air ambient temperature data. Like our initial

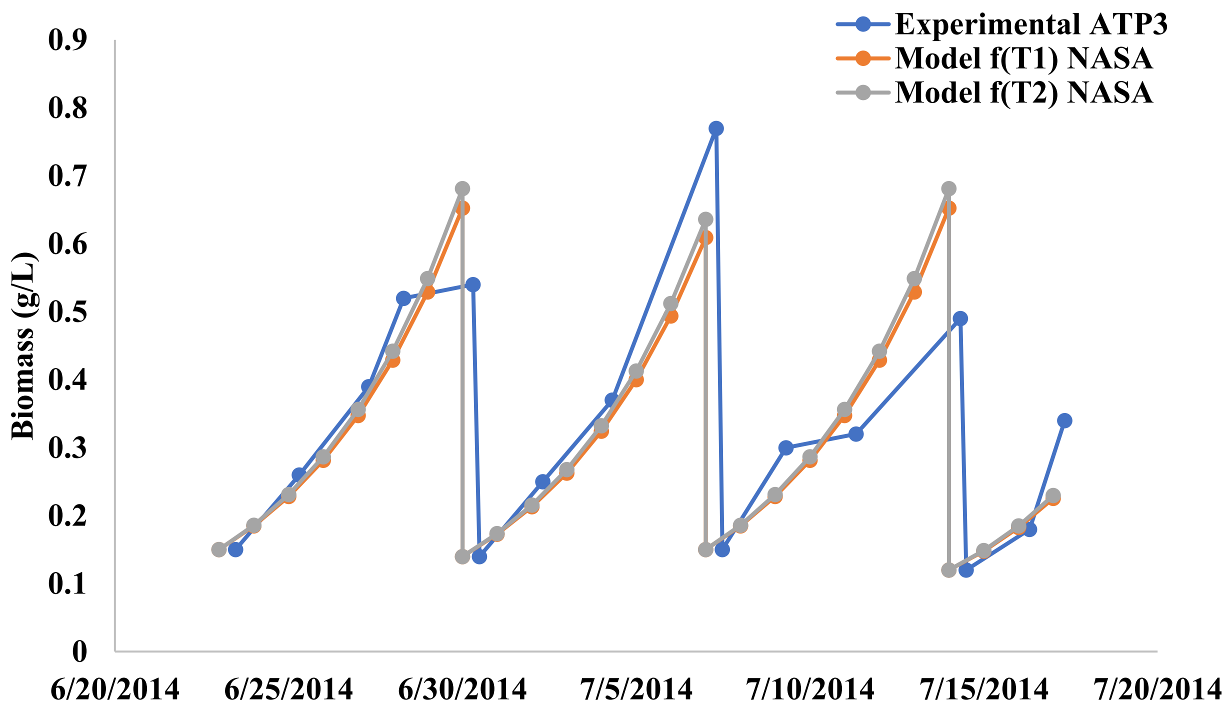


Figure 3: Algae growth – experimental vs model – Mesa, AZ – June 23 – July 17, 2014 NASA

analysis, the predicted results correlated well with experimental results. See Figure 3.

Model adjustments were made to K_p in the analytical formulas to minimize the standard deviations between modeled and experimental data sets and to provide agreement with the experimental yield (2.14 g). The recorded standard deviation for model T_1 and T_2 were 0.00878 and 0.00681 for K_p values 0.034543 and 0.019813, respectively. K_t was maintained at 0.000011 (see Table 7)

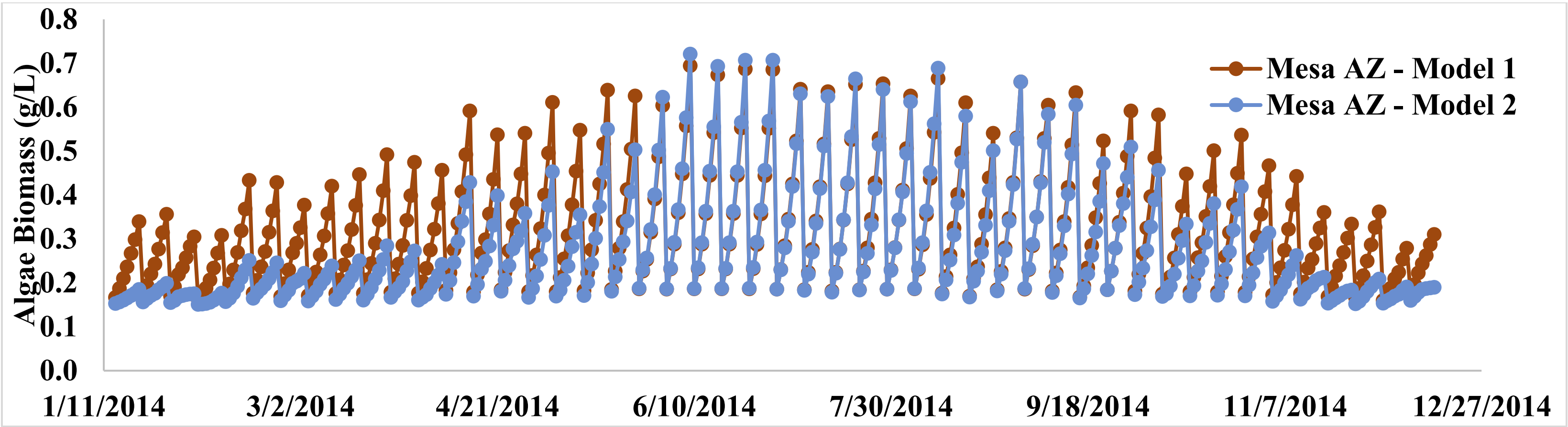


Figure 4: Predicted annual algae growth from 2 models, Mesa, AZ, 2014

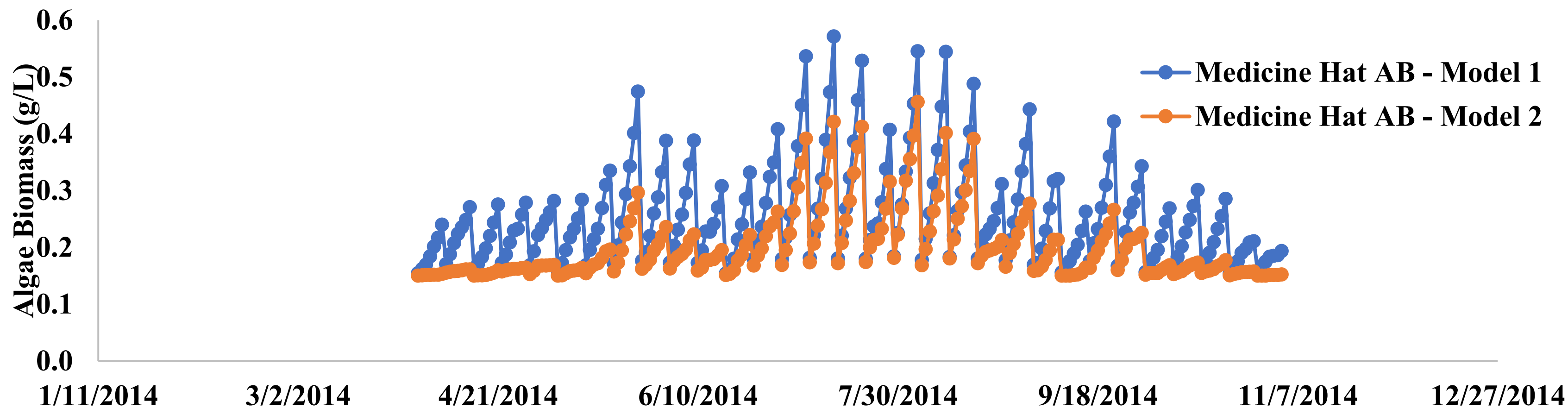


Figure 5: Predicted annual algae growth from 2 models, Medicine Hat, AB, 2014

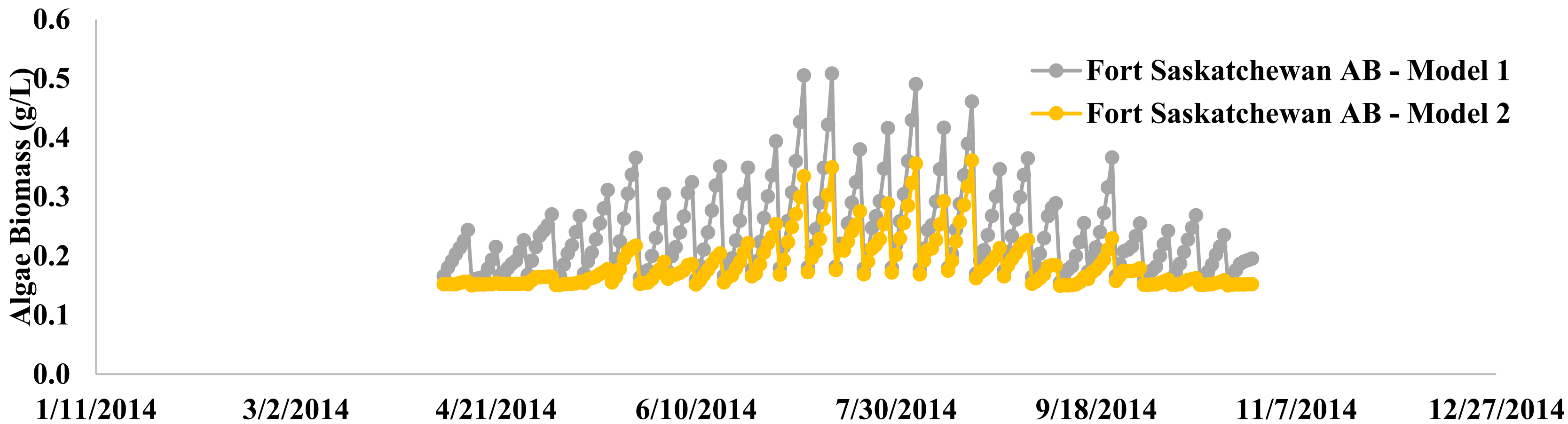


Figure 6: Predicted annual algae growth from 2 models, Fort Saskatchewan, AB, 2014

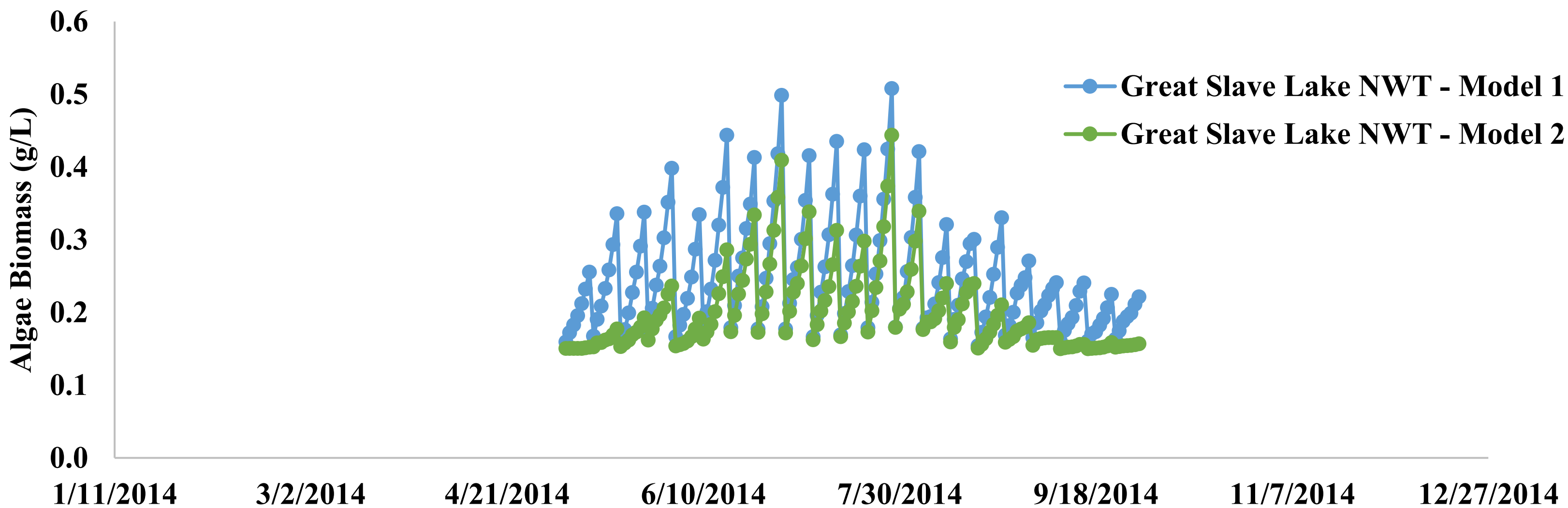


Figure 7: Predicted annual algae growth from 2 models, Great Slave Lake, NWT, 2014

Table 7: Model coefficients for the case where biomass yield equals experimental yield (2.14 g) based on NASA data

Model	K_t	K_p	Standard Deviation	Experimental (g)	Model 1 (g)	Model 2 (g)
$f(T_1)$	0.000011	0.034543	0.00878	2.14	2.14	
$f(T_2)$	0.000011	0.019813	0.00681	2.14		2.14

Modeled results

The SATOPR model was run for four different sites and the following results may be seen: Mesa, AZ (Figure 4), Medicine Hat, AB (Figure 5), Fort Saskatchewan, AB (Figure 6), and Great Slave Lake, NWT (Figure 7).

The effect of temperature

It is interesting to note that in Mesa, AZ (Figure 4), where media temperatures fluctuate relatively closely around the optimum growth media temperature, there is little difference in results between approaches in calculations from model T_1 and model T_2 (June through August). However, as media temperatures continue to decrease across the shoulder and winter seasons, the predicted difference in results becomes much more pronounced.

Table 8: Predicted results – 7-day harvest schedule

Harvest Schedule		**Weekly**			**Optimized Media T = 26.7℃**			
LOCATION	**Growing (days)**	**Growing (weeks) # harvests**	**$f(T_1)$ Predicted Biomass $gL^{-1}yr^{-1}$**	**$f(T_2)$ Predicted Biomass $gL^{-1}yr^{-1}$**	**$f(T_1)$ Predicted Biomass $gL^{-1}yr^{-1}$**	**$f(T_2)$ Predicted Biomass $gL^{-1}yr^{-1}$**	**$f(T_1)$ Biomass Factor Increase**	**$f(T_2)$ Biomass Factor Increase**
Mesa, AZ	336	48	23.6	17.3	37.4	33.8	1.58	1.95
Med Hat, AB	217	31	8.2	3.9	19.8	18.1	2.41	4.64
Ft Skwn, AB	203	29	7.0	2.6	17.6	16.2	2.51	6.23
GrtSlvLk, NWT	147	21	5.6	2.8	12.5	11.5	2.23	4.11

A year-long consistent experimental study would be required to determine which temperature model more accurately predicts yield outcomes across a broader range of cultivation media temperatures.

Predicted results based on the two approaches for calculating the impact of $f(T)$ are seen to be significantly different from one another in the above graphs, with the annualized results presented in Table 8.

More of the power of the SATOPR model becomes apparent in that parameters may be changed to consider cultivation alternatives. Table 8 shows that not only are we able to establish the advantage of constructing the OPR in Mesa versus the alternative Canadian sites, we can also see the predicted dramatic impact of maintaining a constant optimum media temperature. In the model, we are able to fix the media temperature T_m in the kinetic formula (Eqn. 12, Eqn. 13) at the optimum level for the algae while still running the model using site specific solar irradiance values.

The effect of harvest schedule

With the model, we were also able to change from a weekly harvest schedule to waiting until the algae density in the biomass reached a certain threshold (i.e., 5 gL^{-1}) (see Table 9). The model construction allows us to conduct simulations that predict optimized harvest yields. In one instance we may set a weekly harvest schedule in the kinetic Eqn. 19 by holding d_t constant at 7 days and solving for B, the final concentration. In another instance, we may choose harvesting to commence at a specific cell density by fixing B and solving for d_t. A review of Tables 8 and 9 shows that for Mesa, AZ, adopting a weekly harvesting schedule over choosing to harvest at 5 gL^{-1} may result in a 15% increase in annual yield as per model $f(T_1)$ calculations.

At Fort Saskatchewan, the same model calculations forecast a 15% improvement by adopting a 5 gL^{-1} harvest schedule over a weekly schedule. The results suggest that for OPR systems with greater media temperature flux, a density harvest schedule will outperform a weekly harvest schedule.

Table 9: Predicted results – Harvest schedule based on cell density

Harvest Schedule		Density $> 5\ gL^{-1}$			
LOCATION	Growing (days)	# harvests	$f(T_1)$ Predicted Biomass $gL^{-1}yr^{-1}$	# harvests	$f(T_2)$ Predicted Biomass $gL^{-1}yr^{-1}$
Mesa, AZ	336	57	20.1	44	15.3
Med Hat, AB	217	27	8.8	14	4.4
Ft Skwn, AB	203	25	8.0	11	3.6
GrtSlvLk, NWT	147	18	5.9	10	3.1

Predicting land requirements

From the constructed SATOPR model, we have extracted a great deal of valuable comparative information from four sites of interest that proves useful for a future techno-economic analysis. Under the prevailing local climatic conditions provided by satellite, we were able to determine the amount of land required for the OPR system to produce 1000 T yr^{-1} of dry biomass at each location (see Figure 8).

When we establish operating parameters that would include algae inoculation concentration, harvesting regime, ensuring that nutrients are in surplus, etc. we are able to determine algae production yield for a given area for a production period using Eqn. 19. Based on a desired production level we are quickly able determine how large an area would be required to produce a desired amount of biomass.

We predicted that a land area of 17-20 hectares in Mesa, AZ can produce a similar amount of biomass as 57-68 hectares at Fort Saskatchewan. Simple math provides the amount of land area required to meet our research objective, the cultivation of 2000 Td^{-1} algae (i.e., 1,000 T yr^{-1} / 330 d yr^{-1} = T d^{-1} [predicted]; 2000 T d^{-1} [objective] / T d^{-1} [predicted] = multiplication factor to be applied). The modeled results for biomass production at Mesa, AZ however, are more conservative than forecast by a NREL model predicting 12 ha to produce 1000 T biomass [155].

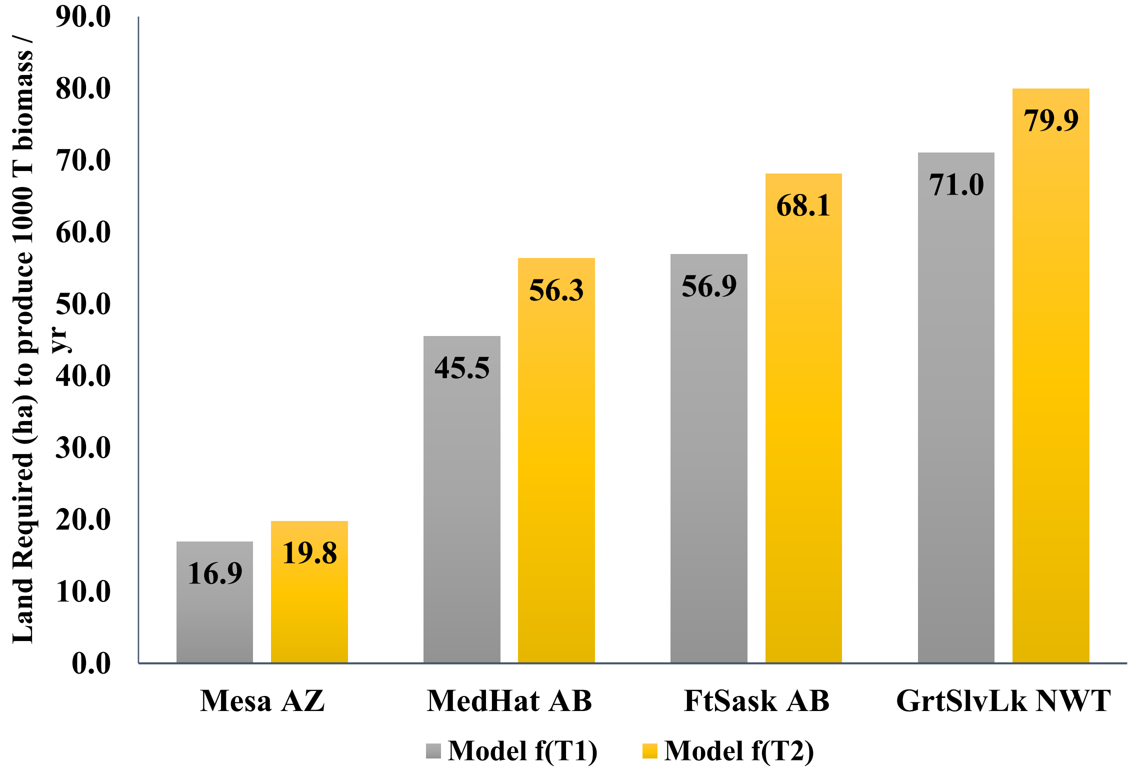


Figure 8: Predicted land requirement to produce 1000 T biomass yr^{-1}

The effect of inoculum concentration

The model also proves useful in assessing the impacts of increasing the concentration of the inoculum for each subsequent growth period on yield and land requirements to produce 1000 T algae yr^{-1} (see Figures 9 and 10). Figure 9 shows a linear and direct relationship between initial inoculum concentration and annual biomass yield. The model using Eqn. 19 is structured to accept values for B_{init} (initial concentration) and in our current scenario, the inoculum concentration. Meanwhile we harvest at 0.5 gL^{-1} (B) and we solve for d_t. at which time the the system is brought back to B_{init}. In Figure 10, the model predicts that increasing the inoculum concentration from 0.2 gL^{-1} to 3.5 gL^{-1} reduces the requirement for land to an inflection point.

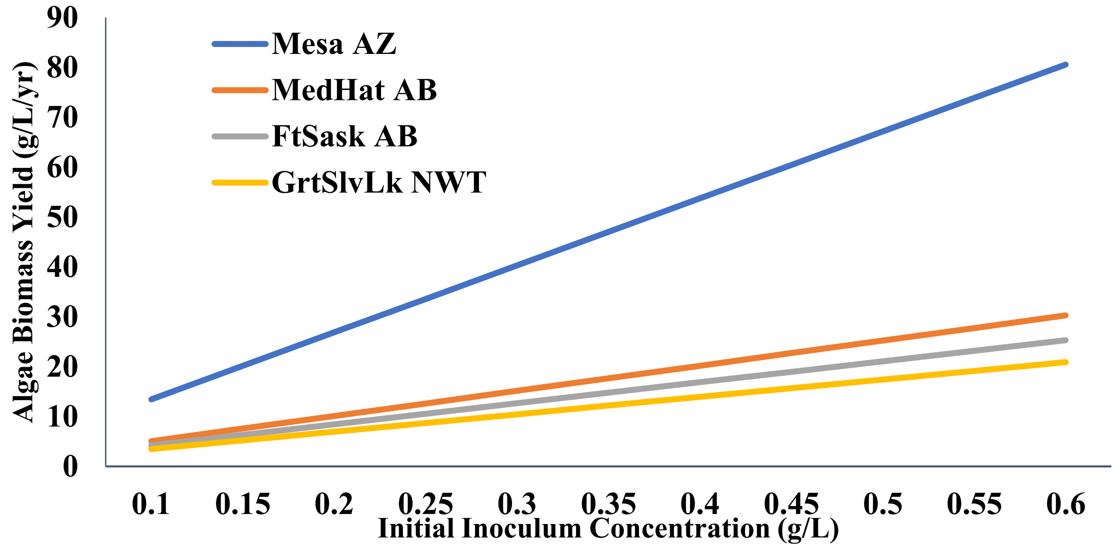


Figure 9: Predicted effect on biomass yield by increasing inoculum concentration (Model f $[T_2]$)

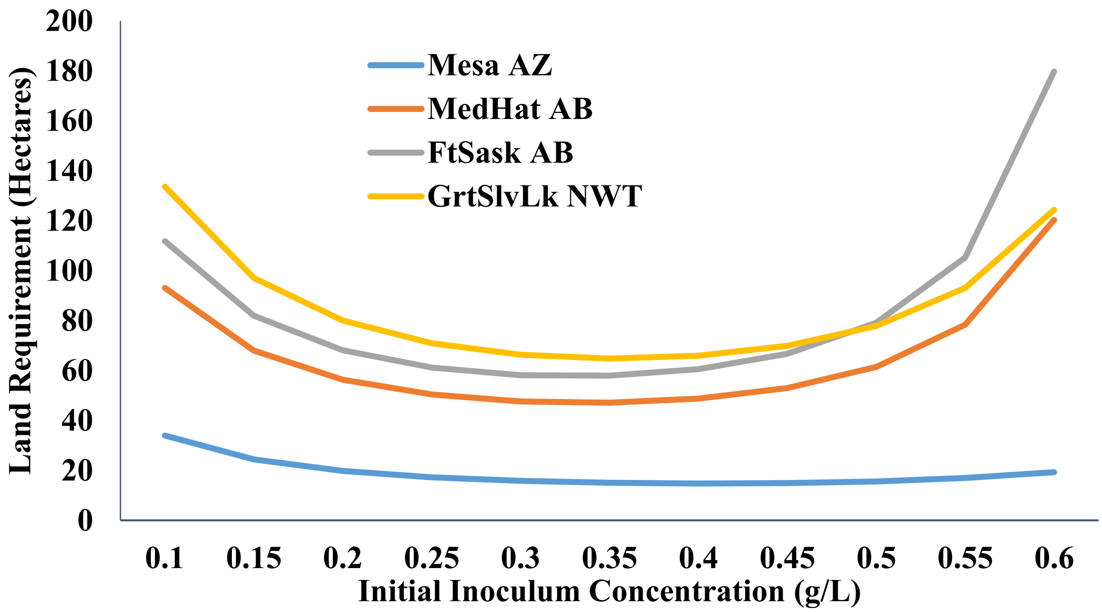


Figure 10: Predicted effect on hectares of land required to produce 1000 T biomass yr^{-1} by increasing inoculum concentration (Model f $[T_2)]$)

If the inoculum concentration exceeds the higher concentration by more than 0.5 gL^{-1}, the requirement for land begins to increase again. It also predicts that impacts of inoculum changes increase, the further from the equator the OPR is located. This is consistent with our understanding that with increased concentration of algae, the ability of light to penetrate the media to provide photosynthetic energy will diminish.

The effect of incremental media temperature increases

We also assessed the impacts of incremental increases in media temperature on algae production and land requirements to produce 1000 T yr^{-1} (see Figures 11 and 12). For the presented results, the incremental increase in temperature is applied throughout the year by incrementally adding a single degree °C value to the calculated value T_m in Eqn. 12 from 0 through 17 degrees. This will in turn affect results in Eqn 19 where we calculate the change in biomass. Given that the media temperature at Mesa is already near the optimal level for much of the year, the addition of more than a few degrees of heat to the media would begin to have adverse effects on annual production.

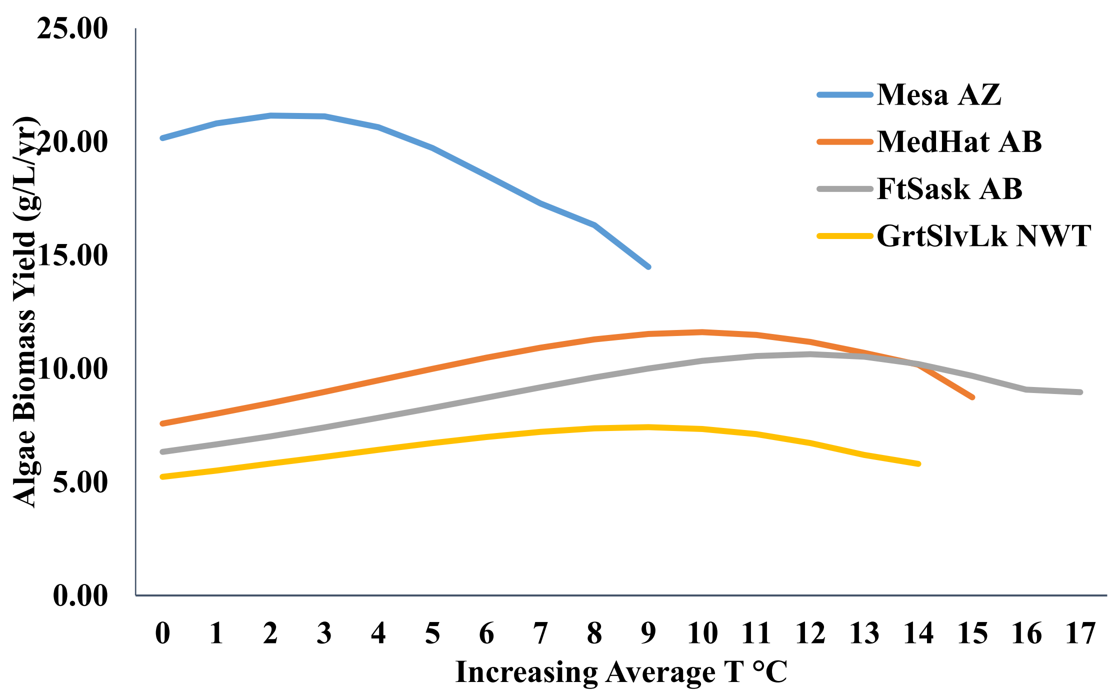


Figure 11: Predicted impact of increasing media temperature on algae biomass yield (Model f $[T_2]$)

Given the more northerly Canadian latitude for the other three OPR systems, it is relatively easy to generalize that these systems could benefit from the application of much higher levels of thermal energy to maintain algae optimized growth.

As seen earlier in the current study, the model can be adapted to maintain the media temperature at its optimum level to support algae growth. Calculations and analyses may also be conducted to determine the amount of thermal energy required for this purpose along with associated costs, depending on the source of heat used.

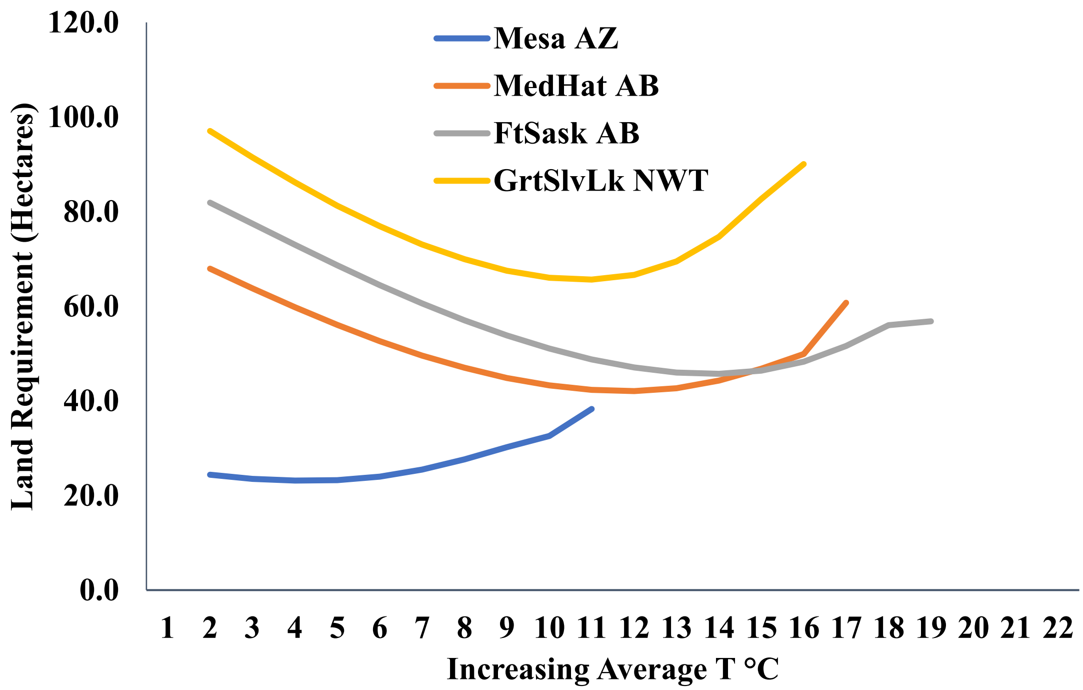


Figure 12: Predicted impact of increasing average media temperature on land requirement (Model $f\ [T_2)]$)

The effect of supplementing light

Similarly, the model allows for the consideration of supplementing ambient light with LED and other sources of light to shift growth toward optimal levels. A simulation was conducted in our original correlation model wherein the system was optimized for the least amount of constant intensity light required to produce an equivalent amount of biomass. The model predicted that where $f\,(I_1)_{avg}$ was fixed (Eqn. 10) and optimized, the 2.14 g of biomass produced during the trial period (Eqn. 19) could be achieved using a light source producing a constant 431 Wm^{-2}. Under $f(I_2)_{avg}$ conditions, the same outcome would be achieved with a 215 Wm^{-2} light source (see Table 10).

The same model predicts that under $f(I_1)_{avg}$ conditions, using a constant 1000 Wm^{-2} light source would improve the yield from 2.14 g to 2.56 g. Under $f(I_2)_{avg}$ conditions, the same 1000 Wm^{-2} light source would improve the yield from 2.14 g to 5.08 g. Consistent with our understanding that light becomes limiting after a certain point, when the light source is changed to 580 Wm^{-2}, the $f(I_2)_{avg}$ scenario still predicts a yield of 4.28 g (see Table 11).

Table 10: Predicted minimum constant light required to achieve the same yield as experimental (2.14 g), holding K_p constant for $f(T_1)$ and $f(T_2)$, respectively, and K_t and media T constant.

Model	K_t	K_p	**Standard Deviation**	**Experimental (g)**	**Model 1 (g)**	**Model 2 (g)**	**Light ($W\ m^{-2}$)**
$f(T_1)$	0.000011	0.000755	0.088935	2.14	2.14		431
$f(T_2)$	0.000011	0.000647	0.207232	2.14		2.14	215

Table 11. Predicted maximum biomass yield when light intensity is varied holding K_p constant for $f(T_1)$, and $f(T_2)$, respectively, and K_t and media T constant.

Model	K_t	K_p	**Standard Deviation**	**Experimental (g)**	**Model 1 (g)**	**Model 2 (g)**	**Light ($W\ m^{-2}$)**
$f(T_1)$	0.000011	0.000755	0.329437	2.14	2.56		1000
$f(T_2)$	0.000011	0.000647	0.072253	2.14		4.28	580
$f(T_2)$	0.000011	0.000647	0.106228	2.14		5.08	1000

As highlighted in the discussion, the SATOPR model demonstrates its ability to predict algae cultivation productivity in different geographies. However, it is also unique and useful for simulating outcomes for optimization scenarios such as changing harvesting schedules, applying units of heat to the media, augmenting natural light with artificial light and adjusting inoculum concentrations.

Conclusions

The objective of our research was to develop an analytical model that would prove useful in the prediction of algae biomass production for OPR sites in Canada. The study has predicted that to commercially produce 1000 T of algae biomass 17-20 ha of land would be required at Mesa, AZ, 45-56 ha at Medicine Hat, AB, 57-68 ha at Fort Saskatchewan, AB and 71-80 ha at Great Slave Lake, NWT.

This work has demonstrated the successful development a data-intensive model whose results show good correlation with a data set from the NREL ATP3 testbed in Mesa, AZ that predicted only 12 ha would be required to produce the 1000 T of algae biomass. Consistent with kinetic models that have been previously developed the uniqueness of the SATOPR model to predict biomass outcomes is based temperature and solar irradiance values provided from satellite source. Given the global reach of satellites, this data source is able to predict OPR system performance both in Canada and the rest of the globe making the model both unique and beneficial for comparative analyses of OPR system performance. There have been no known attempts to utilize satellite data has to model OPR algae yields. Because of its ability to predict highly localized algae yields SATOPR may be used as an initial algae cultivation site screening tool, an alternative and complementary analysis tool useful for comparing system performance between locations.

Given that both techno-economic analyses (TEAs) and life cycle assessments (LCAs) related to algae production, rely on site-specific productivities, the SATOPR model is able to provide supportive analytic capabilities for these purposes, especially where comparative analysis between sites is desired.

Future research with this model would benefit from access to timely experimental yield data (i.e., 15-minute incremental results that could be matched with other model parameter results that are provided at these same intervals). This would enable more accurate analysis and assist in refining capabilities in the SATOPR model. It is anticipated that the ultimate value of the model will be revealed as results from the model are correlated with experimental field data from multiple sites using identical species and operating protocols.

4

4. Development of cost models of algae production in cold climate using different production systems[3]

Abstract

Research into the potential to use microalgae to produce biofuels continues even though under current cultivation practices it would be economically unsustainable. In cold climates similar to countries like Canada, the unsustainability is exacerbated since algae cultivation in open raceway pond (ORP) systems is limited to a short period of the year when pond surface water temperatures and ambient light conditions enable optimal culture growth. In this study we develop techno-economic assessment models to predict, evaluate, and compare the techno-economic results from three autotrophic algae cultivation scenarios to produce algae biomass. The first is a modeled OPR site located

[3] A version of this chapter has been published as a peer-reviewed journal. Development of cost models of algae production in cold climate using different production systems, *Biofuels, Bioproducts & Biorefining*, 2019 *(in press)*.

in the lower US that shows a minimum biomass selling price (MBSP) for algae of \$541 tonne^{-1} (T^{-1}). The second scenario models an identical ORP system co-located at a site near Fort Saskatchewan, a norther city in the province of Alberta, Canada. The resulting MBSP is \$1,288 T^{-1}. A third scenario models a photobioreactor (PBR) cultivation system co-located at the same central Alberta site and shows algae production with an MBSP of \$550 T^{-1}. Each system is scaled to produce 2000 T d^{-1} AFDW (ash free dry weight) algae biomass. The study concludes that PBR systems deployed at this scale have the potential to significantly reduce production costs compared to similarly sited OPR systems in Canada despite climatic factors and high initial capital costs associated with PBR construction. Furthermore, the modeled PBR vs OPR cultivation platforms required 0.3% of the water (153 x 10^3 m^3 vs. 59,527 x 10^3 m^3) and 0.04% of the land (32 ha vs. 82,038 ha).

Introduction

The thrust to find more sustainable and economical pathways to bio-renewable fuels continues. Large investments in algae research are unabated; these microorganisms hold tremendous untapped potential to produce high-energy fuels and become a new source for food and a host of other high-value products while mitigating CO_2 emissions. Much research has already been done to identify strains of algae that produce high lipid yields suitable for biofuel production [84, 186]. However, commercialization focused narrowly on biofuels is unsustainable from a techno-economic assessment (TEA) perspective. To overcome the economic hurdle, investigation has been broadened to consider a biorefinery model [92, 187]. White and Ryan [188] argue that the key barrier facing large-scale algae production is understanding the biology of optimal biomass production. This is coupled with the inability to replicate reliable, high lab-scale yield levels in field- and large-scale production (the “lab-to-field yield gap”).

Quinn et al.[189] have developed a multi-factor model that predicts realizable, near-term, large-scale open-pond algae lipid productivity potential across the United States. Results of the study predict relatively low annual lipid productivity results (<14 m^3 $ha^{-1}yr^{-1}$ for colder northerly regions. This work was expanded to evaluate 4,388 sites globally in 2014[190].

Currently, raceway ponds and photobioreactors are the predominant means of cultivating micro-algae[191]. However, there are a variety of algae production systems with increasing scale that have been developed for moderate and hot climates (e.g., USA[192, 193], Europe[194], China[195], and Australia[191, 196]). A recent review by Pankratz et al.[7] has identified algae cultivation technologies that may have applicability for the colder northerly regions found in Canada.

Open pond raceway

Large algae cultivation systems (i.e., four hectares (ha), such as Earthrise Farms, CA) [197], and others as large as 5 ha [198]) are constructed based on the open raceway pond (OPR) design. Ponds, however, do not usually exceed 0.5 ha [150]. A 1997 global review identified well over 100 commercial algae producers with annual capacities of between 3 and 500 tonne (T) and pond areas up to 43 ha [199]. Generally these are constructed as closed-loop oval shape channels 0.2 to 0.5m deep [114]. In many cases, the channels are constructed in clay soils to prevent water loss and minimize construction costs. Other channels are lined with costly membrane systems. The algae cultivation media, composed of water, nutrients and algae, are circulated using low-cost, energy-efficient paddle wheel systems that keep biomass in suspension [114]. Challenges with these designs include temperature fluctuations related to climatic conditions, susceptibility to contamination, gas dissolution and exchange in the culture media, photo-inhibition, evaporation, and transitioning from standardized lab conditions into the highly variable open pond fields [188, 191]. These autotrophic systems have limited applicability in Canada, given its northerly climatic conditions (including cooler ambient temperatures and shorter growing days, especially in winter).

Photobioreactors

Many challenges noted with OPR systems may be overcome with photobioreactor (PBR) cultivation systems, of which there are several types. Tubular and columnar PBR systems constructed of plastic or glass provide good light penetration into the cell media, contributing to algae cell densities that may be significantly higher than found in in OPRs [200-202]. The algae slurry is circulated with pumps to provide nutrient mixing and gas exchange. Because the system is enclosed, there is limited opportunity for contamination and almost no evaporation. However, given that algae tend to stick to surfaces, fouling may be a problem. Given the relatively small volumes of cultivation media within the tubes, larger amounts of land may be required, and thus may limit scalability.

Flat-plate PBRs are known for high biomass production attributed to high photosynthetic activity and high surface areas, enabling great CO_2 and O_2 exchange and mitigating potential gas exchange limitation issues [203, 204]. A third general type of PBR is columnar and offers high volume mass transfer, efficient mixing, controlled growth conditions, low cost, and ease of operation [191].

There is consensus that closed PBR systems have advantages over OPR systems [205]. PBRs yield more biomass, in large measure due to controlled environmental conditions including temperature, evaporation, light [206]. They are also associated with a lower probability of contamination, lower requirement for land [187], and reduced water requirement and dewatering costs. However, they generally have higher capital and operating costs and, as these costs increase, there is skepticism that meaningful and economically sustainable algae cultivation can be achieved. Depending on PBR design, other challenges may also negatively affect costs [207].

Research objectives

Algae are recognized as a potential source of highly renewable biomass and thus energy. Biofuel production grew from 10 million tonnes (MT) of oil equivalent in 2000 to 42 MT in 2008, or 2.5% of transportation fuels[191]. While the economics of producing biofuels from algae are currently not sufficient to warrant the cultivation of biomass for this purpose, there is a growing consensus that valorizing microalgae co-products would help improve the economic viability of microalgal biofuels[208]. Meanwhile, the body of literature focused on techno-economic assessment (TEA) of the production of algae biomass for biofuel production continues to grow[191, 209]. Thomassen et al.[208] claim that the “raison d’être” of the existing microalgae industry is based on its potential to produce biofuels. However, the industry is under attack because of its inability to clearly demonstrate economic sustainability or to ensure that environmental impacts are significantly lower than those of fossil fuels. Thomassen et al.’s review, along with Hoffman et al.’s[210], reveals that part of the challenge lies in the disparate assumptions applied to address the complexities of the interrelated dimensions, and processes of these studies. Others concur that techno-economic and environmental analyses need to be coordinated to resolve competing objectives[211, 212].

This paper presents a comparative TEA of discrete cultivation systems that produce wet algae biomass (20% solids by weight). Three algae cultivation systems producing similar amounts of algae biomass were evaluated using published results and our modeled results. A sensitivity analysis was conducted for the key operating parameters associated with each approach. The analysis provides valuable insights into factors that are common between systems and those that are different.

Given the foregoing, the motivation for this research study includes the following:

- to compare the performance of two open pond cultivation systems based on very different climatic conditions,
- to provide a comparison in performance between the open pond and a photobioreactor technology cultivation systems, both located in central Alberta,
- to determine the impact that geography plays in the cost of producing algae biomass through comparative economic analysis,
- to comparative impact of key parameters that affect algae biomass pricing in both open pond and photobioreactor systems and how geography may affect system parameters and change biomass pricing,
- to demonstrate the usefulness of analytical modeling to predict algae cultivation yields globally.
- to provide an economic outlook on the viability of cultivating algae biomass in Canada compared with the production of biomass in other geographic regions.

The first OPR system was modeled as located at Mesa, AZ. A second identical system was modeled in the northerly Canadian context at Fort Saskatchewan, AB. A third cultivation system based on PBR closed environmental technology providing optimized temperatures and lighting was modeled at Fort Saskatchewan. Using an analytical model constructed by Pankratz et al.[213] to arrive at system costs, we selected Fort Saskatchewan as the reference point given the opportunity to co-locate with industrial CO_2 producers and the potential to offset associated greenhouse gas (GHG) emissions. Fort Saskatchewan, in Alberta's Industrial Heartland, (See Figure 13) is home to one of Canada's largest petrochemical processing regions, producing MT of CO_2 annually[214]. There may be opportunity for \$20 CDN T^{-1} CO_2 emissions credits as of January 2017

Fig. 13. Map showing location of Fort Saskatchewan

from the province of Alberta. These credits would increase to \$30 CDN T^{-1} in January 2018[215].

Every T of algae biomass produced sequesters 1.8 T of CO_2 [11, 105]. Although not used in this study, Fozer et al.'s [206] findings indicate that 2.02 T and 2.09 T CO_2 sequestered for each T of algae biomass cultured in OPRs and PBRs, respectively, would be more appropriate for calculations. However, given the limited validation of Fozer's findings, we used 1.8 T to predict the potential for qualifying algae biomass to receive carbon credits of $28 US T^{-1} in 2017 and $42 US T^{-1} in 2018 and beyond.

Given the absence of published research related to the cultivation of algae in cold climate, the main objective of this study is to conduct costing of commercial scale (2000 Td^{-1}) algae biomass cultivated in cold climate like Canada. through development of techno-economic models. Specific objectives include:

1) Estimating the cost of producing algae at commercial scale at Fort Saskatchewan, AB. via OPR cultivation through development of data-intensive techno-economic models
2) Estimating the cost of producing algae at commercial scale at Fort Saskatchewan, AB. via PBR cultivation through development of data-intensive techno-economic models,
3) Conducting comparative economics between OPR algae cultivation in Canada and in a hot climate.
4) Conducting comparative economics between PBR algae cultivation in Canada and OPR algae cultivation in a hot climate.
5) Conducting sensitivity analysis to study the impact of variation of parameters on the overall cost of production of algae through the two production systems.

Methods

This study focuses on a comparison between the two broad categories of cultivation technologies (OPR and PBR). OPR and PBR systems (see schematic Figure 14) are relatively similar to one another in design. However, given the diversity of PBR technologies we have selected a columnar PBR to represent this group (see schematic

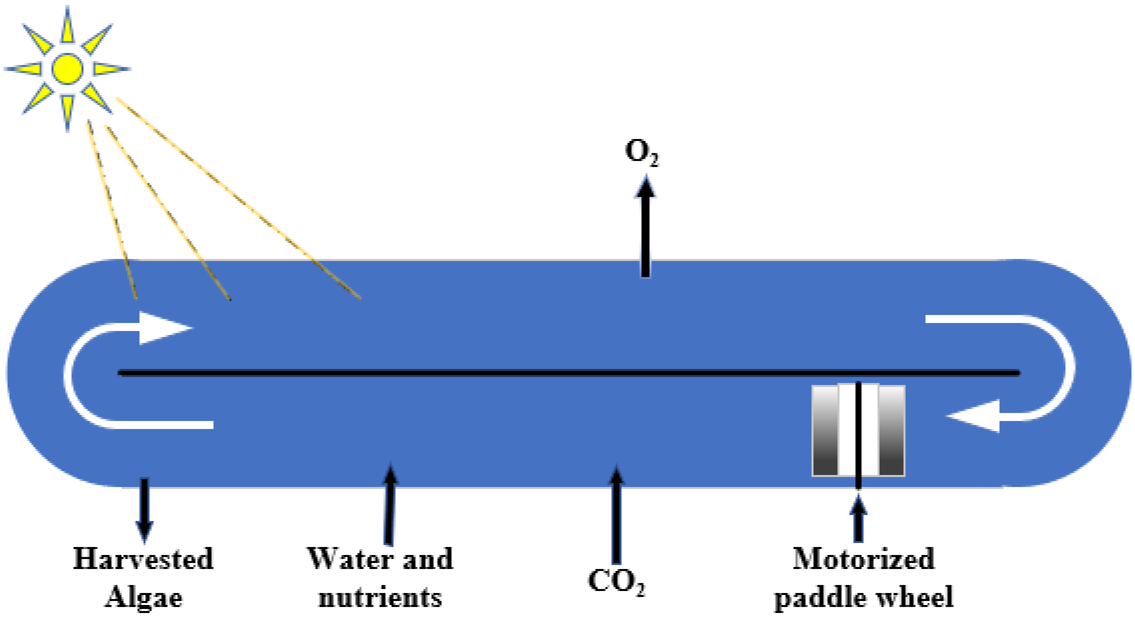


Figure 14. Schematic of open pond raceway (OPR) algae cultivation system

Figure 15). To develop the techno-economic model it is important to analyze the energy and mass flows between unit operations and to calculate the associated operating costs.

More specific details follow below. Figure 16 is a flow diagram that identifies the key inputs, systems, and processes that precede algae cultivation and lead to wet algae biomass production (i.e. 20% solids by weight). The 20% solids represent both the dewatering that can be achieved through a centrifugation process and also the amount of dewatering that would be required for potential downstream thermochemical processing by hydrothermal liquefaction. The single celled microalgae plants in the inoculum system require access to dissolved CO_2 and primary nutrients like nitrogen, phosphorus, potassium and sulfur to grow using the suns radiant energy to replicate. Although not mentioned in Figure 16, other minerals are essential to the health of these plants including Mg, Ca, Na, Cl, Fe, Zn, Cu, Mo, Mn, B, and Co [216]. However, given the relative micro-quantities required and that these elements are often found in adequate quantities within the water being used for cultivation, they have not been factored into cost estimates. Upon reaching a high cell density (e.g. 0.05 wt% solids, the density at which algae would normally be harvested at)[155] the media is transferred to a much larger cultivation vessel where much more water is added to bring the algae concentration down to 0.01 wt%

solids[155]. Again, CO_2 and nutrients continue to be added to ensure growth and replication continue. Over time, because of evaporation (in OPR systems) and blowdown (the constant removal of a small portion of the growth media to prevent the ionic buildup in the media) additional makeup water will be required. When the algae culture reaches a prescribed cell density (e.g. 0.05 wt% solids) it becomes time to harvest and dewater the algae biomass from the media. In a preliminary step the algae cells are allowed to settle to the bottom of the cultivation system helping to concentrate the algae.

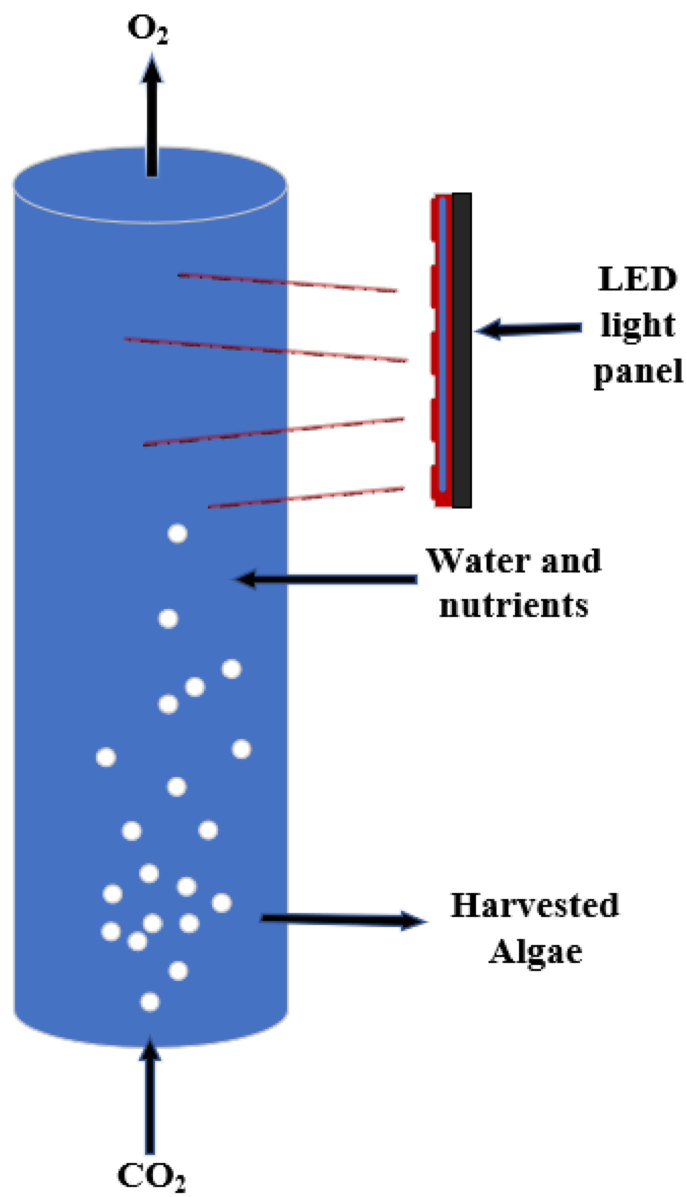


Figure 15. Schematic of photobioreactor (PBR) algae cultivation system

The remaining unit operation technologies found in the process diagram (dewatering, harvesting and storage) are assumed to be identical between systems. The concentrated cells are drained off and pumped through a micro-filtration system that removes much more of the water and recycles it back into the cultivation vessel. However, more water must be removed by a centrifugation process to get the algae biomass to a desired 20% solids concentration for later downstream thermochemical processing. Because the algae biomass is not able to be processed immediately following harvesting, there is need to chill the media for a short period before being transferred for post cultivation processing.

For the purpose of techno-economic assessment, the mass and energy balances were calculated for key inputs including equipment for media circulation, nutrients, dewatering and artificial lighting as may apply with each cultivation technology. Nutrient requirements for the algae cultivation are based on the stoichiometric macro-elemental quantities found in the resulting biomass: 54% C, 1.8% N, and 0.22% P. An additional 20% of these quantities were added to ensure that a nutrient surplus was maintained. Commercially available diammonium phosphate (DAP) provided the necessary phosphorous and anhydrous ammonia (NH_3) supplemented nitrogen already available from DAP [155].

Table 12: Key metrics cost factors (Calculation of results may be found in Appendix A)

	OPR	PBR
Capital Costs (x $1000)		
Production ponds	1,866,235	
Photobioreactors (PBR)		691,773
Inoculum ponds	189,568	
Building for PBRs		69,923
CO_2 delivery	76,533	
Circulation	84,775	
Dewatering	277,064	154,091
Storage	62,405	20,576
Land	268,985	233
Indirect costs	1,528,370	508,666
Total Capital Invested	**4,353,935**	**1,439,262**
Cultivation Costs ($/T biomass)		
CO_2	100	100
NH_3	17	17
DAP	7	7
Power	58	54
Chilling	4	4
Fixed costs	208	66
Capital depreciation	189	69
Average Income Tax	129	42
Average Return on Investment	576	190
MBSP	**1,288**	**549**

Carbon in the form of CO2 is assumed to come from neighboring industrial processes. OPR construction and operating costs are based on literature values provided by Davis et al. [155].

The associated calculations are based on a data intensive analytical model described in a paper published by Pankratz, et al[213]. Table 12 provides a list of calculated key cost factors. The satellite (SATOPR) model simulates OPR cultivation results for any site-specific geographic area. Algae growth kinetic formulas were applied including the Beer-Lambert law to account for the impact of sunlight on algae growth and the equation forwarded by James and Boriah[114] to account for media temperature to predict algae production.

Calculations are indexed to 2011 USD[155] and based on site-specific climatic factors[182], cultivation days[169], and local land, nutrient and energy pricing. A number of assumptions are associated with the model. Algae minimum growth temperature -0.2C; maximum growth temperature 33.3C; and optimum growth temperature 26.7C [144]. The cost of land is assumed to be \$3000 $acre^{-1}$ [155]. However, industrial land near CO_2 emitters at Fort Saskatchewan is reported above \$75,000 $acre^{-1}$ [4]. In particular for an OPR system the large number of sections of land that would be required at commercial biomass production levels would enable much more favorable pricing.

Cost of electricity is projected at \$0.68 kWh^{-1} with cost of CO_2 \$45 T^{-1} at 90% utilization efficiency from a local natural gas fired power plant without consideration of a potential gas purification step prior to use for cultivation [155]. The average algae productivity is 16 $gm^{-2}d^{-1}$ and 1250 $gm^{-2}d^{-1}$ for the OPR and PBR systems respectively[213]. The OPR pond depth is 25 cm [155].

An OPR system at commercial scale (2000 Td^{-1}), based on 10-acre ponds was modelled and collocated with access to CO_2 at a landfill site producing electricity from landfill methane, using a combined heat and power (CHP) system, near Fort Saskatchewan. The commercial scale was chosen to match feedstock input requirements in downstream

[4] http://www.loopnet.com/for-sale/fort-saskatchewan-ab/?sk=9a3b0f1e5d3dcbfb2ec8554cb7a9b07c

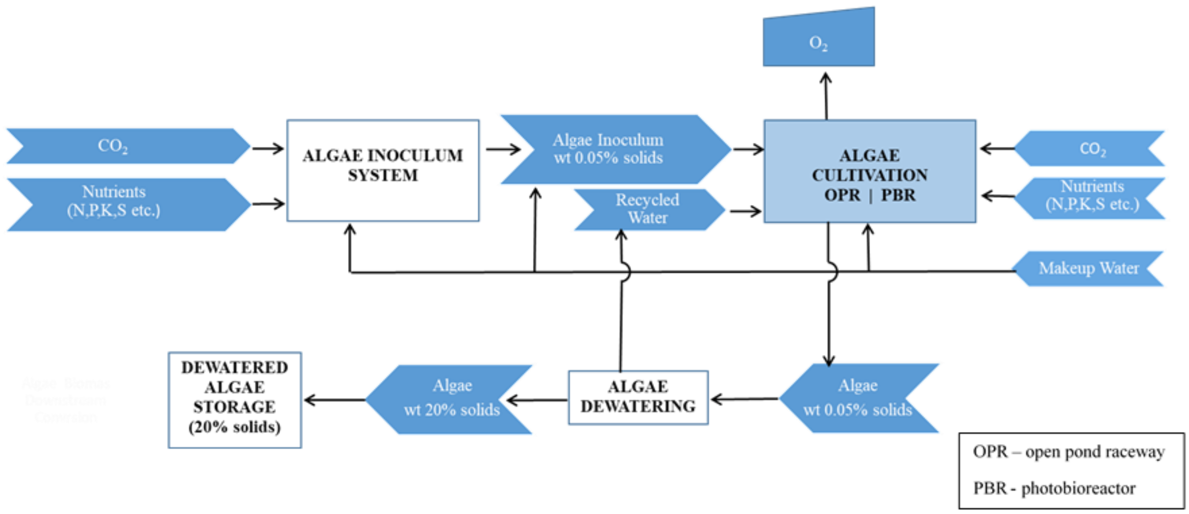


Figure 16. Simplified process flow diagram showing algae biomass cultivation activities

processing[217]. Pond sizing was based on literature values presented by Davis et al.[218] where the forecasted algae MBSP at Mesa, AZ. was established at \$541 T^{-1}. The CHP generation was modelled around the regional landfill methane production. However, calculated power generation was insufficient for operations, and therefore electricity was only accessed from the Alberta grid. Similarly, CO_2 was accessed from neighboring petrochemical facilities. OPR construction and operating costs are based on published data presented in the National Energy Research Laboratory (NREL) report by Davis et al.[218].

A columnar photobioreactor (PBR) system was also modeled at the same Fort Saskatchewan site requiring only 14 acres of land[213]. The PBR design allows for consistent lighting and temperature control thus enabling more optimized cultivation conditions. Enclosing the PBR systems in a temperature-controlled building reduces culture contamination and enables more effective control of media temperature. Each of thousands of low-cost cultivation media bags each containing approximately 7 m^3 of media (Bob Mroz, HyTek Bio LLC, Dayton, MD, personal communication, Feb 20, 2017). They are connected to an automated management system to monitor and control system parameters including nutrient delivery, LED lighting, electrical conductivity, pH, gas exchange, and media mixing (Bob Mroz, HyTek Bio LLC, Dayton, MD, personal communication, Feb 20, 2017). Algae culture densities achieved in this controlled environment are more consistent and considerably higher than those achieved in OPR systems, up from 16 $gm^{-2}d^{-1}$ (0.1 $gL^{-1}d^{-1}$) to 1250 $gm^{-2}d^{-1}$ (5 $gL^{-1}d^{-1}$), a factor of 50. The productivity of this design is consistent with the high-density productivity described by Apel et al. at 4 $gL^{-1}d^{-1}$[219]. Apel et al. report having attained algal cell densities of up to 67 gL^{-1}. The SATOPR model for predicting the cultivation of biomass was not required for this scenario since there is no reliance on ambient solar irradiance and temperatures. These parameters can be controlled throughout the entire growing period.

Although site-specific literature values for costing were available, for comparative purposes it is important that these values be correlated to experimental results based on local solar irradiance, media, and ambient temperature values. The modeled results were compared to experimental results and showed good correlation, confirmed by the analysis of standard deviations.

Harvesting, downstream dewatering and storage

In each scenario, after cultivation, biomass is harvested, dewatered, and placed into cold storage to retain biomass value for additional downstream processes not covered in this study. Harvesting in the OPR system commences at 0.5 gL^{-1}, at which time 80% of the media is drawn off and dewatered[218]. The system is refilled with recycled water and topped up with fresh make-up water, thus resetting the remaining concentration to 0.1 gL^{-1} algae concentration. In the PBR system, harvesting begins once the algae reach a targeted 5.0 gL^{-1} density. At this predicted steady state, 10% of the algae media is harvested every 2.4 hours (i.e., 10x / day)[213].

In both OPR and PBR systems, preliminary dewatering takes place through gravity settling to increase the biomass concentration to 10 gL^{-1} [218]. This is followed by a secondary dewatering operation and continues through microfiltration and centrifugation, to achieve a final concentration of 200 gL^{-1} (20% solids by weight) required for downstream processing[220]. In each case, water removed by dewatering is recirculated back into the cultivation media. Given that there will be continual water loss through evaporation, hydrolysis during photosynthesis and post-cultivation processes, a certain amount of make-up water will be added to replenish the losses and to mitigate the potential for ionic build-up in the media. It is assumed that the make-up water has a negligible impact in the TEA. For OPR systems, although it is estimated that 2.1 L of water are required for the production of 1 kg of algae biomass the associated cost of the water will be insignificant related to the MBSP. For PBRs, the water requirement is estimated to more than 100 times less[213].

Techno-economic assessment

Capital operating and production costs for the production of algae are based on a 30-year facility lifetime. The internal rate of return (IRR) is modeled at 10%[155]. Capital costs include land, construction/installation, engineering and contingency costs. Land requirements include cultivation system space for open ponds systems, buildings, roadways, administrative, processing and laboratory requirements. For OPR systems, this would also include civil work, creating, shaping raceway burns and leakage control, installation of piping, pumps, paddle wheels, settling area, inoculum ponds, etc[155]. For PBRs, construction and installation with pumps, piping, supervisory control and data acquisition (SCADA systems, light emitting diode (LED) lighting systems, chillers, along with buildings[5] that would enclose them would be included (Bob Mroz, HyTek Bio LLC, Dayton, MD, personal communication, Feb 20, 2017).

Dewatering assets would include membrane filtration units, centrifuges and chillers along with biomass storage prior to downstream processing. Operating costs would include energy for circulation of media, sparging for CO_2, nutrient supplementation, chilling, lighting, pumping, filtration and centrifugation, water costs, staff salaries, system maintenance and transport of algae biomass for downstream processing. Fertilizer costs were projected to represent less than 5% of the cost of production and were not evaluated with respect to costing sensitivity.

For each system, the sum of each of the above costing factors lead to the calculation of minimum biomass selling price (MBSP).

[5] Estimate source from www.sprung.com and www.altusgroup.com

Results and discussion

Validation

OPR biomass productivities were predicted using the SATOPR analytical model developed by Pankratz et al.[213] in which satellite climatic data for 2014, including ambient temperature and solar irradiance at Fort Saskatchewan was used[6]. OPR modeled results were validated using literature-based algae cultivation experimental data sets[7]. The modeled PBR system was validated through Hy-Tek Bio LLC's experimental results in cooperation with the University of Maryland (Bob Mroz, HyTek Bio LLC, Dayton, MD, personal communication, Feb 20, 2017)[8], which demonstrated volumetric productivity algae yields of 5 g L^{-1} d^{-1}.

Techno-economic results

Table 13 presents techno-economic assessment results for key metrics including a calculated minimum biomass selling price (MBSP) for each of the two algae cultivation systems discussed above. For the OPR system MBSP was determined to be $1,288 USD T^{-1} and for the PBR system, MBSP was $550 USD T^{-1}. These results may also be compared with those, calculated for a similar OPR system located in Mesa, AZ reporting at $541 T^{-1}. Figure 17 provides a visual representation of the data in Table 12 of costs that comprise the respective MBSPs.

With the SATOPR model we predicted the duration of the growing season for OPR systems at both locations and determined annual yields for that time period.

With the analytical SATOPR model[213] we can visualize the algae cultivation results. As shown in Figure 18, Fort Saskatchewan's climate supports algae growth for 203 days where the mean growing media temperatures remains above -2°C producing 13.0 $gL^{-1}y^{-1}$ of biomass. Meanwhile, the PBR system, which is not limited by either ambient

[6] These data were obtained from the NASA Langley Research Center (LaRC) POWER Project funded through the NASA Earth Science/Applied Science Program.
[7] https://openei.org/wiki/ATP3
[8] https://www.umces.edu/feng-chen

temperatures or solar irradiance, will function 365 days of the year and is predicted to produce 1825 $gL^{-1}y^{-1}$ of biomass.

The SATOPR analytical model was able to predict yields based on a regimented 7-day harvesting routine. A number of other harvesting regimes were run and predicted the opportunity to achieve more optimized outcomes[213]. For this study, the model was run to harvest biomass from the OPR systems on the day cell density was determined to be above 0.5 $g\ L^{-1}$ and diluting the remaining algae back to 0.2 $g\ L^{-1}$ as a starting concentration.

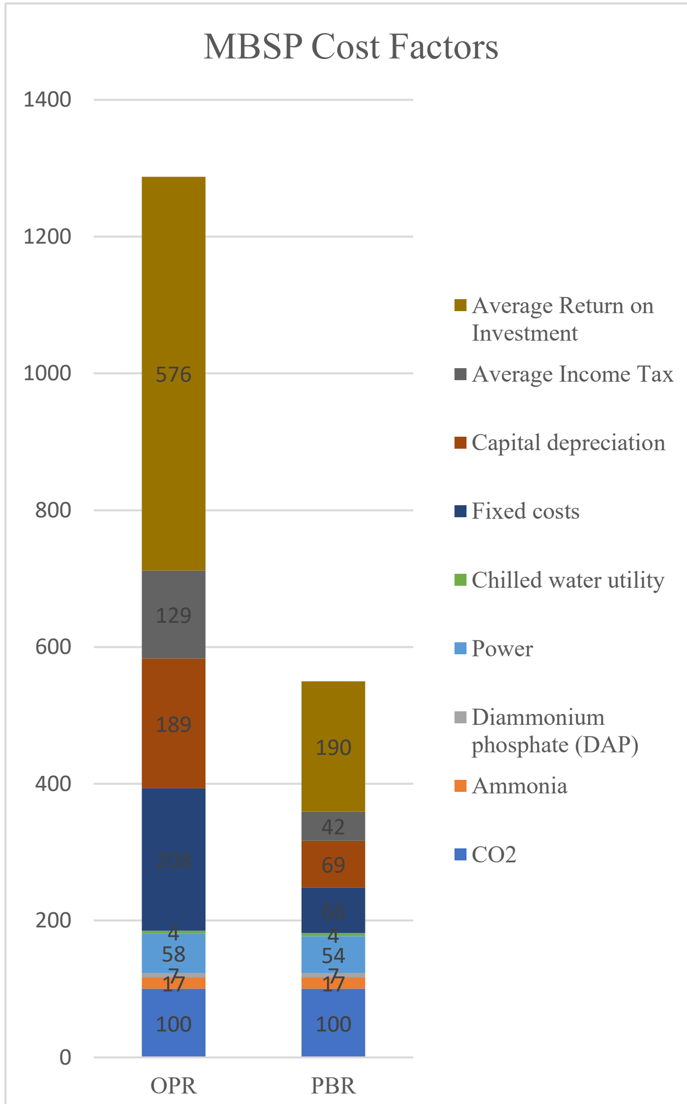
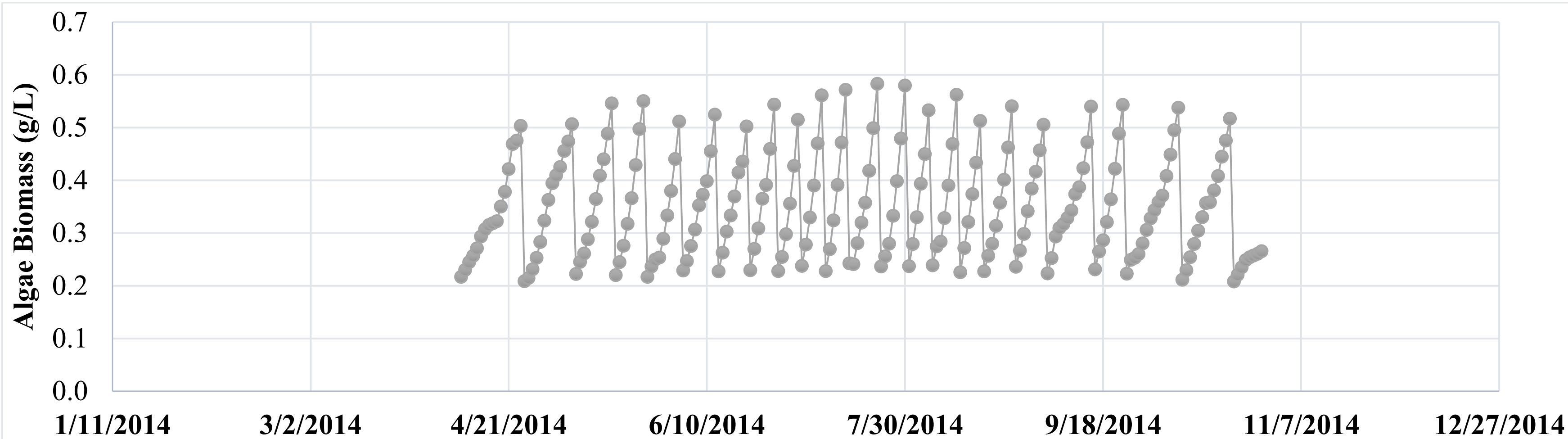


Figure 17. Key MBSP cost factors for OPR and PBR systems at Fort Saskatchewan AB

As shown in Figure 18, in Fort Saskatchewan, AB summer harvests would occur every 5th or 6th day. Meanwhile, algae were harvested in a semi-continuous manner for the PBR system by withdrawing 10% of the media every 2.4 hours, or 10 times each day. This regime enables maintaining a much higher media algae density. The PBR system was modeled to produce algae by providing light 24 hd^{-1} using LEDs (light emitting diodes). However, we explored the possibility of improved economics by using available sunlight.



(b)

Figure 18. Predicted annual algae OPR growth at Fort Saskatchewan, AB – 2014.

Table 13. Key metrics for annual biomass production

	Units	OPR Ft.Sk., AB	PBR Ft.Sk., AB
Average productivity	$gm^{-2}d^{-1}$	16	1250
Land required	$m^2\ T^{-1}yr^{-1}$	1243	0.5
MBSP	$\$\ T^{-1}$	$1,288	$550
Total capital investment	$\$\ T^{-1}$	$6,593	$2,179
Land cost (at $3000 ($75000)acre^{-1}))	$\$\ T^{-1}$	$407 ($10,183)	$ 0.4 ($8.8)
System water volume T^{-1}	m^3	90.193	0.231
Annual cultivation days	Days	203	365
Annual productivity	$gL^{-1}y^{-1}$	13.0	1825

Assuming that 40% of our light (daylight hours) could come from sunlight, we determined that when the PBR takes advantage of sunlight, the MBSP would improve by $2.70 T^{-1} (a 0.5% change in MBSP).

The analytical model also predicted that cultivating algae biomass in Fort Saskatchewan, AB would require 555 m^2T^{-1} with an OPR system, vs. 0.5 m^2T^{-1} via a PBR system. The cultivation area to produce 2,000 Td^{-1} of biomass with an OPR system requires over 82,000 ha and only 32 ha with a PBR system. See Table 14.

Table 14 Key metrics for annual biomass production of 2000 Td^{-1} (660,000 Tyr^{-1}) biomass

	Units	OPR Ft.Sk., AB	PBR Ft.Sk., AB
System water required	m^3 x 1000	59,527	153
Land required	ha	82,038	32
MBSP	$\$\ T^{-1}$	$1,288	$550
Annual cultivation days	Days	203	365

Table 15. Key variables with associated impact on MBSP T^{-1} of biomass

	OPR Mesa, AZ	**OPR Ft. Sk. AB**	**PBR Ft. Sk. AB**
Open raceway pond avg. productivity ($gm^{-2}d^{-1}$) Mesa AZ (40:25: 15) Ft Sk.AB (34:21:13)	(\$127) : \$0 : \$243	(\$384) : \$0 : \$735	-
PBR avg. productivity ($gL^{-1}d^{-1}$) (8 : 5 : 3) equivalent to $gm^{-2}d^{-1}$ (2000:1250:750)	-	-	(\$134) : \$0 : \$238
Scaling PBR capacity (L PBR^{-1}) (20K, 6.8K, 3.5K)	-	-	(\$190) : 0 : \$268
Composition + Productivity ($gm^{-2}d^{-1}$) (HPSD@35 : HCSD@25 : HLSD@15)	(\$11) : \$0 : \$248	(\$11) : \$0 : \$248	(\$11) : \$0 : \$248
CO_2 (cost T^{-1}) (\$0 : \$100 : \$120)	(\$100) : \$0 : \$20	(\$100) : \$0 : \$20	(\$100) : \$0 : \$20
Land (cost $acre^{-1}$) (\$1000 : \$3000 : \$75000)	(\$9) : \$0 : \$345	(\$29) : \$0 : \$1045	\$0 : \$0 : \$1
Total capital investment (-25% : 0 : +25%)	(\$83) : \$0 : \$83	(\$415) : \$0 : \$243	(\$81) : \$0 : 81
Leakage control (shift from in-situ clay to fully lined)	\$0 : \$0 : \$139	\$0 : \$0 : \$421	-
Scaling cultivation area (acres) (10000 : 5000 : 1000)	(\$18) : 0 : \$112	(\$18) : 0 : \$112	-
On-stream factor, days yr^{-1} (360 : 330 : 300)	(\$39) : \$0 : \$37		
On-stream factor, days yr^{-1} (220 : 203 : 185)		(\$117) : \$0 : 114	
On-stream factor, days yr^{-1} (360 : 365 : 330)			\$0 : \$0 : 26
Flue gas vs. CO_2	(\$49) : \$0	(\$49) : \$0	(\$49) : \$0
Labor costs (-50% : 0 : +50%)	(\$21) : \$0 : \$21	(\$64) : 0 : \$64	(\$26) : \$0 : \$26
CO_2 recycle (30% : 0%)	(\$33) : \$0	-	-
N recycle (90% : 0%)	(\$15) : \$0	-	-
Power cost (\$ kWh^{-1}) (\$0 : \$0.068 : \$0.10)	(\$31) : \$0 : \$13	(\$58) : \$0 : \$28	(\$54) : \$0 : \$25
Increasing cultivation media T 10 Deg.C using low grade heat.	-	(\$530) : \$0	-
Staff - # PBR's each person can manage (5000 : 2500 : 1000)	-	-	(\$26) : \$0 : \$78
Alberta carbon credit (\$ T^{-1} biomass)	-	(\$28)	(\$28)

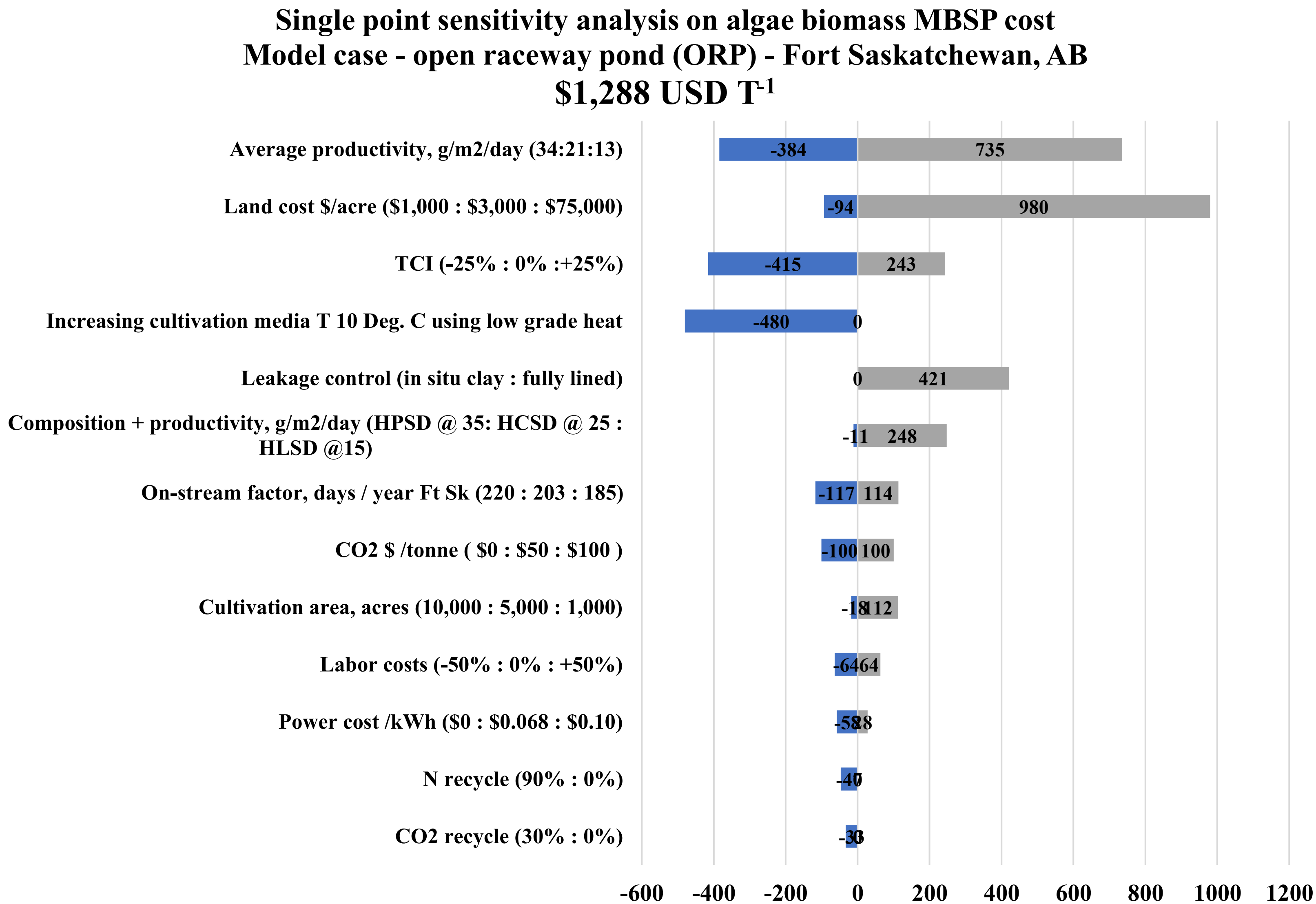


Figure 19: Sensitivity analysis of algae biomass cost for OPR located at Fort Saskatchewan, AB

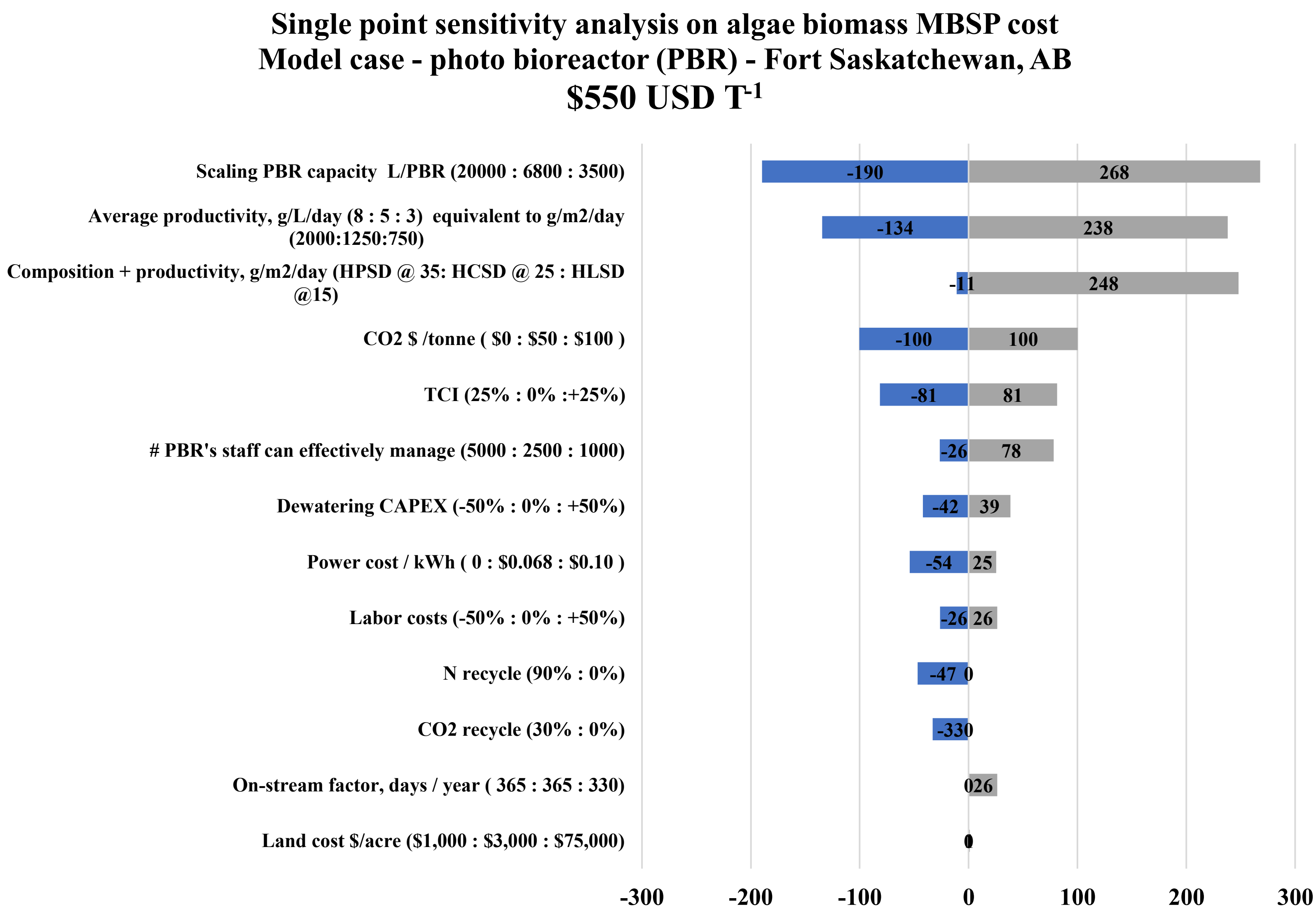


Figure 20: Sensitivity analysis of algae biomass cost for PBR located at Fort Saskatchewan, AB

Sensitivity analysis

A sensitivity analysis was conducted for each of the key cultivation factors found within both the OPR and PBR systems. Table 15 provides a list of theses variables and allows us to make comparisons between OPR and PBR cultivation systems and demonstrates the sensitivity that changes to each parameter will have on the cost of producing biomass.

Figures 19 and 20 show tornado sensitivity analyses of both the OPR and PBR cultivation scenarios considered in this study.

In the OPR systems (Figure 19), average productivity is found to have the greatest sensitivity with respect to minimum biomass selling price (MBSP). Increasing productivity in the OPR system by 60% from 21 $gm^{-2}d^{-1}$ to 34 $gm^{-2}d^{-1}$, would reduce the MBSP by \$384 T^{-1} (17%). If yields fail to achieve the current average production of 21 $g\ m^{-2}\ d^{-1}$ and fall by 60%, to 13 $g\ m^{-2}\ d^{-1}$, biomass cost is predicted to increase by \$735 T^{-1} (33%). For the PBR technology, a 60% increase in yield from 1250 $gm^{-2}d^{-1}$ to 2000 $gm^{-2}d^{-1}$ (8 $gL^{-1}d^{-1}$) would reduce the biomass price by \$123 T^{-1} (21%), whereas a decrease in yield to 750 $gm^{-2}d^{-1}$ (3 $gL^{-1}d^{-1}$) would increase the biomass price by \$267 T^{-1} (45%).

Land cost, introduced earlier, may have a significant impact on MBSP and highlights the importance of siting, especially for OPR systems. The significance of this can be seen when land prices are negotiated from our assumptive \$3,000 $acre^{-1}$ down to \$1,000 $acre^{-1}$ with a realized MBSP benefit of \$94 T^{-1}. The same land priced at \$75,000 $acre^{-1}$ would increase the MBSP by \$980 T^{-1}. It becomes obvious that land price is a major sensitivity factor affecting MBSP in OPR systems, yet this same factor (changing land price from \$1,000 $acre^{-1}$ to \$75,000 $acre^{-1}$) plays only a minor role in a PBR system with an impact of \$1 T^{-1} on the MBSP.

Fluctuations in total capital investment (TCI) for OPR systems would see the MBSP price fall by \$415 T^{-1} when TCI decreases by 25% and increase by \$243 T^{-}

^{1} when TCI increases by 25%. For the Canadian PBR system, TCI fluctuations 25% result in an \$81 T^{-1} MBSP swing in both directions.

Given the tremendous amount of available low-grade heat from industrial operations, there is an opportunity to transfer the heat to the cultivation media to bring the temperature closer to optimum algae growing temperature within the OPR system. If successful in raising cultivation media temperature by an average of 10 ºC this would significantly improve yield and reduce MBSP by approximately 1/3 (\$480 T^{-1}). The offset not considered in this calculation would be engineering / capital costs required to provide heat transfer. Choosing to use full leakage control for the OPR would increase MBSP \$421 T^{-1}. Neither of these factors would apply to PBRs.

Building on the topic of productivity, biomass composition, a factor influenced by cultivation and harvesting practices, also impacts MBSP. Batch harvests considered in this study for OPR systems may be taken in early, mid and late cultivation states. An early harvest would result in nominal nutrient depletion. For mid-harvest, no additional nutrients would be added, and the batch would be maintained an extra 3-5 days to achieve a mid-nutrient depletion state. A late harvest would occur 6-9 days post early harvest, thereby using up more primary nutrients. This regime corresponds to composition and nitrogen (N) availability in the media as follows: low N state promotes high protein (HPSD) composition; mid N promotes high carbohydrate (HCSD); and high N promotes high lipid (HLSD) composition. The trade-offs between states in the sensitivity analysis indicate that a mid-harvest regime (our assumption for this study) may strike an appropriate balance between yield and value for downstream processing. Choosing HLSD would provide a nominal \$1 T^{-1} reduction in MBSP. High lipid composition biomass would produce higher heating values but at the cost of significant biomass yield, thereby increasing the associated biomass MBSP by \$248 T^{-1}. Depending on plans for downstream processing, an economic decision would be made to determine which harvest regime would provide the greatest economic benefit from a cost / benefit perspective. While the choice of early, mid, or late harvest has significant production cost implications, the costs are not ones where we can differentiate between the cultivation technologies employed since the impacts are assumed to be identical for both OPR and PBR systems.

The on-stream factor is related to the percentage of time a given facility is anticipated to operate annually. Currently, this figure ranges widely between cultivation technologies and affected by culture crashes, pond upsets, pond freeze-up, maintenance, and other factors. This study predicts a 90% on-stream factor to be consistently attainable. Economic analysis indicates that a 10% change from the predicted 203-day on-stream factor will affect the OPR MBSP by 9%. The price will increase by \$114 T^{-1} if the system remains on stream 185 days (on-stream factor decreases by 10%) and decrease by \$114 T^{-1} if the system operates 220 days (on-stream factor increases by 10%). Given the much higher degree of system control with the PBR, a 99% on-stream factor is proposed. For PBRs, since already contemplating working the full year, we only considered the case where only a 90% on-stream factor is achieved, and this would result in an increase of MBSP by 5% (or \$26 T^{-1}).

Similarly, since CO_2 is common to both cultivation technologies, this is not a differential factor by itself between ORP and PBR technologies. At \$50 T^{-1} for the purchase of CO_2, it ranks eighth for costs in OPR systems and 4th for the PBR system. At 90% utilization, and the requirement for 1.8 T of CO_2 for every tonne of algae biomass produced, this translates into \$100 T^{-1} MBSP. The price can be reduced by \$100 T^{-1} if the CO_2 is free and goes up by \$100 T^{-1} if the CO_2 price increases to \$100 T^{-1}.

Considerable engineering work has been conducted on OPR algae cultivation system design in order to predict the impact of enlarging pond size from the existing 5,000 wetted acres and scaling to 10,000 acres[155]. At the scale of the OPR system in this study 5,000-acre wetted areas were proposed. Doubling the wetted areas to 10,000 acres would improve MBSP by \$18 T^{-1}, whereas reducing the size to 1,000 acres would increase costs by 112 T^{-1}. For the PBR system, the design size could theoretically be tripled. Interestingly, tripling the PBR cultivation volume is predicted to provide the strongest benefit of the weighted sensitivity factors by improving MBSP by \$190 T^{-1} (34%).

Each of the cultivation systems considered would be similarly affected by CO_2 and N recycling and improve MBSP between \$41-47 for N and \$33-38 for CO_2.

Labor cost sensitivities on MBSP range from 4-5% between scenarios based on a 50% salary fluctuation. These fluctuations represent a potential MBSP change of +/- \$64, and +/- \$26 T-1 for the OPR and PBR systems, respectively.

Given that electrical power has economic and environmental impacts, both of which affect the ability to use carbon credits, it is useful to evaluate its economic sensitivity. For the OPR siting we determined the possibility of accessing free electricity from combined heat power (CHP) plants run on methane from an adjoining municipal solid waste (MSW) plant as part of their parasitic load (electricity not transmitted to consumers but used at source location). To understand the potential impact, we conducted more detailed calculations for the cultivation sites at Fort Saskatchewan [221-223]. Approximately 200,000 T yr^{-1} of MSW are produced in the region with the potential to generate 9.6 MW power. However, the PBR system requires 98 MW of power. Hence, the CHP would produce less than 10% of the energy required by the PBR system and approximately one-third of the power requirement for the OPR system. However, obtaining power at no cost from this source would provide a benefit of \$58 T^{-1} for the Fort Saskatchewan OPR and \$54 T^{-1} for the PBR system.

There are several important insights to be gained from the comparison of TEAs of autotrophic OPR and PBR systems sited in Fort Saskatchewan, AB.

1. In terms of the potential to reduce the MBSP, the most important common factor is increasing average productivity (yield). Whether yield is calculated by $gL^{-1}d^{-1}$ or gm^2d^{-1} or other productivity metrics, the results are the same. Given that PBRs have been shown to outperform OPR systems by a factor

of 50, it is more likely that greater productivity gains will be realized in the PBR than the OPR system. It may be argued that gains made by using a PBR are linked directly to the higher level of control of all biological system parameters than is possible in OPR systems.

2. The importance of total capital investment (TCI). Every parameter in an algae cultivation system affects the amount of capital that must be invested to both create and operate the system. This knowledge is instructive to algae cultivation system architects and designers; by focusing on every design detail, they can eliminate any unnecessary costs.
3. Access and co-location with cheaper nutrient sources and power for operations will reduce MBSP.
4. While OPRs have reached an upper limit with respect to scaling, tremendous opportunities for scaling and resulting reduced MBSPs may be possible by using PBR systems.
5. Designing algae cultivation systems to take advantage of automation will lower the MBSP.
6. Carbon credits, especially when the algae industry struggles to gain traction, from a techno-economic perspective, will enable companies to begin operations while they find long-term economic footing.
7. The study does not support the placement of an OPR algae cultivation system at Fort Saskatchewan, AB, from a techno-economic perspective. Although summer growing conditions are favorable because of both long days and warm temperatures, the actual growing season is too short. There may be an opportunity to capitalize on industrial low-grade heat to augment growing conditions. However, unless the added heat allows both the growth media to be maintained at close to optimal growing temperatures and cultivation at least an additional 60 days annually, the MBSP would remain (potentially) double that of an OPR system in Mesa, AZ.
8. Co-locating either the OPR or the PBR system to an MSW site is a great strategy, providing the electricity generated is free and considered a parasitic load with no negative environmental impacts. It would be

important to match the scale of operations to the available electricity. Furthermore, power generated from the landfill methane would produce flue gases with adequate CO_2 generated to support biomass growth. Any CO_2 absorbed in this way would mitigate the CO_2 emissions and potentially qualify for associated carbon credits. Heat generated through the production of power as well as landfill geothermal heat could be used to optimize media temperatures for an OPR system. This could also increase the number of on-stream days. The 0.9 MW CHP (combined heat and power) engines assumed in this study release 8.5 million BTU hr^{-1} and close to 1 T CO_2 hr^{-1}. Siting at or near landfills may provide access to lower-priced land.

The cumulative gain from extracting benefits at every level will lead to more favorable and sustainable techno-economic MBSP for algae biomass. It may be argued that OPR cultivation systems still provide the most economic means of producing algae biomass. This study however, determined that PBR systems will outperform OPR systems in Canada. Given that PBR systems may be sited adjacent to CO_2 producers to access this free key nutrient, the systems will have a 10-20% economic advantage over OPR systems.

While OPR systems may only be viable in specific geographic regions with moderate temperatures and good solar radiation most days, the advantage of PBR systems is that they can be sited anywhere around the globe.

An opportunity for future research would be to conduct a Monte Carlo simulation to determine the probability of positive outcomes in each cultivation technology in the next 5 years. The results of the current analysis suggest that the future development and refinements to PBR systems may lead to more ubiquitous deployment of algae cultivation around the globe and eventually to a lower and more sustainable MBSP than offered by current OPR technologies. Sensitivity factors that can dramatically impact the MBSP in PBR systems may be easier to positively alter and control than similar sensitivity factors in OPR systems. As outlined in this study, it is conceivable with PBR technologies, over a five-year horizon, to triple the size of the current bioreactor and increase average productivity from 5 $gL^{-1}d^{-1}$ to 8 $gL^{-1}d^{-1}$ while reducing capital investment by 25%. Attaining these goals could place algae biomass MBSP well below \$200 T^{-1}.

Conclusions

The objectives of this research project have been met in that MBSP costing has been achieved for both OPR and PBR based algae cultivation systems at Fort Saskatchewan, AB, Canada via the development of data-intensive techno-economic models. A comparative techno-economic analysis (TEA) of these cultivation platforms has been made and referenced to an OPR system in Mesa, AZ. The findings of this comparative research are that the MBSP T^{-1} for the production of algae biomass from OPR and PBR cultivation systems in Fort Saskatchewan, AB, would be \$1,288 T^{-1}, and \$550 T^{-1}, respectively, whereas it would be \$541 T^{-1} if produced in Mesa, AZ using the OPR system. Therefore, PBR MBSP could rival that of OPR systems located in even the most favorable climatic locations.

The sensitivity analysis applied to the Canadian sited PBR and OPR systems reveal that key factors affecting MBSP in both systems are different and indicate that PBR systems may succeed in driving down MBSP quicker than OPR systems. Environmental and operating parameters have been identified that show potential for improving MBSP in both systems and are recommended for further study.

5. Life cycle assessment

Comparative life cycle assessment of fuel and chemical production from microalgae cultivated in Canadian open raceway pond and photobioreactors in colder climate[9]

Abstract

Microalgae are considered renewable energy candidates and are characterized by high yields, integration with waste streams, and ability to grow on poor or marginal lands and therefore not competing with food production. This paper evaluates the environmental sustainability of open pond raceway and photobioreactor algae cultivation systems in colder climate such as Canada to process microalgae into hydrogen and diluent in conjunction with oil sands operations. Four different thermochemical bio-oil conversion systems were assessed including hydrothermal liquefaction and pyrolysis for diluent production and supercritical water gasification and thermal gasification for hydrogen production. On a system level, the processing of industrial scale (2000 T d^{-1}) dry biomass is modeled for all four

[9] A version of this chapter will be submitted for publication to a peer-reviewed journal. Comparative life cycle assessment of fuel and chemical production from microalgae cultivated in open raceway ponds and photobioreactors in colder climate, *Algal Research*, 2019 *(to be submitted)*.

conversion pathways. A "cradle-to-gate" process-based life cycle assessment is developed to quantify the greenhouse gas (GHG) emissions associated with the material and energy requirements at each life cycle stage. The system boundary includes microalgae cultivation through to downstream processing into hydrogen and diluent. Of the thermochemical conversion pathways considered in our study, supercritical water gasification shows the best GHG emissions mitigation in the production of hydrogen (92.1-138.3 g $CO_{2\text{-eq}}$ MJ^{-1}). With respect to diluent production, hydrothermal liquefaction processing has environmental benefits and avoids energy use and consequently GHG emissions associated with the feedstock drying required in pyrolysis (10.2-45.65 g $CO_{2\text{-eq}}$ MJ^{-1}). This research is unique due to its focus on colder climate like northern Canada.

Introduction

Western Canada's oil sands have been a subject of considerable interest because of declining conventional oil reserves and rapidly growing energy market demand. Alberta's oil sands have been evaluated to hold 170.2 billion barrels of oil reserves, next in capacity to reserves found in Saudi Arabia and Venezuela [224]. Fossil fuel combustion has been directly linked to climate change [225]. Global warming due to rising greenhouse gas (GHG) emissions from anthropogenic activities is an ever-growing concern both regionally and globally [226-228]. Given that the production, conversion, and combustion of energy are significant sources of CO_2, there are concerted efforts to create a paradigm shift toward renewable and reduced GHG emissions energy sources such as microalgae [229].

The ability of microalgae to take up CO_2 using photosynthetic energy offers significant potential in terms of developing an economic and sustainable renewable energy resource [202]. Microalgae have the acknowledged advantages of not competing with arable land for food production, high yield potential, and the ability to develop high value co-products such as nutraceuticals, lipids, proteins, carbohydrates, pigments, and vitamins [7]. Moreover, microalgae can use municipal, agricultural, and industrial wastes as a source of key metabolic growth nutrients.

In Western Canada, bitumen extraction and petroleum production are expected to increase to around 3.8 million barrels per day by 2022 [230]. Coupled to this is the significant increased requirement for light hydrocarbon chemicals such as diluent to transport bitumen to upgrading and refinery facilities [231]. In oil sands industries, diluent refers to naphthenic and paraffinic hydrocarbons used to reduce the viscosity and density of heavy hydrocarbon molecules in bitumen [232]. Diluent, a diluting agent, is a chemical substance used to aid viscous fluidity of heavy molecules through pipelines [233]. Mostly, diluents are known as natural gas condensates, which are comprised of compounds with lighter fractions [234]. Given the requirement for large amounts of diluent in transporting heavy oils, there is an interest in evaluating thermochemical process conversion technologies that have the potential to transform algal biomass to diluent [235-238]. The production of a liquid product, bio-diluent, through pyrolysis has been investigated [235]. Extracting oil using bitumen via the Fischer-Tropsch method has been studied [236]. Kumar et al. [237] studied diluent production through thermochemical pathways for oil sands applications. Moreover, several thermochemical process conversion technologies that may transform algae biomass to both diluent and hydrogen are being investigated. The key thermochemical approaches, hydrothermal liquefaction (HTL) and pyrolysis, allow biomass conversion to bio-crude in order to produce diluent [237, 239]. Both technologies have been proven to be feasible for algal conversion and offer the advantage of converting both lipid and non-lipid fractions of biomass into bio-oil [240]. The HTL pathway avoids the energy-intensive drying step required for alternative processing [237], while pyrolysis requires a dry feedstock [241]. Though pyrolysis has gained significant attention for processing woody biomass [241-244], relatively few studies have focused on microalgae as a feedstock [245-247].

In Western Canada, hydrogen derived from a renewable source like algae, could be used as an alternative to fossil fuel-based hydrogen to upgrade bitumen into synthetic crude oil (SCO). Hydrogen, a key component in many chemical reaction is widely used throughout the petroleum industry [248]. In 2005, some 3 million tonnes of hydrogen were produced and used to upgrade 527 thousand barrels of bitumen/day [249]. There is a projected increase in bitumen upgrading to over 2 million barrels/day by 2020, bringing with it an extraordinary increased demand for hydrogen [249]. Currently, almost all the hydrogen is produced from natural gas. Hydrogen could be produced from algae biomass via thermochemical processing including supercritical water gasification (SCWG) and thermal gasification (TG) [250, 251]. SCWG allows wet biomass to be converted to a hydrogen-rich gas. It does not entail energy-intensive drying and is known to provide high gas yields with low char/tar formation [252]. Moreover, the fuel produced is devoid of nitrogen, permitting the use of the protein-rich microalgae [253]. Algal thermal gasification is regarded as a promising pathway to produce clean hydrogen fuel and generate electricity [254-257] using several gasification agents like steam, air, and CO_2 [254].

Commercial microalgal-based thermochemical energy conversion platforms encompass the steps from feedstock production to end products. Open pond raceway (OPR) cultivation systems are conventionally seen as the most economical way to autotrophically produce microalgae feedstock in hot climates [39, 113, 125, 148, 149]. Other approaches to producing algae include photobioreactor (PBR) systems, in which algae are cultivated under controlled phototrophic/autotrophic conditions, and employing flat plates, plastic tube systems [258], and biofilms [259]. In addition, fermenters take advantage of algae's unique ability to grow in heterotrophic conditions in the absence of light and use carbon sources other than sunlight for the energy used in growth [260]. Other algae cultivation systems use both autotrophic and heterotrophic conditions (mixotrophic) to achieve their growth objectives [261].

Life cycle assessment (LCA) is a useful tool to evaluate the environmental impacts associated with a product, process, or service [262, 263]. Several LCA studies have quantified the environmental impacts of algae on energy systems and reported a wide range of outcomes [264-267]. The associated energy process conversion pathways implemented in these studies are varied, as are their results due to differences in production technologies and assumptions. Significant research efforts have thus far focused on conventional lipid-based extraction systems [268-275], and a few studies consider thermochemical systems [276-279]. Where thermochemical HTL processing of algae has been researched and reported on quite extensively in published literature, pyrolysis, another thermochemical technology, has received less attention [277]. Moreover, the segregation of upstream and downstream methods in such studies limits the use of the results for commercial applications. Hence, it is imperative to analyze thermochemical conversion methods in such a way that energy requirements and GHG emissions can be compared holistically over the life cycle. Furthermore, the environmental impacts of various thermochemical pathways using microalgae as a feedstock need to be evaluated and compared.

This study aims to estimate life cycle GHG emissions associated with diluent and hydrogen production from microalgal systems through thermochemical technologies in Western Canada. An industrial scale (2,000 T d^{-1}) microalgae cultivation system in open raceway ponds and photobioreactors for processing biomass into hydrogen and diluent is modeled. Several biomass conversion pathways are considered, and the results vary because of differences in production technologies and assumptions. The specific objectives and uniqueness of this study are:

- To conduct a comparative LCA based on the conversion of microalgae feedstock cultivated in OPR and PBR systems in Canada:
  - via hydrothermal liquefaction and pyrolysis to produce diluent; and,
  - via hydrothermal gasification and thermal gasification to produce hydrogen.
- To provide life cycle GHG emissions information to help government and industry make informed decisions related to industry investment and policy formulation.

The analysis provides useful insights for decisions that may mitigate environmental burdens associated with oil sands activities and the potential for improving the economics of hydrogen and diluent production in Canada.

Method

LCA, according to the ISO-14040/44 principles and framework, and guidelines, is developed to evaluate energy and GHG emissions [280, 281]. LCA involves the identification and quantification of mass and energy balances by looking at system inputs and outputs at each process stage to identify the associated environmental impacts.

Goal, scope and system boundaries

The goal of the current LCA is to evaluate and compare two algae cultivation scenarios and four thermochemical conversion pathways leading to the production of diluent and hydrogen. Each activity involved in these processes is energy intensive and has associated GHG emissions. The LCA follows an "attributional" approach in which environmental impacts are normatively allocated and then introducing changes to a process. Environmental impacts associated with these changes are evaluated over a 100-year time horizon, thereby providing comparative results. Engineering models of diluent and hydrogen production from the microalgae were developed to establish LCA results of four different conversion pathways. The analysis included energy and material requirements for various sub-processes including cultivation, dewatering, and conversion systems for all pathways studied. The LCA is set geographically in Fort Saskatchewan, Alberta, Canada. The Fort Saskatchewan region is recognized for the energy-intensive industrial petrochemical processing facilities associated with oil-sands activities (see Figure 21).

Figure 22 shows the main systems included in the assessment. The functional unit to which the input and output requirements are scaled up is 1 MJ of energy. Together with the LCA, the net energy ratio (NER) is determined as the ratio of output energy to input fossil-fuel energy. The current study, consistent with other studies of microalgae to biofuels processes, excludes the environmental impacts associated with algae cultivation ponds and photobioreactor system construction[282].

The engineering approach used to model the cultivation and downstream processing of algae biomass is shown in the system process flow diagram (Figure 22). The model computes material and energy balances for each unit operation. The cultivation section was constructed in a spreadsheet-based model with the downstream thermochemical conversion computed more rigorously through development of process model using Aspen Plus software [283]. Cultivation yields

Figure 21. Map showing location of Fort Saskatchewan and general oil sands deposits

were predicted based on experimental yield data found in the literature and through consultation with industry experts, coupled with stoichiometric calculations and making assumptions on suitable surplus nutrients (20%) [155] being available to ensure maximum productivity. However, these calculations were completed by a fellow PhD researcher, Mayank Kumar.

Cultivation yields were predicted based on experimental yield data found in the literature and through industry interviews, coupled with stoichiometric calculations and making assumptions on suitable surplus nutrients (20%) being available to ensure maximum algae productivity.

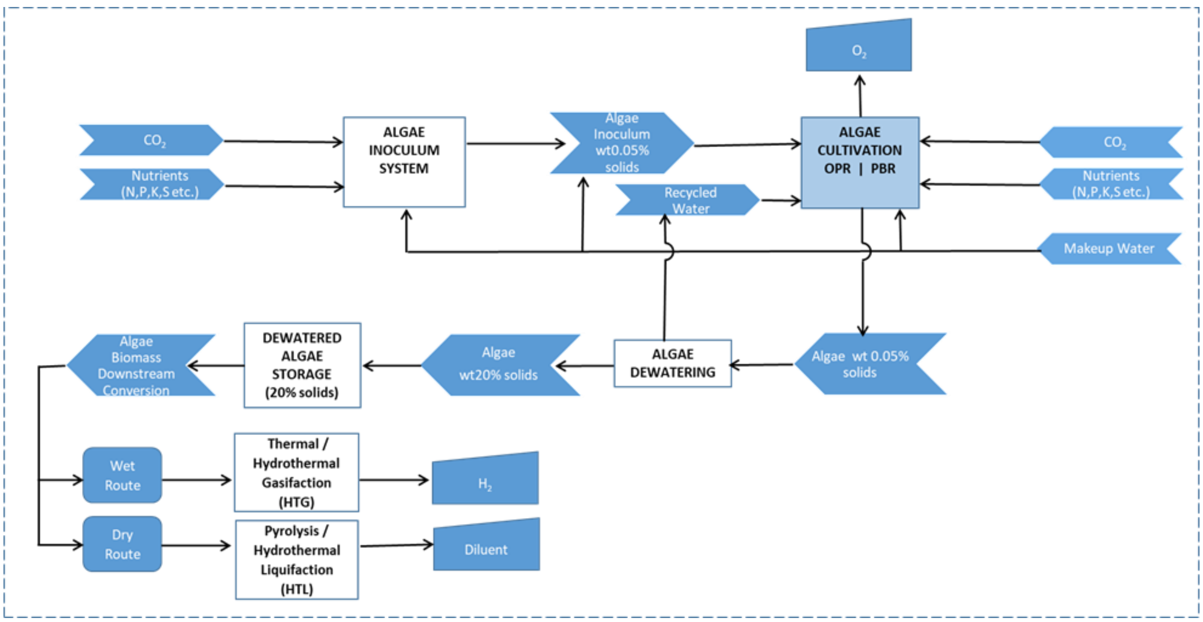


Figure 22: System boundary of thermochemical pathways considered for diluent and hydrogen production

Life cycle inventory assessment

The life cycle inventory assessment was developed for all stages, from algae cultivation to deliver 1 kg AFDW algae biomass, and subsequently thermochemically processed to deliver 1 MJ of product. Algae cultivation was modeled for OPR and PBR systems. Much of research to date for algae-to-energy systems has been conducted at the bench scale [284].

Microalgae is cultivated in an aqueous media. Nutrients such as carbon dioxide (CO_2), nitrogen (N) and phosphate (P), sourced from local industries, as well as light and temperature are required to support algae growth. Diammonium phosphate (DAP), a commercial fertilizer, is considered the source for P, while ammonia (NH_3) is the source for nitrogen (N) [155]. The inventory calculations include the upstream GHG emissions associated with the production of these fertilizers. GHG emissions from direct land use, water use in algae cultivation, dewatering via settling, ultrafiltration, and centrifugation to a produced biomass with 20% solids are evaluated. GHG emissions from the use of equipment such as air compressors for sparging CO_2 into the algae media, pumps and paddlewheels for circulation, LED lighting in the PBR system to promote growth are included. Table 16 provides a summary of parameters and input requirements considered in the inventory assessment. Productivity is based on experimental lab scale results [213, 285]. Land and water requirements are based on productivity, site climatic conditions, and assumptions related to cultivation operations. Water loss due to blowdown is related to the replacement of media to prevent the buildup of ion concentrations in the media.

Table 16: Data related to the production of 1 kg of algal biomass

Parameters	OPR	PBR	Units
Productivity	5.8	1825	g/L/yr
Land	1.24	0.00048	m2/kg/yr
Water	1.06	0.023	m3 or T
Cultivation period	203	330	days/yr
Water loss - evaporation	0.5	0	%/day
Water loss - blowdown	0.5	0.5	%/day
Water loss - harvesting	0.2	0.2	%/harvest
Harvests	11	365	#/yr
Potential for cultivation crash	5	1	%

(Calculation of results may be found in Appendix A)

The OPR system was modeled based on values found in Olivares et al. [157] and extrapolated from site-specific satellite climatic data using the predictive analytical model developed by the authors [213]. The OPR operating performance was predicted based on Fort Saskatchewan's metrological data including local daily temperature and irradiance values. 80% of the OPR algae was harvested when cell densities rose to 0.5 gL^{-1}, at which time pond algae density returned to 0.2 gL^{-1} based on the author's developed model[155]

The PBR system's input and output requirements are determined based on a unique columnar photobioreactor design [286] that provides a fully controlled algae growth environment. CO_2 is sparged into the PBR, which allows light photons to penetrate deeper into the media and the continuous mixing of media for nutrient exchange. Lighting is provided by flashing tuned LEDs that provide photons at wavelengths that optimize growth and minimize the amount of energy that is required [287-289]. Under these optimized conditions, cultivation yields of 5 $g\ L^{-1}d^{-1}$ are predicted. The productivity from this design is expected to be consistent with other high density productivity such as that described by Apel et al. [219] and Mata et al [290].

Since PBR systems are enclosed, negligible water is lost through evaporation. Apart from water loss from evaporation, blowdown, and harvesting, water and the remaining nutrients are recycled into the cultivation system. CO_2, N, and P were modeled to be provided at 20% above actual cultivation requirements. Harvesting the PBR biomass is semi-continuous; 10% is removed for processing every 2.4 hours, thereby maintaining cell density at approximately 5 gL^{-1}.

Energy required for dewatering the algae feedstock after cultivation in both OPR and PBR systems is assumed to be the same and based on literature values provided by Davis et al. [291]. The algae biomass undergoes settling followed by hollow fiber membrane ultrafiltration and is then centrifuged to concentrate the biomass to 200 gL^{-1} [1] in preparation for downstream thermochemical conversion, described in the second part of this study.

As seen in Table 17, key energy requirements from the technosphere (man-made biotic resources [292]) are from system operations, i.e., the paddlewheel, sparging, dewatering pumps, and LED lighting. In this study, the 2016 Alberta electricity generation mix emission intensity factor of 0.83 kg CO_2e kWh^{-1} was considered [293]. The large areas of land impacted to cultivate algae for 2000 Td^{-1} dry biomass using OPR systems are given consideration in the study. Transportation is not part of the study's scope since the selected location for algae cultivation adjoins the refineries that produce both commercial nutrients and also utilize the biomass output of production. The focus in this study is not on a specific species of algae to be cultivated, given that a number of strains, among thousands [36], have been identified for their high growth yield and lipid content [294].

Table 17. OPR and PBR system assemblies with input / output operations

ASSEMBLIES	OPR	PBR	Units
Algae inoculum system			
INPUTS			
Makeup Water	0.398		m^3 or
Land for inoculum	0.12		m^2
Nutrients	0.24		kg
Energy - Electrical	0.025		kWh
OUTPUTS			
O2 from hydrolysis of water	0.14		kg
Inoculum media moved to cultivation	2.14		m^3 or
Water loss	1.84		m^3 or
CO2 lost to air	0.038		kg
N loss to water blowdown / air	0.001		kg
Algae cultivation system			
INPUTS			
Inoculum media with water	2.14		m^3 or
Makeup Water	21.5	0.011	m^3 or
Land for cultivation	12.4	0.00048	m^2
Nutrients	2.4	2.4	kg
Energy - Electrical	0.257	0.785	kWh

OUTPUTS				
O2 from hydrolysis of water	1.4		kg	
Water loss	1.84	0.011	m^3	or
CO2 lost to air	0.38	0.38	kg	
N loss to water blowdown / air	0.016	0.016	kg	
Algae dewatering - Ultra / micro filtration				
INPUTS				
Cultivation media (10 g/L – 1% solids)	0.155	0.000	m^3	or
Energy - Membrane Filtration	0.11	0.020	kWh	
OUTPUTS				
Algae biomass (130 g/L – 13% solids)	0.012	3.8E-05	m^3	or
Water for recycling	0.143	0.00046	m^3	or
Algae dewatering - Centrifuge				
INPUTS				
Algae biomass (130 g/L)	0.012	3.8E-05	m^3	or
Energy - Centrifuge	0.27	0.048	kWh	
OUTPUTS				
Algae biomass (200 g/L - 20% solids)	0.007	2.5E-05	m^3	or
Water for recycling	0.004	• 0.0000	m^3	or
Algae storage - Chilling				
INPUTS				
Energy - Chilling biomass / kg	0.007	0.0073	kWh	

*Values / kg dry biomass (Nitrogen Surplus) under lower heating value calculations. Inoculum based on 10% of cultivation values

*assume use of naturally occurring algae species that performs similar to species grown in other parts of the world. Will remain dormant in ponds during winter period.

(Calculation of results may be found in Appendix A)

The algae cultivation model developed to simulate the production of dry biomass at 2,000 T d^{-1} incorporated design features found in the literature that use site-specific satellite meteorological data. This model has been detailed in an earlier publication by the authors [67] and relies on meteorological satellite data. The OPR system modeled to produce this biomass in Alberta would encompass an area of some 82,000 ha (8.8 townships), whereas the modeled PBRs used to produce the same biomass would require approximately 50 ha. Similarly, the OPR-modeled system would require 4.3 million m^3 of water, whereas the PBR system would only require 23.2 thousand m^3. In both cases, given that every T of biomass requires 1.8 T of CO_2 to produce 660,000 T biomass annually, nearly 1.2 MT of CO_2 is sequestered [11, 105]. While published algae biomass yields vary tremendously, the model assumes that 0.1 $gL^{-1}d^{-1}$ for the OPR systems and 5 $gL^{-1}d^{-1}$ for the PBR systems are achievable.

Table 18 highlights that the cultivation of biomass produces 0.8 and 0.96 kg CO_2 for the modeled OPR and PBR systems respectively. Net CO_2 emissions through this process were calculated at 1.00 and 0.86 kg CO_2 absorbed kg^{-1} algae biomass produced (0.041 and 0.035 kg CO_2 absorbed MJ^{-1} algae biomass produced) respectively for OPR and PBR systems.

Calculations were also completed to determine the impact of including ambient sunlight available for algae photosynthesis in conjunction with using PBRs. It was determined that 0.033 kg CO_{2eq} absorbed kg^{-1} algae produced AFDW and would therefore improve net GHG results by 3.8%.

Table 18. CO_2 emission results

OPR	PBR	
1.8	1.8	kg CO_{2eq} absorbed kg^{-1} algae produced AFDW [11]
0.800	0.936	kg CO_{2eq} produced kg^{-1} algae produced AFDW
1.000	0.864	Net kg CO_{2eq} absorbed kg^{-1} algae produced AFDW
0.074	0.074	kg CO_{2eq} absorbed MJ^{-1} algae produced AFDW
0.033	0.038	kg CO_{2eq} produced MJ^{-1} algae produced AFDW
0.041	0.035	Net kg CO_{2eq} absorbed MJ^{-1} algae produced AFDW

(Calculation of results may be found in Appendix A)

The results of this study are supportive of results published by Zaimes [295]which predict net absorption of CO_2 at 0.046 and 0.049 kg MJ^{-1} algae biomass produced.

The mass and energy balance of downstream processing for LCA calculations were estimated through the development of the process model using Aspen Plus. This model has been described in earlier publication by the authors [237, 296]. The life cycle assessment was conducted based on the steps outlined in ISO 14040 [262]. The inventory values are translated to GHG emissions per functional unit using the IPCC one-hundred-year time horizon emissions factor [263]. The outcomes of the study are subject to a certain amount of uncertainty associated with the chosen theoretical conditions, system boundary selection, data used, and modelling approach. A sensitivity analysis was performed to estimate the effects of key input parameters on the outcome of the study for better interpretation of the results. Table 19 provides electrical energy requirements of unit operations for four thermochemical pathways for the processing of the algae biomass.

Table 19. Energy (electricity) use in various sub-processes for diluent and hydrogen production

Parameters	kWh/year	MJ/kg product	MJ/MJ product
HTL			
Hydrothermal liquefaction	81,058,492	0.509	0.01
Upgrading	7,241,917	5.706	0.17
Pyrolysis			
Pyrolysis	519,800,765	36.84	1.08
Upgrading	32,084,804	2.27	0.07
SCWG			
SCWG	1,629,757,311	315.94	2.23
Gas purification	359,639,212	69.72	0.49
Thermal Gasification			
Gasification	3,319,237,600	371.30	2.99
Gas purification	574,461,474	293.53	2.07

Results and discussion

This section presents and discusses the main findings of the study. First, the GHG emission results for algal cultivation were identified by comparing unit operation environmental impact results from OPR and PBR cultivation and dewatering processes. Then unit-process thermo-chemical conversion results were compared. The aggregate results from these comparative calculations are presented below.

Algal cultivation

The environmental impacts associated with algae cultivation in both OPR and PBR systems are discussed in this section. Figure 23 provides a breakdown of the emissions associated with unit operations for both OPR and PBR algae production systems. OPR appears to have a relatively better GHG emissions performance than PBR. In both scenarios, electricity accounts for the majority of the energy requirements associated with the algae cultivation processes, 70-76%, followed by the fertilizer (23-30%). The contribution from water use is minimal, less than 1% in both cases. The calculated net results for OPR and PBR are 1.0 and 0.9 T of CO_2 removed from the atmosphere T^{-1} biomass produced, respectively. The results are lower than those reported by Verma et al. [202] at 0.42 and 0.39 T of CO_{2eq} removed from the atmosphere for every T biomass produced in a study using *Nannochloropsi sp* and *A. platensis* algae species. Although the electricity use differs significantly, outcomes are relatively close. In the case of OPR systems, the paddlewheel and pumping systems used to move water through the vast pond systems come relatively close to the relatively minor use of pumps in the PBR systems, but a greater amount of energy is required to drive the artificial lighting systems.

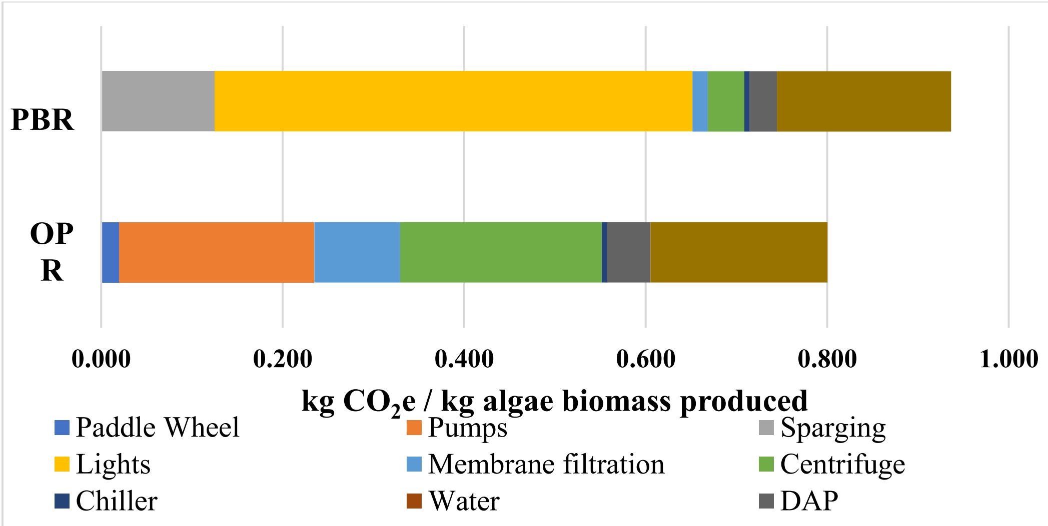


Figure 23. Algae biomass production – CO_{2eq} emissions contribution

Because of the commercial scale of the operations modeled, it is useful to compare CO_2 sequestration through algae cultivation with carbon sequestration in existing forests in the region. Spruce and aspen trees can be harvested every 80 years and they yield 180 m^3ha^{-1} or 2.25 m^3yr^{-1}; 1 m^3 of wood has approximately 200 kg C [297]. This can be calculated as 0.165 kg CO_2 sequestered $m^{-2}yr^{-1}$. For our modeled OPR algae cultivation system, 0.804 kg CO_2 $m^{-2}yr^{-1}$ is sequestered; this is an approximate 5-fold increase in CO_2 sequestration. The PBR system can sequester 2008 kg CO_2 $m^{-2}yr^{-1}$ or an approximate 12,170-fold increase in CO_2 sequestration.

Process conversion

It is essential to consider the unit operations pertaining to algal biomass thermochemical conversion via hydrothermal liquefaction, fast pyrolysis, supercritical water gasification or thermal gasification. The basic unit operations for hydrothermal liquefaction and fast pyrolysis involve algal biomass production and dewatering, drying (for fast pyrolysis only) and bio-conversion of resulting biomass to bio-crude/bio-oil and, hydrotreating to bio-crude/bio-oil to diluent. The thermochemical conversion pathway for hydrothermal liquefaction and fast pyrolysis is shown in Figure 24 and Figure 25. For supercritical water gasification and thermal gasification, the unit operations involve biomass cultivation and dewatering, drying (for gasification only), algal thermochemical conversion to hydrogen production. The conversion pathway for supercritical water gasification and thermal gasification is presented in Figure 26 and Figure 27, respectively. In this analysis, the cultivation and conversion facilities are considered to be closely located and thereby, the effects of transportation are negligible. For conversion, the algae production facility is considered to be 2000 dry tonnes/day which is based on the scale designed for large-scale biomass-based systems [238, 298].

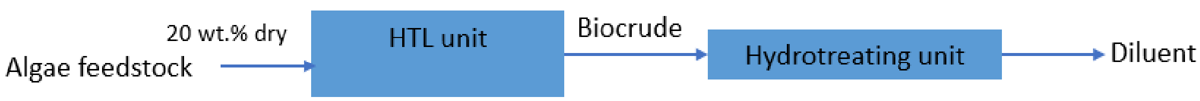


Figure 24. Schematic for algal hydrothermal liquefaction conversion pathway

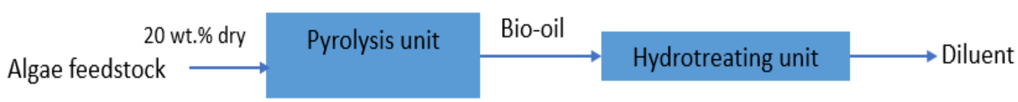


Figure 25. Schematic for algal pyrolysis conversion pathway

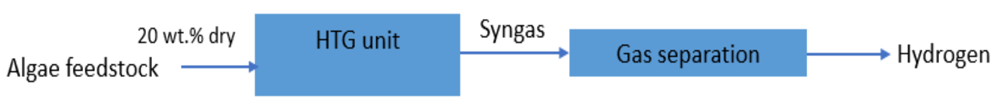


Figure 26. Schematic for algal hydrothermal gasification conversion pathway

Figure 27. Schematic for algal thermal conversion pathway

The GHG emissions for diluent production from algae biomass feedstock through HTL and pyrolysis, as well as for hydrogen produced from SCWG and TG, are discussed in this section. The GHG emissions in the HTL pathway contribute 29.6 g $CO_{2\text{-eq}}$ MJ^{-1}, as shown in Figure 28. 60.13% of GHG emissions in the HTL are from the hydrothermal liquefaction unit, and the rest are from the hydrotreating section of the hydrothermal liquefaction plant. This is mainly due to the high energy

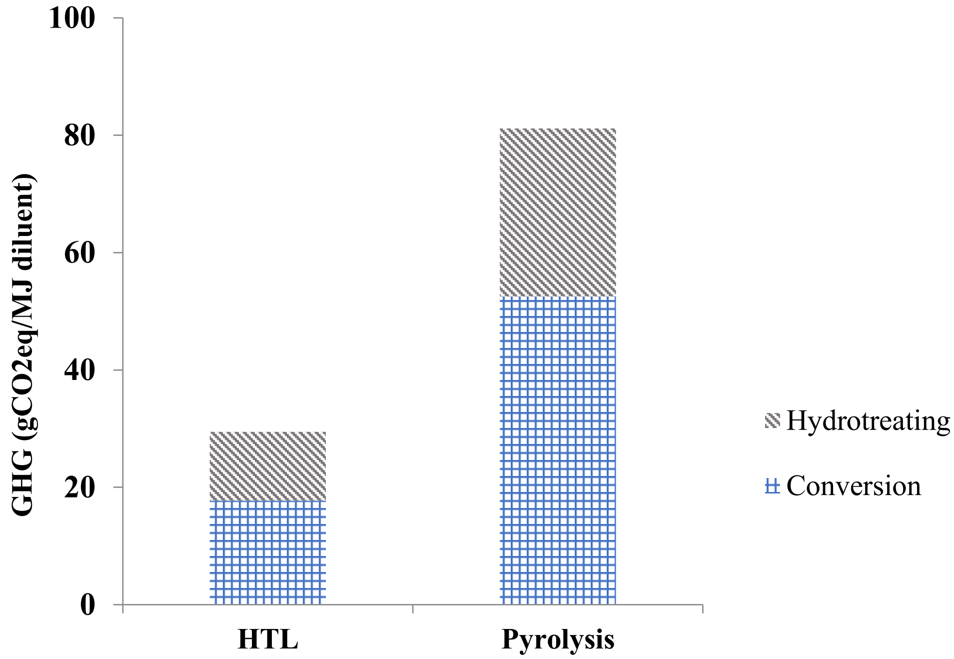


Figure 28. Breakdown of GHG emissions from HTL and pyrolysis in diluent production

demand in the high temperature and pressure reactor of the HTL plant. Diluent production from HTL has advantages in that it can handle high moisture containing microalgae, thereby avoiding the energy use and corresponding emissions of microalgal drying. The GHG emissions from fossil fuel-based products are more than 67% (90.8 g $CO_{2\text{-eq}}$ MJ^{-1}) [299] higher than from HTL.

The algal-based pyrolysis pathway results in 81.1 $gCO_{2\text{-eq}}MJ^{-1}$ of diluent. In pyrolysis, microalgae conversion incorporates two main processes, both of which are energy intensive: microalgae drying and pyrolysis requiring heat for the reactor using natural gas.

Together these processes have a direct influence on environmental impacts and make up 64.7% of the GHG emissions. The hydrotreating plant contributes 35.3%, which is higher than HTL due to the requirement for a two-step hydrotreating process in pyrolysis. If char which is produced during the pyrolysis process is used instead of natural gas for heat supply from pyrolysis, the GHG emissions are reduced to 51.3 $gCO_{2\text{-}eq}MJ^{-1}$ of diluent. HTL offers better environmental performance than pyrolysis, mainly due to the requirement for dry biomass and excessive energy demand in the pyrolysis reactor.

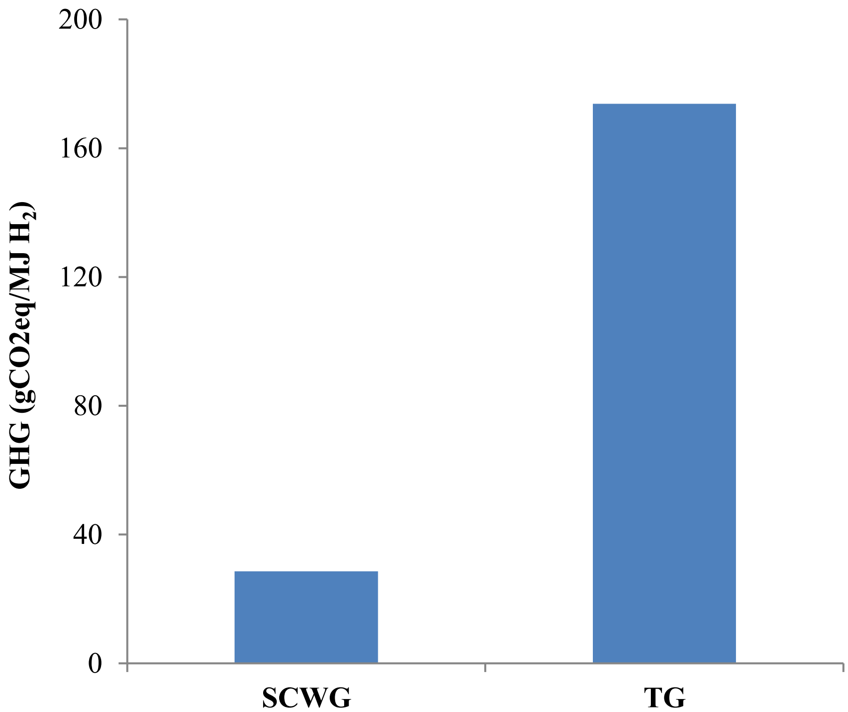


Figure 29. Breakdown of GHG emissions from SCWG and TG in hydrogen production

For hydrogen production, the SCWG pathway has lower GHG emissions than TG, as shown in Figure 29. Hydrogen production in the supercritical water gasification (SCWG) pathway emits GHGs of 28.5 g $CO_{2\text{-}eq}$ MJ^{-1} of hydrogen. SCWG uses high moisture containing biomass such as microalgae, thereby reducing the energy and corresponding emissions from microalgal drying. Microalgae conversion using the TG pathway has higher GHG emissions (173.8 $gCO_{2\text{-}eq}MJ^{-1}$) than the SCWG pathway as it involves the energy intensive drying process. The use of hydrogen for drying in thermal gasification reduces the GHG emissions to 133.2 $gCO_{2\text{-}eq}$ MJ^{-1}.

Combined LCA

The state-of-the-art development of thermochemical technologies for microalgae to desired products has prompted an evaluation of such technologies with respect to global warming potentials. LCA allows us to compare various sub-processes in an entire process to understand and quantify GHG emissions. The combined results for algal thermochemical conversion systems including growth, cultivation, and conversion systems for diluent and hydrogen production are summarized in Table 20. In general, the global warming potential values reported for algal-based fuel systems range widely, from -75 to 534 g $CO_{2\text{-eq}}$ MJ^{-1} [282]. In this study, a negative

Table 20. LCA of thermochemical technologies for diluent and hydrogen production (gCO_2eq MJ^{-1})

Cultivation Process	PBR		OPR		PBR		OPR	
Hydro Thermal Process	HTL	Pyrolysis	HTL	Pyrolysis	SCWG	TG	SCWG	TG
Production of diluent (Base case)	-5.90	45.65	-11.5	40.05				
Production of diluent (Scenario)	-5.90	15.8	-11.5	10.2				
Production of hydrogen (Base case)					-7.0	138.3	-12.56	132.68
Production of hydrogen (Scenario)					-7.0	97.7	-12.56	92.1

5.9-11.5 g $CO_{2\text{-eq}}$ MJ^{-1} of GHG emissions was estimated in the HTL process. HTL conversion of algae biomass to diluent represents slightly less than half (43% PBR and 47% OPR) of the combined emissions. Juneja et al. [300] conducted a life cycle analysis of renewable diesel production from microalgae grown on wastewater and estimated total GHG emissions of -110 g $CO_{2\text{-eq}}$ MJ^{-1} of renewable diesel. Bennion et al. [301] conducted a life cycle analysis reporting GHG emissions for the conversion of microalgae to renewable diesel via the HTL pathway of -11.4 g CO_2-

$_{eq}$ MJ^{-1}. At a productivity of 25 g (afdw) $m^{-2}d^{-1}$ with a bio-crude yield of 38 % (afdw), a GWP of -44 g $CO_{2\text{-}eq}$ MJ^{-1} was reported by Frank et al. [279], signifying a net negative GWP resulting from the carbon credit due to CO_2 uptake during algal growth.

Very few studies have evaluated microalgae as a biomass for pyrolysis. In our study, 10.2-45.65 g $CO_{2\text{-}eq}$ MJ^{-1} of GHG emissions was estimated for the pyrolysis process. Pyrolysis accounts for 68% (PBR) and 71% (OPR) of the combined emissions for conversion to diluent. With respect to GWP, producing diluent through HTL offers significant benefits compared to pyrolysis as it avoids the energy penalty and GHG emissions associated with drying.

The requirement of dry biomass together with energy demands in the pyrolysis reactor make it challenging to obtain an environmentally favorable algal-based product. In addition, microalgae drying and reactor heating have a direct influence on the environmental impact in pyrolysis. Bennion et al. [301] studied the energy requirements for the pyrolysis of microalgae and found GHG emissions from 166-210 g $CO_{2\text{-}eq}$ MJ^{-1}. Grierson et al. [277] performed an environmental assessment of microalgal pyrolysis systems with GHG emissions of 290.24 g $CO_{2\text{-}eq}$ MJ^{-1}. It is believed that the key factor influencing the outcome of life cycle analysis is the energy recovery in the form of a desired product [302]. Hence, any amelioration in process technologies ranging from algal productivity to conversion methods will reduce environmental impacts.

In this study, a negative 7.0-12.56 g $CO_{2\text{-}eq}$ MJ^{-1} of GHG emissions was estimated in the supercritical water gasification (SCWG) process leading to the production of hydrogen. The SCWG process represents 43% (PBR) and 47% (OPR) of the combined emissions, similar to the HTL pathway leading to diluent. Galera et al. [303] conducted an LCA of hydrogen and electricity production via supercritical water reforming of glycerol and attributed 19.14 g $CO_{2\text{-}eq}$ MJ^{-1} (2.68 g$CO_{2\text{-}eq}$ H_2 g^{-1}) production to sub-processes involving supercritical water reforming, including water-gas shift and pressure swing absorption (PSA) systems. Gasafi et al. [304]

studied the environmental impacts of SCWG using sewage sludge at approximately 5 $gCO_{2\text{-eq}}$ MJ^{-1} (0.7 $gCO_{2\text{-eq}}$ H_2 g^{-1}).

There are few published LCA studies that have evaluated environmental impacts associated with the thermal gasification (TG) of algae for the production of hydrogen. In the current study, GHG emissions in the algal thermal gasification pathway to produce hydrogen had a predicted range from 92.1-138.3 $gCO_{2\text{-eq}}$ MJ^{-1}. TG conversion to hydrogen production make up 82% (PBR) and 84% (OPR) of the combined emissions. These high GHG emissions in the thermal gasification pathway are due to the drying step involved with high moisture containing algae.

Net energy ratio

Along with calculating GHG emissions in this study, the thermochemical pathways for diluent and hydrogen production were also evaluated on the basis of net energy ratio. The NER is the relationship between energy produced and energy consumed. The NER is an indicator of energy effectiveness within a system. Hence, an NER greater than one is desirable.

In this study, an NER of 1.26 was obtained for large-scale hydrothermal liquefaction to produce diluent. This value is in accordance with others reported previously, ranging from 1-1.23 [279, 301, 305-307]. The differences in NERs from HTL conversion pathways are due to differences in product yields, recovery, and heating values. The NER for pyrolysis was 0.59; this is in accordance with the values reported in the literature [301]. The more favorable HTL NER results are attributed to HTL not requiring the energy intensive drying step necessary for the pyrolysis pathway This finding is supported by other studies [308], [309]. Further improvements in process efficiency would help increase diluent yield, thereby improving the NER of the HTL pathway.

For hydrogen production, an NER of 1.15 was obtained for both the supercritical water gasification (SCWG) and thermal gasification pathways (TG). The NER for such processes depend on microalgae yield and energy input requirements as they relate to cultivation and processing, respectively [310] .

Sensitivity analysis

A sensitivity assessment was conducted to understand input parameters that influence life cycle GHG emission results. To understand the sensitivity of the environmental impacts of key factors involved in the production of algae biomass, the factors were changed by 10%. The results clarify environmental impact differences between OPR and PBR technologies.

Figure 30 provides the key GHG emissions associated with OPR systems. Apart from the fertilizer nutrient inputs, these factors all consume electricity. The greatest sensitivity, at 0.023 kg $CO_{2\text{-eq}}$ kg^{-1} biomass produced, is attributed to electricity required to process (dewatering via centrifugation) a shift of 10% in the volume of media. This is followed by the associated pumping requirement (0.022 kg $CO_{2\text{-eq}}$ kg^{-1} biomass produced), the additional (reduction) media to be processed, which in

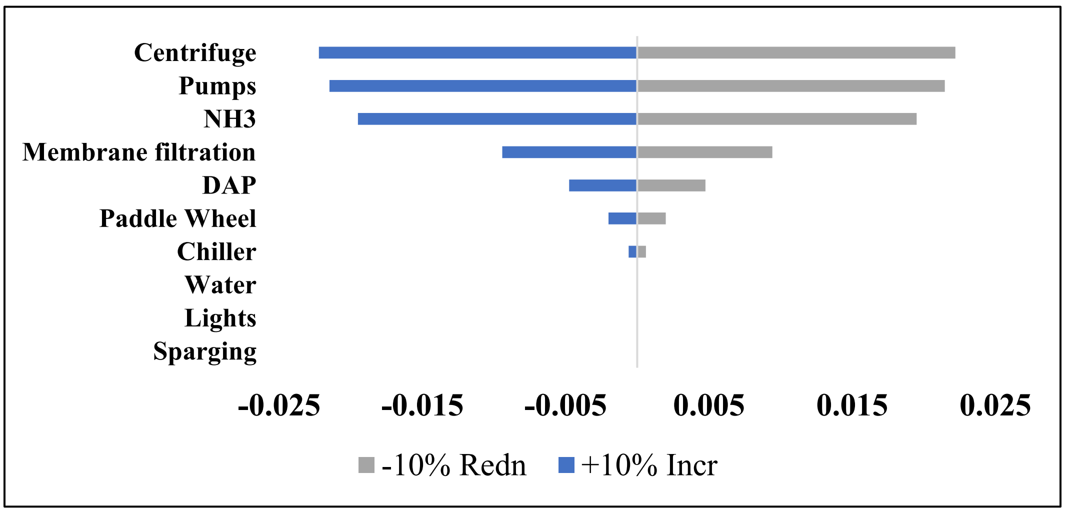


Figure 30. Key factor environmental impact sensitivity for OPR algae cultivation systems by kg $CO_{2\text{-eq}}$ kg^{-1} biomass produced

a similar manner impacts the power used for the filtration of the media (0.0095 kg $CO_{2\text{-eq}}$ kg^{-1} biomass produced), and the paddlewheels (0.002 kg $CO_{2\text{-eq}}$ kg^{-1} biomass produced) required to keep the media in motion. A 10% shift in the amount of NH_3 and DAP commercial fertilizer used in cultivation results in a 0.019 kg $CO_{2\text{-eq}}$ kg^{-1} biomass produced and 0.005 kg $CO_{2\text{-eq}}$ kg^{-1} biomass produced change in environmental impact, respectively. Environmental impacts related to water use, lighting, chiller and sparging have minimal impact (cumulatively <0.001 kg CO_{2-eq} kg^{-1} biomass produced).

Figure 31 shows the key environmental impacts associated with PBR systems. In this scenario, although environmental factors are again primarily related to electrical energy use, the most significant sensitivity is from the PBR lighting systems at close to 0.053 kg CO_{2-eq} kg^{-1} biomass produced for a 10% shift in the amount of energy required for this factor. Altering the amount of fertilizer used by 10% would shift environmental impacts the same as found in the OPR system, by 0.019 kg CO_{2-eq} kg^{-1} biomass produced for NH_3 and 0.005 kg CO_{2-eq} kg^{-1} biomass produced for DAP. Sparging impacts would increase (0.013 kg CO_{2-eq} kg^{-1} biomass produced) due to the higher pressures and volumes of air / CO_2 required for the

respective technology's application. However, since much lower quantities of media are processed with PBRs, impacts would be lower than those experienced by OPR systems, 0.004 and 0.002 kg CO_{2-eq} kg^{-1} biomass produced for centrifugation and membrane filtration, respectively. Environmental impacts related to 10% shifts in chilling, water use, and pumping are below 0.001 kg CO_{2-eq} kg^{-1} biomass produced cumulatively, and there is no requirement for the use of a paddlewheel.

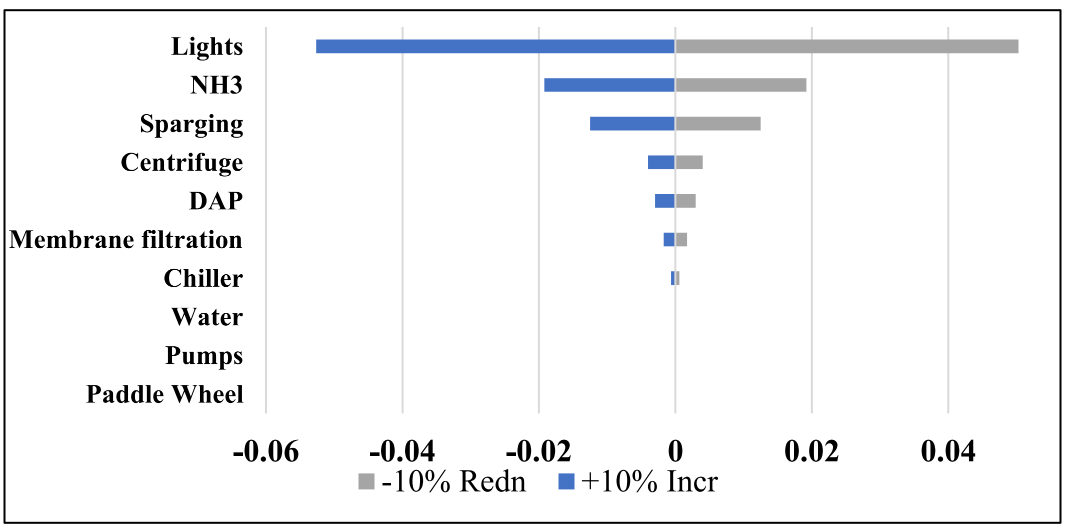


Figure 31. Key factor environmental impact sensitivity for PBR algae cultivation systems by kg CO_{2-eq} kg^{-1} biomass produced

We note that where changes in key cultivation factors have measurable environmental impacts, the factors with greatest sensitivity to change differ depending on the system (OPR or PBR). In OPRs, centrifugation and pumping are the primary factors. In PBRs, the lighting system will have slightly greater environmental impacts than those of the centrifugation and pumping associated with the OPRs.

Improvement measures and comparison with other known systems

Improved energy integration through optimized energy use for diluent and hydrogen production, the use of renewable electricity, and adopting efficient algal cultivation systems would considerably improve environmental performance metrics. Developing advanced catalysts in terms of selectivity and ability to withstand high temperatures would improve the energetics and reduce the environmental impacts of the system [303]. For gasification systems, the gasifier could be optimized to produce more hydrogen and less methane. Power recovery methods from turbines and the use of heat exchangers to transfer waste heat from one operation to another would also save energy, thereby reducing environmental impacts. Using autothermal processes and combusting a portion of the produced gas for the heat required in the reactor would reduce heat losses during heat transfer, a method employed in supercritical water oxidation [304]. More refined sensitivity analysis would help us understand process sensitivity to variations in operating parameters and identify opportunities for additional energy savings.

Figure 32 shows the comparison of GHG emissions in a variety of thermochemical technologies used in the production of fuels and chemicals. The methods and results are difficult to compare given differences in system boundaries, assumptions, and criteria, all of which lead to different environmental outcomes [303]. The consideration of different processes and units with respect to a particular technology may change with different performance metrics and data standards. Nevertheless, analysis and comparison help us evaluate technologies against each other. The widely adopted conventional method of hydrogen production through gasification using fossil fuels (including coal) and steam methane reforming generates high GHG emissions, with coal gasification and natural gas thermolysis approaching 29.33 g $CO_{2\text{-eq}}$ H_2 g^{-1} [311] and 37.11 g $CO_{2\text{-eq}}$ H_2 g^{-1} [312], respectively. Biochemical hydrogen production through photosynthetic routes helps mitigate environmental impacts. Hydrogen production via dark fermentation results in a 5.5 g $CO_{2\text{-eq}}$ H_2 g^{-1} GWP [313], but this technology is still at a nascent stage of development. Similarly, gasification technologies using renewable biomass have considerably lower GHG emissions (e.g., 5.40 g $CO_{2\text{-eq}}$ H_2 g^{-1}) [314] than those cited above. Compared to these known carbon footprints for hydrogen production, the SCWG of algal biomass offers a considerably better environmental profile with respect to global warming potential and has the potential to produce a promising energy resource.

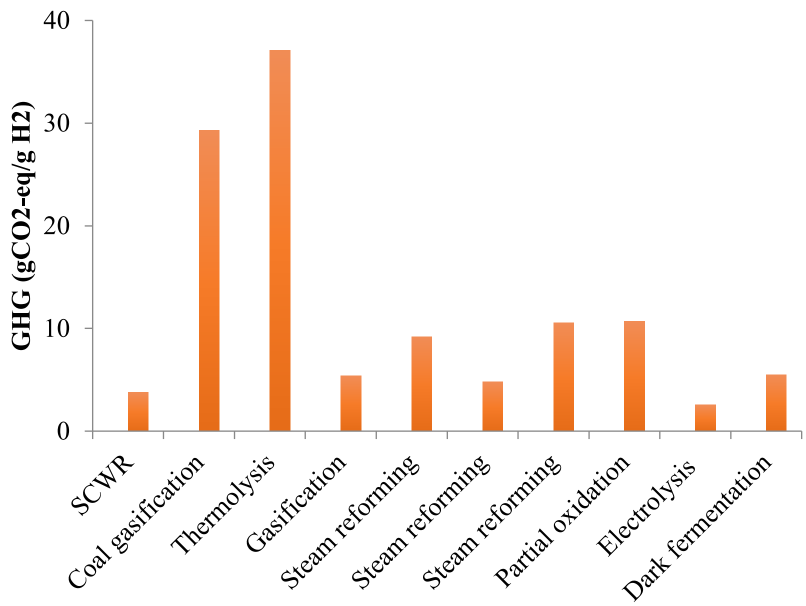


Figure 32. Comparison of life cycle analysis of key technologies for hydrogen production [303]

Conclusion

In keeping with the objectives of our research project we conducted a comparative LCA on Canadian microalgae feedstock cultivated in both open raceway pond and photobioreactor systems and subsequently processed via thermochemical conversion to end products (diluent and hydrogen) based on a commercial scale of 2,000 T d^{-1}. Of the thermochemical conversion pathways considered in our study, the best performance in terms of GHG emissions for hydrogen production is via SCWG (92.1-138.3 g CO_{2-eq} MJ^{-1}) and an NER of 1.15, followed by TG. Similarly, for diluent production through HTL and pyrolysis, only HTL processing shows environmental benefit (10.2-45.65 g CO_{2-eq} MJ^{-1}) and an NER of 1.26. This is because it can use wet biomass feedstock, thereby avoiding energy use and the GHG emissions associated with feedstock drying. These results will be useful for making better informed investment decisions related to these processes.

6. Conclusions and recommendations

Conclusions

The purpose of this research was to study the suitability of implementing an algae cultivation strategy in colder climate like Canada as part of a primary mitigation strategy to offset GHG emissions associated with oil sands operations. This not been studied before and thus is the knowledge gap addressed in the current research.

To assess the suitability of an algae cultivation strategy, two important questions needed to be answered. The first was whether it is possible to cultivate algae in an economically sustainable manner at commercial scale. In other words, is there sufficient economic value associated with the production of algae that can more than offset operating costs? There must be a viable economic driver in place before contemplating the follow-up second question.

The second question was: what are the environmental impacts of a commercial-scale algae biomass production system? In other words, is it possible that the production of algae might assist in the mitigation of GHG emissions, and, if so, what is the associated environmental impact at the proposed commercial scale?

To answer these questions, the research objectives presented in the introduction of this thesis were laid out, starting with: review current microalgae cultivation technologies that may be applicable to Canada's geography; evaluate existing analytical models to predict biomass yields in Canada based on open pond raceway (OPR) and photobioreactor (PBR) algae cultivation systems; construct a unique, data-intensive analytical model based on satellite ambient temperature and irradiance measurements to predict site-specific algae cultivation yields and facilitate rapid comparative evaluation of cultivation systems found in different geographic locations; provide a techno-economic analysis (TEA) of algae biomass cultivation based on a comparison of Canadian OPR and PBR cultivation systems.

Prevailing and conventional logic advocate algae cultivation via open pond raceway (OPR) systems and the belief that OPRs are the lowest cost approach to production. However, the primary autotrophic alternative cultivation system with the potential to address environmental impacts is the photobioreactors (PBR). In Canada, the northerly cold climate significantly limits algae production to warm months when OPRs would not freeze.

Since there are no known commercial attempts to cultivate algae using OPRs in Canada, the research began with a review of existing cultivation technologies applicable to Canada's northerly climatic conditions. The research work culminated in a comprehensive review on this subject.

In order to compare and evaluate algae cultivation technologies including OPR systems, we needed to be able to predict biomass yields in Canada. These were achieved by developing a novel analytical model to predict algae production in Canada at commercial scale. There is no published work that uses ubiquitous satellite data to predict OPR cultivation yields.

Predicting the OPR algae cultivation yields helped to conduct a comparative techno-economic analysis (TEA) of OPR and a PBR cultivation systems. This step indicated the economic viability of establishing an algae industry in Canada based on these technologies (Chp 3 Figure 6 Predicted annual algae growth – Fort Saskatchewan, Table 8 Predicted results, Figure 8 Predicted land requirement).

Once the TEA was complete, a life cycle assessment (LCA) on these same cultivation systems was conducted to determine the associated environmental impacts and to quantify the degree to which these commercial algae cultivation systems might mitigate GHG emissions.

The comparative LCA assessments on the use of OPR and a PBR cultivation technology built on the results of both the analytic model for predicting OPR yields and the TEA. The work is unique and not found elsewhere in published academic literature.

The downstream thermochemical processing of algae biomass into hydrogen and diluent for oil sands applications was introduced through the collaborative efforts of other researchers. The results, based on novel methods with a unique comparison between four different conversion pathways, have made a significant contribution to scientific knowledge. The collaborative results of this research have been compiled into a paper prepared for publication.

The conclusions of this research are:

- Algae cultivation via OPR systems in Canada would occur at a significant cost disadvantage compared to OPR cultivation in warmer geographic areas more suitable for these purposes. Costs for algae production in Alberta (\$1,288 USD T^{-1}) are projected to be more than double the projected costs for similar systems in Arizona (\$541 T^{-1}) (Chp 4 Techno-economic results).
- On the other hand, the economics of algae cultivation using PBR systems in Canada (\$550 USD T^{-1}) are projected to be on par with current OPR systems located in favorable climates. Furthermore, PBRs are seen to hold the potential to produce algae at increasingly lower costs. Current estimates of commercial production of algae have a minimum biomass selling price (MBSP) of \$541 USD T^{-1} (Chp 4 Techno-economic results). This research is optimistic that an MBSP using advanced PBRs could reduce this price to

well below \$200 USD T^{-1}(Chp 4 Sensitivity analysis). Taking advantage of ambient sunlight would improve economics by \$2.70 T^{-1} (a 0.5% change in MBSP) (Chp 4 Techno-economic results).

- From an environmental perspective, commercial autotrophic cultivation of algae by either OPR or PBR systems in Canada would result in favorable GHG emission mitigation. OPR systems have been projected to reduce emissions by 1.00 kg CO_2 kg^{-1} algae biomass produced, whereas current projections are that PBR systems would reduce emissions by 0.86 kg CO_2 kg^{-1} algae biomass (Chp 5 Table 18). For PBR systems in Canada that incorporate ambient sunlight, emissions reductions could be improved to 0.90 kg CO_2 kg^{-1} algae biomass (an improvement of 0.033 kg CO_2 kg^{-1} algae biomass or 3.8% over the current modeled results) (Chp 5 Life cycle inventory assessment).
- Using algae biomass as a feedstock to produce diluent and hydrogen via HTL, TG, and HTG (or SCWG) show favorable environmental impacts and would help mitigate GHG emissions in Alberta. Using a pyrolysis thermochemical pathway would not help mitigate these emissions. For the production of hydrogen, the research determined the following (gCO_2eq MJ^{-1}) results: SCWG (-7.0 to -12.6), TG (92 to 138). For the production of diluent, the following positive (gCO_2eq MJ^{-1}) results were determined: HTL (-5.9 to -11.553), pyrolysis (10.2 to 45.7) (Chp 6 Table 20). Furthermore, net energy ratios (NER) or 1.25 and 0.59 were calculated for the pathways utilizing algae feedstock to produce diluent via HTL and pyrolysis respectively. Similarly, NER calculations for the production of hydrogen via SCWG and TG yielded values of 1.15 for both process pathways (Chp 6 Net Energy Ratio).

Recommendations for future research

Although there has been significant interest in assessing the potential of microalgae for bio-feedstock production in Canada since the 1950's, given the chemical composition of microalgae, including significant amounts of lipids, proteins, and carbohydrates, research to date has not addressed important factors that impede the mass implementation of algae cultivation. To address these shortcomings, the following recommendations are offered.

Focus in Canada on using PBR systems for cultivating algae

Given the information supported by this research, it is evident that Canada will not be able to compete with warm climates and year-round sunlight in cultivating algae autotrophically using OPR systems. Geography places significant climatic challenges on this form of cultivation both from an environmental and an economic perspective. In Canada we need to focus research and development activities around PBR algae cultivation systems where there is greater potential for both positive environmental impacts and long-term economic sustainability.

Conduct research in Canada that leads to consistent yield equivalents of 5,000 $gm^{-2}d^{-1}$ (20 gLd^{-1}) for PBR systems

As this research found, improving yield is the factor that can most impact the MBSP. To reiterate: at Mesa, AZ, increasing productivity in the OPR by 60% (from 25 $gm^{-2}d^{-1}$ to 40 $gm^{-2}d^{-1}$) would lower the MBSP by \$127 T^{-1} (23%). The impact of the same OPR in Canada would be much greater because of the scale factor. Costs would decrease by over \$384 $tonne^{-1}$ (17%) from a 60% productivity increase. For PBR technology, a 60% yield increase (from 1250 $gm^{-2}d^{-1}$ to 2000 $gm^{-2}d^{-1}$ [8 $gL^{-1}d^{-1}$]) would lower the price by 21% (\$123 T^{-1}).

As in many areas of life, the challenge of achieving success has often less to do with actual failure than it has to do with low aim, that is, not setting one's objective high enough. It is proposed that algae cultivation research in Canada set an objective to attain consistent yields of 5,000 $gm^{-2}d^{-1}$ (20 gLd^{-1}) through PBR technology. This should be achieved using any algae species that meets specific compositional objectives (i.e., >40% lipid, not known to produce toxins).

The achievement of this single objective would establish Canada's position as the global leader in algae cultivation technology and open the door to establishing multiple bio-refinery scenarios to in this country. It would also signal the advent of a new agricultural sector in algae cultivation that would provide opportunities for rural development, support a new class of highly educated workers, and add meaningfully to a more diversified economy.

Canada and industry to support and conduct research to rapidly scale technologies that meet targeted performance, TEA, and LCA standards

Once algae yields improve, the associated technologies are put through a series of scaling operations to determine the limits of scale-up. We expect to achieve economies of scale that will improve profitability, thereby improving TEA outcomes while maintaining minimum benchmark LCA performance.

Conduct research leading to improving the efficiency of dewatering and harvesting algae and isolating active compounds from the biomass

Given that the highest energy requirements in algae cultivation are in harvesting, dewatering, and drying, research and development activities must focus on how to conduct these operations more efficiently and effectively.

Establishing microalgae cultivation bio-refinery platforms

As already indicated above, using an algae species that has not only high lipid concentration but also relatively high concentrations of other active compounds that have much greater value than diluent or hydrogen, albeit with a more limited market than diluent and hydrogen, should be pursued as part of a bio-refinery production platform to achieve higher profitability. Research into both potential bio-actives in algae and identifying species where the bio-actives are found to be synthesized in higher concentrations is recommended.

Research to determine a host of eligible micro-algae species that would be accepted as safe to enter the food chain

In preparation for the emergence of an agricultural algae cultivation industry it is important that research broaden the opportunities for cultivating a wide variety of algae species for different nutritional and health benefits. What is envisioned is similar to regional agricultural research stations already established across Canada for this purpose for conventional terrestrial plant material / crops. Integration of an algae cultivation program at each of these facilities is warranted.

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Appendix A

Supplementary Information

Calculation of results

Table 12. Key metrics cost factors

Capital Costs

- OPR Production ponds = NREL data x scaling factor for increased land requirement (3.0328) and increased production (3.88) at Fort Saskatchewan [155]
- Photobioreactors = PBR cost x units required to produce 2000 T d^{-1}
- Inoculum ponds = NREL data x scaling factor for increased land requirement (3.0328) and increased production (3.88) at Fort Saskatchewan [155]
- Building for PBRs = Area (for housing PBRs + 10% for admin + 10% for racking to stack PBRs) x cost to construct (\$28 ft^{-2}) (www.sprung.com)
- CO2 delivery
    - OPR system = NREL data x scaling factor for increased land requirement (3.0328) and increased production (3.88) at Fort Saskatchewan [155]
    - PBR system – assumed free because ability to co-locate adjacent to petrochemical facilities producing CO_2 at Fort Saskatchewan
- Circulation
    - OPR system = NREL data x scaling factor for increased land requirement (3.0328) and increased production (3.88) at Fort Saskatchewan [155]
    - PBR system – not required because of system design using bubbles sparged from the bottom of the tank to effect mixing action
- Dewatering
    - OPR system = NREL data x scaling factor for increased land requirement (3.0328) and increased production (3.88) at Fort Saskatchewan [155]
    - PBR system = NREL data x 0.9 (reduced capacity requirement for dewatering since PBR system has potential to maintain production at 365 days vs. 330 days projected by NREL) x increased production (3.88) at Fort Saskatchewan [155]
- Storage
    - OPR system = NREL data x scaling factor for increased land requirement (3.0328) and increased production (3.88) at Fort Saskatchewan [155]

- PBR system = NREL data x scaling factor for increased production (3.88) at Fort Saskatchewan [155]
- Land
  - OPR system = NREL data x scaling factor for increased land requirement (3.0328) and increased production (3.88) at Fort Saskatchewan [155]
  - PBR system = calculated land area required for direct cultivation x 1.4 (add 40% for admin, parking, storage) x land cost (@$3,000 acre^{-1})
- Indirect costs
  - OPR system = NREL data ((Added Dir + Indirect costs as % of TCI) - Land Cost) x scaling factor for increased land requirement (3.0328) and increased production (3.88) at Fort Saskatchewan [155]
  - PBR system = used NREL data ((Added Dir + Indirect costs as % of TCI) - Land Cost) to determine how the calculations were determined. Rationalized that we would apply the same calculation to the PBR calculation. Then multiplied x scaling factor for increased production (3.88) at Fort Saskatchewan [155]

Cultivation Costs

- CO2, NH3, DAP, Chilling – from NREL data – common to both PBR and OPR systems for comparative purposes [155]
- Power
  - OPR system = NREL data x scaling factor for increased land requirement (3.0328) conversion from tons to tonnes x change in days of cultivation at Fort Saskatchewan [155]
  - PBR system = calculated power use of PBRs kg^{-1} biomass produced
- OPR system - Fixed Costs, Capital depreciation, Average Income Tax, Average return on investment = NREL data x scaling factor for increased land requirement (3.0328) conversion from tons to tonnes [155]
- PBR system - Fixed Costs, Capital depreciation, Average Income Tax, Average return on investment = attempt to calculate these based on the same factors as used for the OPR system but applied to the HiTek Bio PBR system

Table 16. Data related to the production of 1 kg of algal biomass.

Productivity

- OPR system – modeled growth at Fort Saskatchewan, harvest at 5 g L^{-1} for 203 growing days [213]
- PBR system – modeled growth at Fort Saskatchewan, harvest at 5 g L^{-1} for 330 growing days [1]

Land

- OPR system - modeled growth at Fort Saskatchewan, harvest at 5 g L^{-1} for 203 growing days [213]
- PBR system - modeled growth at Fort Saskatchewan, harvest at 5 g L^{-1} for 330 growing days [1]

Water

- OPR system - modeled growth at Fort Saskatchewan, harvest at 5 g L^{-1} for 203 growing days [213]
- PBR system - modeled growth at Fort Saskatchewan, harvest at 5 g L^{-1} for 330 growing days [1]

Cultivation period

- OPR system - modeled growth at Fort Saskatchewan, harvest at 5 g L^{-1} for 203 growing days [213]
- PBR system - modeled growth at Fort Saskatchewan, harvest at 5 g L^{-1} for 330 growing days [1]

Water loss - evaporation

- OPR system – from NREL [155] and adjusted for pond depth of 25 cm
- PBR system – system enclosed. Therefore, no water loss due to evaporation

Water loss - blowdown

- OPR system - from NREL [155]
- PBR system - from NREL [155]

Water loss - harvesting

- OPR system - from NREL [155]
- PBR system - from NREL [155]

Harvests

- OPR system - modeled growth at Fort Saskatchewan, harvest at 5 g L^{-1} for 203 growing days [213]
- PBR system - modeled growth at Fort Saskatchewan, harvest at 5 g L^{-1} for 330 growing days [1]

Potential for cultivation crash

- OPR system - from NREL [155]
- PBR system – working assumption. Literature concurs that open pond systems are much more susceptible to pond crashes.

Table 17. OPR and PBR system assemblies with input / output operations

O_2 from hydrolysis of water

- From photosynthetic stoichiometric equation. Start with algae biomass composition. Calculate weight of carbon as percentage of biomass and for 1 MJ of biomass energy at lower heating value of 24.3 MJ kg^{-1} dry biomass. Convert weight of carbon for 1 kg biomass. Calculate moles of carbon. Since equal, moles O_2 produced for each mole of C, can then calculate amount of O_2 kg^{-1} dry biomass. [123]

Inoculum media moved to cultivation

- Make up water – restart every 2^{nd} harvest

Water loss

- Sum of water loss = evaporation + photosynthetic hydrolysis + blowdown
- Evaporation = Volume to cultivate 1 kg biomass * cultivation days * % evaporation d^{-1} (0.36% [155])
- Photosynthetic hydrolysis = H_2O calculation from reaction stoichiometry
- Blowdown = Assumed avg. 0.63 mm L^{-1} d^{-1} / 25 cm*100 = 0.252% d^{-1} * Vol (m^3) kg^{-1} biomass yr^{--1} * # cultivation days

CO_2 lost to air

- From photosynthetic stoichiometric equation. Assume 20% surplus.

N loss to water blowdown / air

- N loss = 20% surplus excess beyond the stoichiometric requirement. [123]

Water for recycling

- Additional water removed from the wet biomass by passing the media across a membrane filter in the filtration step as well as when processing the biomass by centrifuging.

Table 18. CO_2 emission results

- 1.8 kg CO_2e [11]
- 0.8 / 0.936 addition of energy unit operations associated with nutrients, paddle wheels (OPR), pumps (OPR), sparging (PBR), LEDs (PBR), membrane filtration, centrifuge, storage chilling.
- 1.0 / 0.86 subtraction
- 0.074 Conversion of 1.8 kg CO_2e kg-1 algae biomass to kg CO2e MJ-1 algae biomass. Conversion factor is 24.3 MJ energy kg-1 algae biomass. (1.8 / 24.3 = 0.74)
- 0.33 / 0.38 Conversion of 0.8 / 0.936 kg CO_2e kg algae biomass to kg CO_2e MJ-1 algae biomass. Conversion factor is 24.3 MJ energy kg-1 algae biomass. (0.8 / 24.3 = 0.033)
- 0.041 / 0.035 subtraction