Environmental performances of diluents and hydrogen production pathways from microalgae in cold climates: open raceway ponds and photobioreactors coupled with thermochemical conversion

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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 compete with food production. This paper evaluates the environmental sustainability of pathways producing diluents and hydrogen through microalgae in cold climatic conditions such as those in Western Canada. Two alternative cultivation systems (open pond raceway and photobioreactor, microalgal cultivation systems) and four different thermochemical production platforms (hydrothermal liquefaction and pyrolysis for diluent production and supercritical water gasification and thermal gasification for hydrogen production) were considered. On a system level,

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the industrial-scale processing of 2000 T d^{-1} dry biomass is modeled for all four conversion pathways. A “cradle-to-gate” process-based life cycle assessment (LCA) based on a global warming potential (GWP) characterization factor is conducted to quantify the greenhouse gas (GHG) emissions associated with the material, mass and energy requirements at each life cycle stage along with a net energy ratio (NER) analysis. 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 cold climates like northern Canada.

Keywords: Diluent; hydrogen; life cycle assessment; microalgae; biomass conversion; Canada

1 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 [1]. The oil sands extraction and petroleum production are expected to increase to around 3.8 million barrels per day by 2022 [9]. Undoubtedly, fossil fuel combustion has been directly linked to climate change [2]. Global warming due to rising greenhouse gas (GHG) emissions from anthropogenic activities is an ever-growing concern both regionally and globally [3-5]. Given that the oil and gas sector contributes significantly to Canada’s GHG emissions, there are concerted efforts to reduce the carbon footprint of the sector. Improving the energy efficiency of oil sands operations, minimizing flaring, venting and fugitive emissions, implementing carbon capture and storage systems, and using alternative renewable energy sources such as microalgae are a way forward [6].

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 [7]. 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 [8]. Moreover, microalgae can use municipal, agricultural, and industrial wastes as a source of key metabolic growth nutrients.

Microalgae can be used as a renewable energy source and a chemical in oil sands' operations. Under reservoir conditions, oil-bearing bitumen is highly viscous by nature and requires energy-intensive recovery and extraction techniques. Large volumes of short-chain, petroleum-based light hydrocarbons are used as a diluent to reduce the density and viscosity of the bitumen to make it flowable through pipelines to upgrading and refinery facilities [9]. In oil sands industries, diluent refers to naphthenic and paraffinic hydrocarbons used to reduce the viscosity and density of heavy hydrocarbon molecules in bitumen [10]. Diluent, a diluting agent, is a chemical substance used to aid viscous fluidity of heavy molecules through pipelines [11]. Mostly, diluents are known as natural gas condensates, which are comprised of compounds with lighter fractions [12]. 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 [13-16]. The production of a liquid product, bio-diluent, through pyrolysis has been investigated [15]. Extracting oil using bitumen via the Fischer-Tropsch method has been studied [16]. Kumar et al. studied diluent production through thermochemical pathways for oil sands applications [13]. 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 [13, 17]. 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 [18]. The HTL pathway avoids the energy-intensive drying step required for alternative processing [13], while pyrolysis requires a dry feedstock [19]. Though pyrolysis has gained significant attention for processing woody biomass [19-22], some studies have also focused on microalgae as a feedstock [23-25].

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 reactions, is widely used throughout the petroleum industry [26]. In 2005, some 3 million tonnes of hydrogen were produced and used to upgrade 527 thousand barrels of bitumen/day [27]. 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 [27]. Currently, almost all 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) [28, 29]. 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 [30]. Moreover, the fuel produced is devoid of nitrogen, permitting the use of the protein-rich microalgae [31]. Algal thermal gasification is regarded as a promising pathway to produce clean hydrogen fuel and generate electricity [32-35] using several gasification agents like steam, air, and CO_2 [32].

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 [36-40]. Other approaches to producing algae include photobioreactor (PBR) systems, in which algae are cultivated under controlled phototrophic/autotrophic conditions, and employing flat plates, plastic or glass tubular systems [41], and biofilms [42]. 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 [43]. Other algae cultivation systems use both autotrophic and heterotrophic conditions (mixotrophic) to achieve their growth objectives [44].

Life cycle assessment (LCA) is a useful tool to evaluate the environmental impacts associated with a product, process, or service [45, 46]. Several LCA studies have quantified the environmental impacts of algae on energy systems and reported a wide range of outcomes [47-50]. 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 [51-58]; a few studies consider thermochemical systems [18, 59-61]. 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 [60]. 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. Within this context, the paper aims to evaluate the environmental sustainability of pathways producing diluents and hydrogen by applying an LCA method to evaluate the associated global warming potential (GWP) together with a net energy ratio (NER) analysis, by considering two microalgae cultivation systems and four thermochemical process pathways.

2 Method

LCA, according to the ISO-14040/44 principles and framework, and guidelines, is developed to evaluate energy and GHG emissions [45, 46]. LCA involves a method that identifies and quantifies mass and energy balances to evaluate GWP by looking at system inputs and outputs at each process stage to identify the associated environmental impacts, along with a NER analysis.

2.1 Goal and scope definition

The goal of the current LCA is to evaluate and compare OPR and PBR algae cultivation scenarios producing at industrial scale (2,000 T d^{-1} dry weight) and four thermochemical conversion pathways leading to the production of diluent and hydrogen. For the diluent production pathway, hydrothermal liquefaction and pyrolysis of the algae were considered. Hydrothermal gasification and thermal gasification of the algae are the pathways leading to the production of hydrogen. Each activity involved in these processes is energy intensive and has associated GHG emissions. The LCA follows an “attributional” approach in which inputs and outputs and the associated environmental impacts are attributed to the functional unit using normative allocation rules. The different allocation methods, including by mass, energy content, and market value, are described in the literature [64-66]. The energy-based allocation was chosen based on similar studies [61, 67, 68]. GHG emissions are used as the environmental metrics to compare the alternative pathways. The GHG emission characterization factors are based on the IPCC one hundred-year time horizon global warming potential. The analysis includes 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 1).

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.

INSERT FIGURE 1

Figure 1: Map showing location of Fort Saskatchewan and general oil sands deposits

Figure 2 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. The net energy ratio (NER) (part of the LCA) 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[69].

The engineering approach used to model the cultivation and downstream processing of algae biomass is shown in the system process flow diagram (Figure 2). 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 a process model developed through Aspen Plus software [70]. Cultivation yields were predicted based on experimental yield data found in the literature and through consultation with industry experts[71], coupled with stoichiometric calculations. 20% of surplus nutrients beyond the stoichiometric biomass compositional demands was assumed to ensure maximum productivity [72] .

INSERT FIGURE 2

Figure 2: System boundary of the thermochemical pathways considered for diluent and hydrogen production

2.2 Life cycle inventory assessment

2.2.1 Algal cultivation

The life cycle inventory assessment was developed for all stages, from algae cultivation to the thermochemical process that delivers 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 [73]. Hence, due to the lack of empirical data quantification of environmental impacts of these systems at a commercial scale, the results are viewed with skepticism. Furthermore, studies are difficult to compare because of modeling difference between studies [74].

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 [72]. 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 [72]. GHG emissions from the use of equipment such as air compressors for sparging CO_2 into the media, pumps and paddlewheels for circulation, and LED lighting in the PBR system to promote growth are included. Table 1 provides a summary of parameters and input requirements considered in the inventory assessment [75]. These results as well as those found in Table 2 are based on experimental and literature values that are included in the first author's previously published work, where data was normalized and evaluated with respect to both mass and energy balances [75, 76]. The input values for the cultivation stage are favorable given an efficient microalgae species and highly controlled, indoor cultivation environment using LEDs to provide both lighting and heat. 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 1: Data related to the production of 1 kg of algal biomass

INSERT TABLE 1

The OPR system was modeled based on values found in Olivares et al. [77] and extrapolated from site-specific satellite climatic data using the predictive analytical model developed by the authors [75]. The algae cultivation model developed to simulate the production of dry biomass at 2,000 T d^{-1} incorporates design features found in the literature that use site-specific satellite meteorological data [75]. The satellite meteorological data set includes daily mean ambient temperature and solar irradiance values for specific latitude and longitude addresses. The data was used to calculate daily algae production volumes for the OPR system located at Fort Saskatchewan. 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} [72].

The PBR system's input and output requirements are determined based on a unique columnar photobioreactor design that provides a fully controlled algae growth environment [71]. 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 [78-80]. Under these optimized conditions, cultivation yields of 5 g $L^{-1}d^{-1}$ were considered based on the developed model [72], [76]. The values are consistent with those in existing literature [81], [82].

Since PBR systems are enclosed, a negligible amount of 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 [72]. 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} [83].

Energy required for dewatering the algae feedstock after cultivation in both OPR and PBR systems is assumed to be the same since the biomass is allowed to settle to similar densities prior to additional dewatering activities; this assumption is based on literature values provided by Davis et al. [84]. The algae biomass undergoes settling followed by hollow fiber membrane ultrafiltration and is then centrifuged to concentrate the biomass to 200 gL^{-1} [83] in preparation for downstream thermochemical conversion, described in the second part of this study.

As seen in Table 2, key energy requirements from the technosphere (man-made biotic resources [85]) 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 [86]. The large areas of land affected to cultivate algae for 2000 Td^{-1} dry biomass using OPR systems are included in the study. Transportation is not part of the study's scope since the selected location for algae cultivation adjoins the refineries that both produce commercial nutrients and use 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 [87], have been identified for their high growth yield and lipid content [88].

Table 2. OPR and PBR system assemblies with input/output operations

INSERT TABLE 2

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, the production of 660,000 T biomass annually would result in sequestering nearly 1.2 MT of CO_2 [89, 90]. While published algae biomass yields vary tremendously, consistent with what published literature and industry believe to be achievable productivities for both OPR and PBR systems [72, 76], the model uses the following values: 0.1 $gL^{-1}d^{-1}$ for the OPR systems and 5 $gL^{-1}d^{-1}$ for the PBR systems. The referenced PBR's high productivities are attributed to a proprietary isolated algae species and highly controlled environmental parameters associated with the PBR design [83]. The mass and energy balances of downstream processing for LCA calculations were estimated through the development of the process model in Aspen Plus. This model is described in earlier publications by the authors [13, 91]. The life cycle assessment was conducted based on a global warming potential (GWP) characterization factor following steps outlined in 2006 IPCC Guidelines for National Greenhouse Gas Inventories. The inventory values are translated to GHG emissions per functional unit using the IPCC one-hundred-year time horizon emissions factor [46]. 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.

2.2.2 Process conversion

The following thermochemical conversions pathways were considered for the algal biomass feedstock: HTL, fast pyrolysis, supercritical water gasification, and thermal gasification. These systems were modeled through Aspen Plus software. Figure 2 shows the basic unit operations involved in each pathway followed by a brief discussion of each process. In this analysis, the cultivation and conversion facilities are considered to be located near each other and thus the effects of transportation are negligible. For conversion, the algae production facility is considered to be 2000 dry tonnes/day based on the scale designed for large-scale biomass-based systems [14, 92].

INSERT FIGURE 3

Figure 3: Schematic of the thermochemical conversion pathway for diluent and hydrogen production from biomass

2.2.2.1 Fast pyrolysis

Fast pyrolysis refers to the thermochemical conversion of biomass to bio-oil at high temperatures in the absence of oxygen. The thermal decomposition process dries the biomass to a moisture content of less than 10% to reduce water content in bio-oil produced [93]. Since the algal biomass from the cultivation facility is 20 wt% dry biomass, it requires additional drying to bring it down to 5-10 wt% [94] before it can be fed into the fast pyrolysis reactor. Other parameters of importance in fast pyrolysis include temperature, pressure, particle size, and residence time. After the drying process, the algal biomass is passed through a fluidized bed pyrolysis reactor at 520 °C at a particles size less than 2 mm [95]. Following this step, solid residues are removed by cyclones, resulting in a bio-oil [91, 96, 97]. Products from the pyrolysis process were found to have mass yields of 55.9%, 23%, and 21.1% for the bio-oil, gases and solid char, respectively. In general, the oil product yield from fast pyrolysis is from 55 to 65 wt% [98, 99]. Bio-oil from the fast pyrolysis is hydrotreated to produce diluent [100]. Table 3 shows the total energy requirement per kg of diluent produced through fast pyrolysis. The primary energy source for drying microalgae is natural gas, which acts as a critical energy burden during algal biomass pyrolysis, as also reported previously [101]. Other energy inputs to the pyrolysis process are in the form of electricity, used to run pumps and compressors [102].

Table 3: Energy requirements for the pyrolysis of algae

INSERT TABLE 3

2.2.2.2 Hydrothermal liquefaction

HTL is a known thermochemical conversion process that converts biomass into bio-crude using water as reactive medium[13]. The process disintegrates macromolecules into smaller fractions and hydrotreats them to lower the amount of deoxygenated compounds. It produces diluent at medium temperature and high reaction pressure and high water concentration, with bio-crude being its intermediate product [13]. During the HTL process, biomass is pumped at 18 MPa and the resulting stream is passed through heat exchangers, which increases its temperature to 350 °C. At this state, water is at slightly below the supercritical point, which allows for the dissolution of biomass in the solution [103]. The incoming effluent goes through the HTL reactor, wherein biomass molecules are converted into bio-crude. Products from the HTL process include bio-crude, an aqueous phase, gases, and solids with yields by mass of 40.3%, 53.8%, 4.9%, and 1%, respectively; these are within the ranges reported by others [104-106]. The bio-crude undergoes hydrotreating where it is deoxygenated to produce diluent [100]. For HTL, no additional drying requirement exists and feedstock is available at 20% dry content at the inlet of the HTL reactor. The inputs to the liquefaction process are natural gas to heat the reactor units and electricity to run pumps and provide cooling, as reported in literature [18, 67, 102]. Table 4 shows the energy requirements for diluent production through algal HTL process.

Table 4: Energy requirements for the hydrothermal liquefaction of algae

INSERT TABLE 4

2.2.2.3 Supercritical water gasification

Supercritical water gasification is the thermochemical conversion pathway that allows the supercritical conditions of water to act as a reactant. This occurs with the initiation of bond cleavage between biomass macromolecules through hydrolysis [107]. The reaction occurs at a range of temperatures (300-600 °C) and high pressures (12-34 MPa) with biomass's initial concentration in the range of 10-30 wt% [108]. The product obtained is syngas, which undergoes purification into H_2 using Selexol and is then enriched into H_2 [91]. Table 5 shows the energy requirement for different operations for the supercritical water gasification of algae.

Table 5: Energy requirements for the supercritical gasification of algae

INSERT TABLE 5

2.2.2.4 Thermal gasification

The thermal gasification process converts biomass feedstock into gaseous products at high temperature (up to 850 °C) and atmospheric pressure. Biomass usually enters the process at a 5-10% moisture content. The algal biomass from the cultivation needs to be dried to reduce its moisture content. Syngas is the output from thermal gasification and it should pass through H_2 treatment unit for purification [91]. Table 6 summarizes the energy requirement for different operations for thermal water gasification of algae.

Table 6: Energy requirements for the thermal gasification of algae

INSERT TABLE 6

3 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.

3.1 Algal cultivation

The environmental impacts associated with algae cultivation in both OPR and PBR systems are discussed in this section. Figure 4 provides a breakdown of the emissions associated with unit operations for both OPR and PBR algae production systems. An OPR appears to have a relatively better GHG emissions performance than a 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 North Saskatchewan River water use is minimal, less than 1% in both cases. Given that 1.8 T of CO_2 is captured in the production of algae biomass, the calculated net results for OPRs and PBRs are 1.0 and 0.9 T of CO_2 removed from the atmosphere, respectively. Although the electricity use differs significantly between the OPR and PBR systems, the 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. The results are higher than those reported by Verma et al., 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 [7].

INSERT FIGURE 4

Figure 4: Algae biomass production – CO_{2eq} emissions unit operation

Because of the commercial scale of the renewable energy operations modeled, it is useful to compare CO_2 sequestration through algae cultivation with carbon sequestration in existing forests in the region that could be considered for the production of renewable energy. 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 [109]. This can be calculated as 0.165 kg CO_2 sequestered $m^{-2}yr^{-1}$. From Table 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 2083 kg CO_2 $m^{-2}yr^{-1}$ or an approximate 12,600-fold increase in CO_2 sequestration.

3.2 Process conversion

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 5. 60% of GHG emissions in HTL are from the hydrothermal liquefaction unit, and the rest are from the hydrotreating section of the HTL plant. This is mainly due to the high energy 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}) higher than from HTL [110].

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; both require 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 more than HTL because of 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.

INSERT FIGURE 5

Figure 5: Breakdown of GHG emissions from HTL and pyrolysis in diluent production

For hydrogen production, the SCWG pathway has lower GHG emissions than TG, as Figure 6 shows. Hydrogen production in the 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}.

INSERT FIGURE 6

Figure 6: Breakdown of GHG emissions for SCWG and TG for hydrogen production

3.3 Global warming potential

The state-of-the-art development of thermochemical technologies for microalgae to desired products has prompted an evaluation of the 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 7. 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} [18, 69]. In this study, a negative 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. conducted a life cycle analysis of renewable diesel production from microalgae grown on wastewater and estimated GHG emissions of -110 g $CO_{2\text{-eq}}$ MJ^{-1} of renewable diesel [104]. Bennion et al. conducted a life cycle analysis reporting GHG emissions for the conversion of microalgae to renewable diesel via the HTL pathway of -11.4 g $CO_{2\text{-eq}}$ MJ^{-1} [102]. 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. [61], 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. studied the energy requirements for the pyrolysis of microalgae and found GHG emissions from 166-210 g $CO_{2\text{-eq}}$

MJ^{-1} [102]. Grierson et al. performed an environmental assessment of microalgal pyrolysis systems and reported GHG emissions of 290.24 g $CO_{2\text{-eq}}$ MJ^{-1} [60]. 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 [82]. 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 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. 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 [111]. Gasafi et al. studied the environmental impacts of SCWG using sewage sludge at approximately 5 g$CO_{2\text{-eq}}$ MJ^{-1} (0.7 g$CO_{2\text{-eq}}$ H_2 g^{-1}) [112].

There are few published LCA studies that have evaluated the 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 g$CO_{2\text{-eq}}$ 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.

Table 7. LCA of thermochemical technologies for diluent and hydrogen production (gCO_2eq MJ^{-1})

INSERT TABLE 7

3.4 Net energy ratio

Along with calculating GHG emissions in this study, we evaluated the thermochemical pathways for diluent and hydrogen production on the basis of net energy ratio (NER). The NER is a ratio of the net energy output to the total net energy input from a non-renewable energy source into the system. The NER is the relationship between energy produced and energy consumed. The NER is an indicator of energy effectiveness in 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, which range from 1-1.23 [61, 102, 113-115]. 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 [102]. 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 [103], [116]. 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 the supercritical water gasification pathway. The NER for these processes depends on microalgae yield and energy input requirements, as they relate to cultivation and processing, respectively [117].

4 Sensitivity analysis

Sensitivity analysis provides an appraisal of how changes to major input factors affect or influence results of a process. In this study, input factors of production were increased and decreased by 10% to understand the sensitivity of these changes in influencing life cycle GHG emissions. The choice to use a 10% variance was sufficient to clarify environmental impact differences between OPR and PBR technologies. (See Appendix Tables A1, A2)

Figure 7 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 the 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 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 environmental impact changes of 0.019 kg $CO_{2\text{-eq}}$ kg^{-1} biomass produced and 0.005 kg $CO_{2\text{-eq}}$ kg^{-1} biomass produced, respectively. Environmental impacts related to water use, lighting, chiller, and sparging have minimal impacts (cumulatively <0.001 kg $CO_{2\text{-eq}}$ kg^{-1} biomass produced).

INSERT FIGURE 7

Figure 7: Key factor environmental impact sensitivity for OPR algae cultivation systems by kg $CO_{2\text{-eq}}$ kg^{-1} biomass produced

Figure 8 shows the key environmental impacts associated with PBR systems. In this scenario, although environmental factors are primarily related to electrical energy use, the most significant sensitivity is from the PBR lighting systems at close to 0.053 kg $CO_{2\text{-eq}}$ 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 the environmental impact by the same amount as in the OPR system, 0.019 kg $CO_{2\text{-eq}}$ kg^{-1} biomass produced for NH_3 and 0.005 kg $CO_{2\text{-eq}}$ kg^{-1} biomass produced for DAP. Sparging impacts would increase (0.013 kg $CO_{2\text{-eq}}$ kg^{-1} biomass produced) because of 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 $CO_{2\text{-eq}}$ 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 $CO_{2\text{-eq}}$ kg^{-1} biomass produced cumulatively, and there is no requirement for the use of a paddlewheel.

INSERT FIGURE 8

Figure 8: Key factor environmental impact sensitivity for PBR algae cultivation systems by kg $CO_{2\text{-eq}}$ 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 the centrifugation and pumping associated with the OPRs have.

5 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 the ability to withstand high temperatures would improve the energetics and reduce the environmental impacts of the system [111]. 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 used in supercritical water oxidation [112]. More refined sensitivity analysis would help us understand process sensitivity to variations in operating parameters and identify opportunities for additional energy savings.

6 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 algae biomass 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 $CO_{2\text{-eq}}$ MJ^{-1}) and an NER of 1.15, followed by TG. Similarly, for diluent production through HTL and pyrolysis, only HTL processing shows an environmental benefit (10.2-45.65 g $CO_{2\text{-eq}}$ 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.

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Declaration of authors' contributions

Each author contributed as follows:

Stan Pankratz: conception and design of the study, acquisition, analysis and interpretation of the algae biomass production data, drafting the article, final approval of the version to be submitted.

Mayank Kumar: conception and design of the downstream processing of algae biomass study, acquisition, analysis and interpretation of the data, drafting the article, final approval of the version to be submitted.

Adetoyese Olajire Oyedun: administrative and technical support, critical revision of the design of the study and the final article, final approval of the version submitted.

Eskinder Gemechu: administrative and LCA technical support, critical revision of the design of the study and the final article, final approval of the version submitted.

Amit Kumar: conception and design of the study, technical and logistic support, critical revision of the article, final approval of the version submitted.

Stan Pankratz and Mayank Kumar take responsibility for the integrity of the work as a whole, from inception to finished article.

Statement of Informed Consent

No conflicts, informed consent, human or animal rights applicable

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FIGURES

Figure 1. Map showing location of Fort Saskatchewan and general oil sands deposits

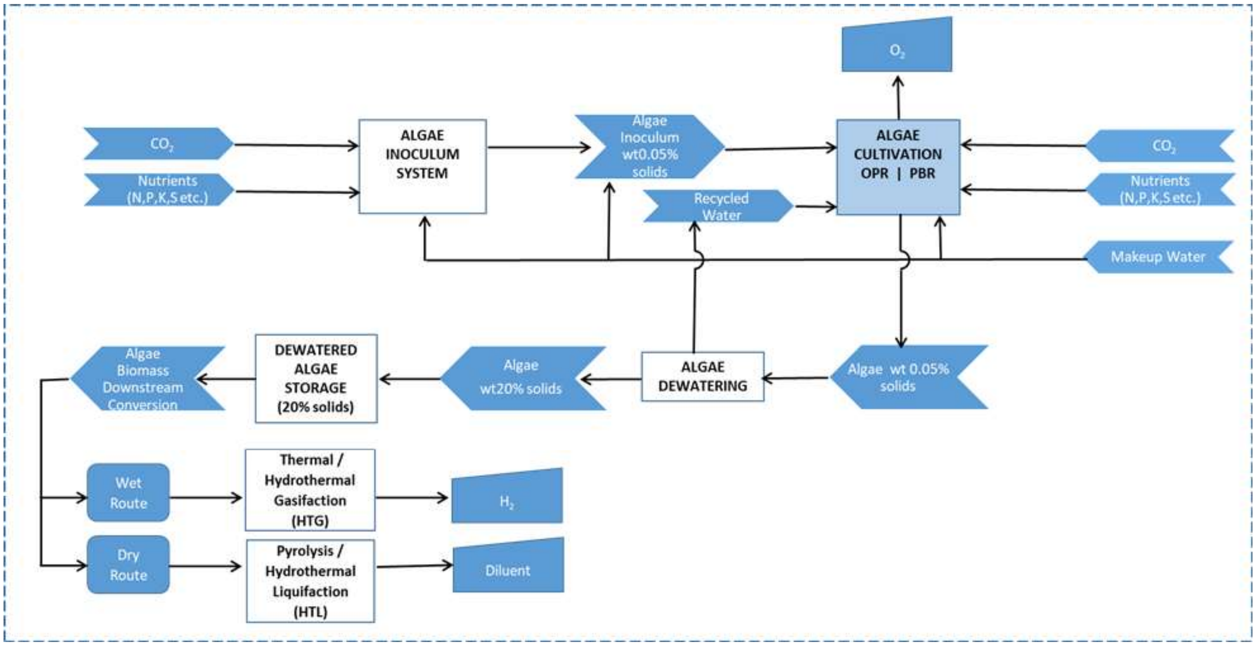

Figure 2: System boundary of the thermochemical pathways considered for diluent (hydrothermal liquefaction [HTL] and pyrolysis) and hydrogen production (hydrothermal gasification [HTG] and thermal gasification [TG]) from microalgae produced via open pond raceway (OPR) and photobioreactor (PBR) systems.

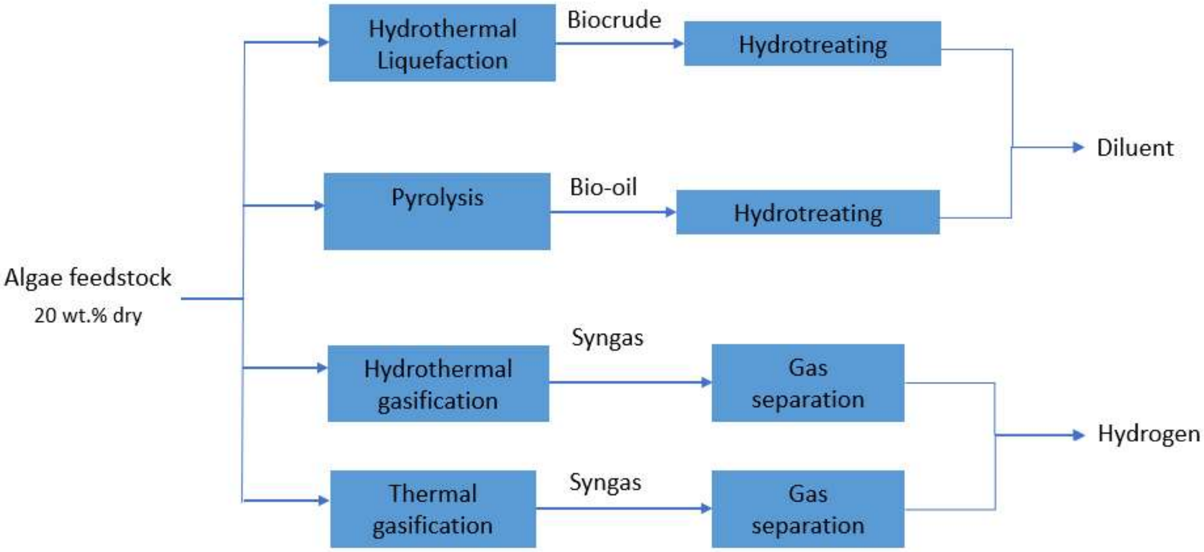

Figure 3: Schematic of the thermochemical conversion pathway for diluent and hydrogen production from biomass

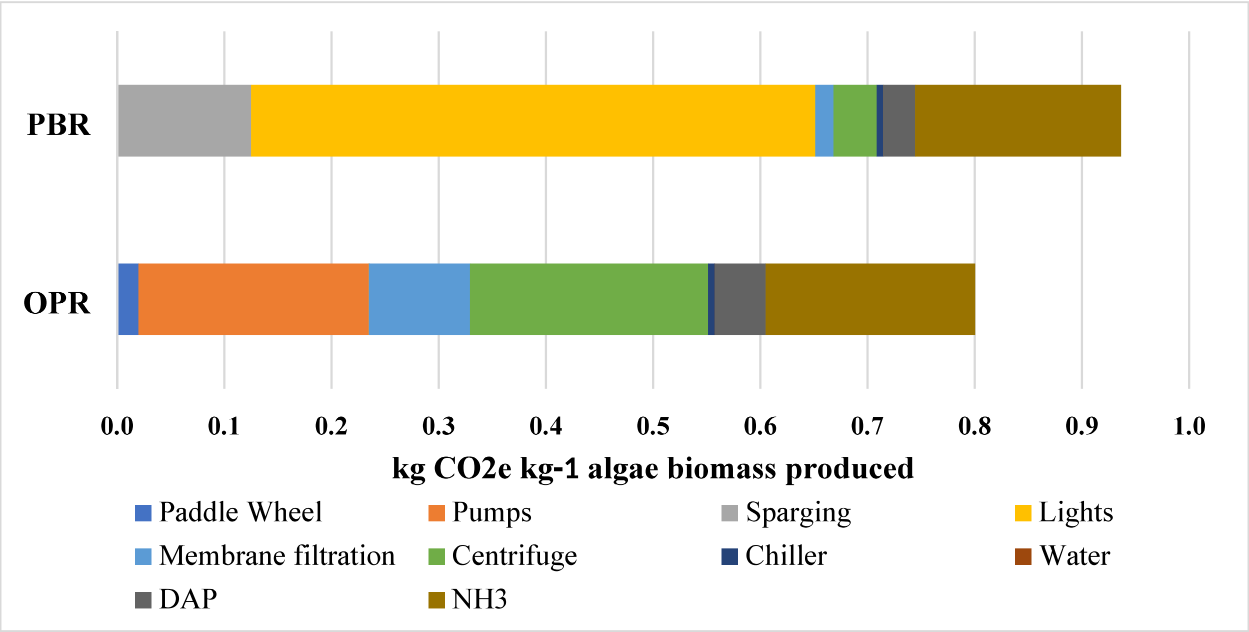

Figure 4. Algae biomass production – CO_{2eq} emissions unit operation for open pond raceway (OPR) and photobioreactor (PBR) (DAP - diammonium phosphate; NH_3 – ammonia)

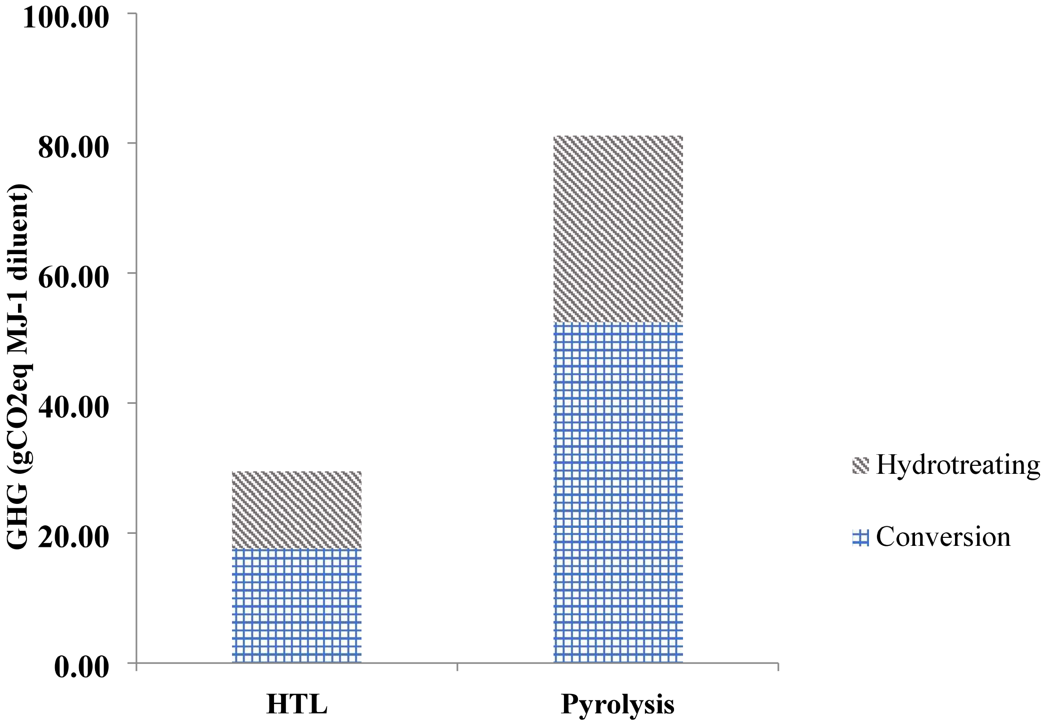

Figure 5. Breakdown of greenhouse gas (GHG) emissions for hydrothermal liquefaction (HTL) and pyrolysis for diluent production

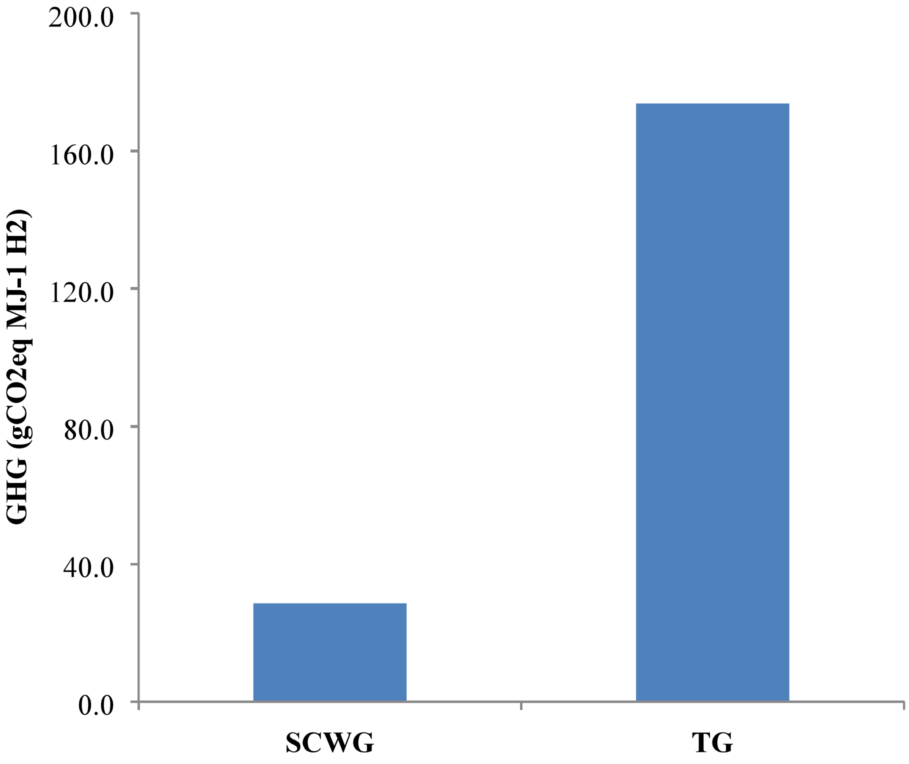

Figure 6. Breakdown of greenhouse gas (GHG) emissions for supercritical water gasification (SCWG) and thermal gasification (TG) for hydrogen production

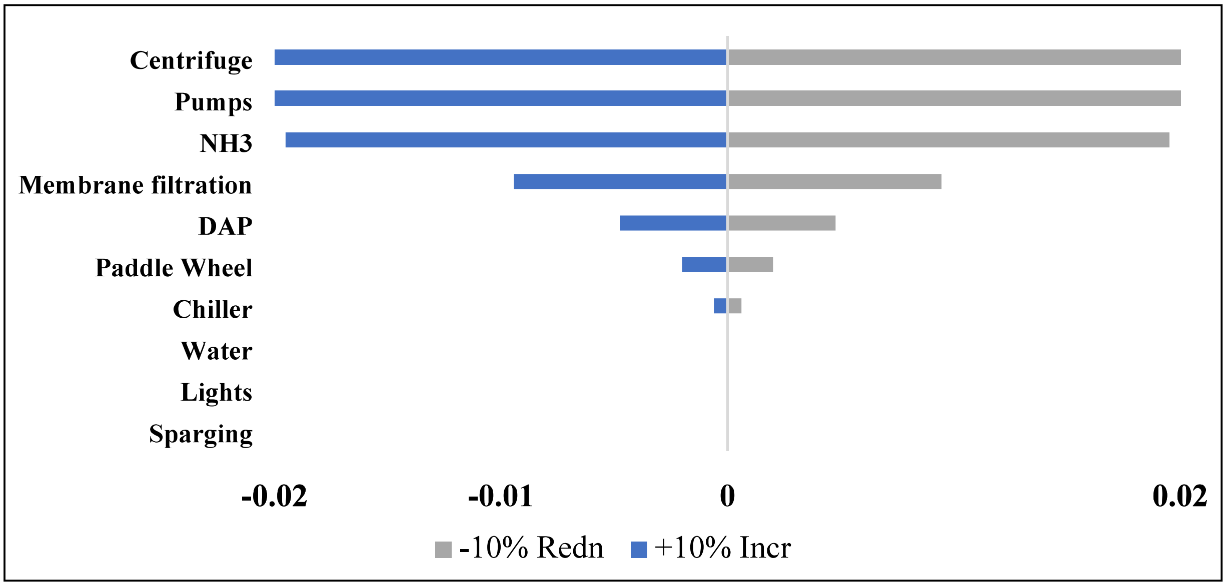

Figure 7. Key factor environmental impact sensitivity for open pond raceway (OPR) algae cultivation systems by kg $CO_{2\text{-eq}}$ kg^{-1} biomass produced (-10% Redn – 10% reduction in the values of the parameters, +10% Incr – 10% increase in the values of the parameters, DAP - diammonium phosphate, NH_3 – ammonia).

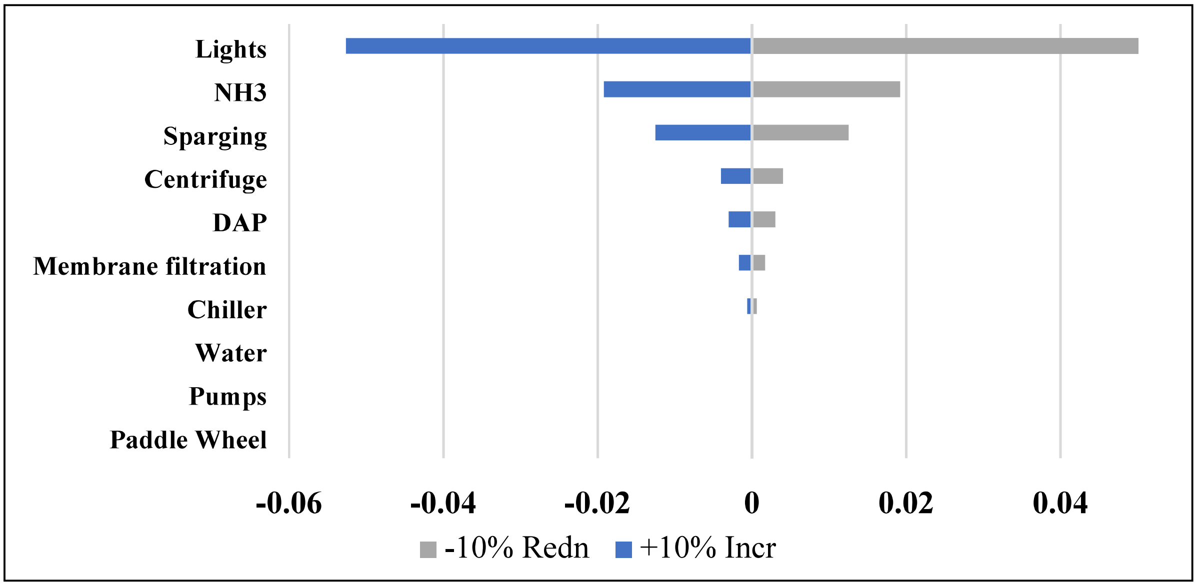

Figure 8. Key factor environmental impact sensitivity for photobioreactor (PBR) algae cultivation systems by kg $CO_{2\text{-eq}}$ kg^{-1} biomass produced (-10% Redn – 10% reduction in the values of the parameters, +10% Incr – 10% increase in the values of the parameters, DAP - diammonium phosphate, NH_3 – ammonia).

TABLES

Table 1: Data related to the production of 1 kg of algal biomass with open pond raceway (OPR) and photobioreactor (PBR) systems

Parameters	**OPR**	**PBR**	**Units**	**References and notes**
Productivity	5.8	1825	$gL^{-1}yr^{-1}$	• OPR system – modeled growth at Fort Saskatchewan, harvest at 5 g L^{-1} for 203 growing days [70] • PBR system – modeled growth at Fort Saskatchewan, harvest at 5 g L^{-1} for 330 growing days [79]
Land	1.24	0.00048	$m^2kg^{-1}yr^{-1}$	• OPR system – modeled growth at Fort Saskatchewan, harvest at 5 g L^{-1} for 203 growing days [70] • PBR system – modeled growth at Fort Saskatchewan, harvest at 5 g L^{-1} for 330 growing days [79]
Water	1.06	0.023	m^3 or T	• OPR system – modeled growth at Fort Saskatchewan, harvest at 5 g L^{-1} for 203 growing days [70] • PBR system – modeled growth at Fort Saskatchewan, harvest at 5 g L^{-1} for 330 growing days [79]
Cultivation period	203	330	d yr^{-1}	• OPR system – modeled growth at Fort Saskatchewan, harvest at 5 g L^{-1} for 203 growing days [70] • PBR system – modeled growth at Fort Saskatchewan, harvest at 5 g L^{-1} for 330 growing days [79]
Water loss - evaporation	0.5	0	% d^{-1}	• OPR system – from NREL [68] and adjusted for pond depth of 25 cm • PBR system – system enclosed. Therefore, no water loss due to evaporation
Water loss - blowdown	0.5	0.5	% d^{-1}	• OPR system - from NREL [68] • PBR system - from NREL [68]
Water loss - harvesting	0.2	0.2	% $harvest^{-1}$	• OPR system - from NREL [68] • PBR system - from NREL [68]

Harvests	11	330	# yr^{-1}	• OPR system - modeled growth at Fort Saskatchewan, harvest at 5 g L^{-1} for 203 growing days [70] • PBR system - modeled growth at Fort Saskatchewan, harvest at 5 g L^{-1} for 330 growing days [79]
Potential for cultivation crash	5	1	%	• OPR system - from NREL [68] • PBR system – working assumption. Literature concurs that open pond systems are much more susceptible to pond crashes

Table 2. Open pond raceway (OPR) and photobioreactor (PBR) system assemblies with input/output operations

ASSEMBLIES	OPR	PBR	Units kg^{-1}*	References and notes
ALGAE INOCULUM SYSTEM				
Inputs				
Makeup water	3.98		m^3 or T	
Land for inoculum	0.12		m^2	
Nutrients	0.24		kg	
Energy - electrical	0.0257		kWh	
Outputs				
Oxygen gas (O_2) from hydrolysis of water	0.14		kg	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.
Inoculum media moved to cultivation	2.14		m^3 or T	Make up water – restart every 2nd harvest
Water loss	1.84		m^3 or T	• Sum of water loss = evaporation + photosynthetic hydrolysis + blowdown • Evaporation = Volume to cultivate 1 kg biomass * cultivation days * % evaporation d^{-1} (0.36% [68]) • Photosynthetic hydrolysis = H_2O calculation from reaction stoichiometry

ASSEMBLIES	OPR	PBR	Units kg^{-1}*	References and notes
				- 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
Carbon dioxide (CO_2) lost to air	0.038		kg	From photosynthetic stoichiometric equation. Assume 20% surplus
N loss to water blowdown / air	0.0016		kg	N loss = 20% surplus excess beyond the stoichiometric requirement.
ALGAE CULTIVATION SYSTEM				
Inputs				
Inoculum media with water	2.14		m^3 or T	
Makeup water	21.5	0.011	m^3 or T	
Land for cultivation	12.4	0.00048	m^2	
Nutrients	2.4	2.4	kg	
Energy – electrical	0.257	0.785	kWh	
Outputs				
Oxygen gas (O_2) from hydrolysis of water	1.4		kg	
Water loss	18.4	0.011	m^3 or T	
Carbon dioxide (CO_2) lost to air	0.38	0.38	kg	

ASSEMBLIES	**OPR**	**PBR**	**Units kg^{-1}***	**References and notes**
Nitrogen (N) loss to water blowdown / air	0.016	0.016	kg	
Cultivation media (10 g/L – 1% solids)	0.155	0.0005	m^3 or T	
ALGAE DEWATERING - Ultra / micro filtration membrane				
Inputs				
Cultivation media (10 g/L – 1% solids)	0.155	0.0005	m^3 or T	
Energy - membrane filtration	0.11	0.020	kWh	
Outputs				
Algae biomass (130 g/L – 13% solids)	0.012	3.8E-05	m^3 or T	
Water for recycling	0.143	0.00046	m^3 or T	
ALGAE DEWATERING - Centrifuge				
Inputs				
Algae biomass (130 g/L – 13% solids)	0.012	3.8E-05	m^3 or T	
Energy - centrifuge	0.27	0.048	kWh	
Outputs				
Algae biomass (200 g/L - 20% solids)	0.0078	2.5E-05	m^3 or T	

ASSEMBLIES	OPR	PBR	Units kg^{-1}*	References and notes
Water for recycling	0.0042	0.000013	m^3 or T	
ALGAE STORAGE - Chilling				
Inputs				
Energy - chilling biomass / kg	0.0073	0.0073	kWh	

- Units kg^{-1} dry biomass (nitrogen surplus) under lower heating value calculations. Inoculum based on 10% of cultivation values.

Table 3. Energy requirements for the pyrolysis of algae

Operation	**Value** [70]	**Unit**
Dryer	5.68	MJ/kg diluent
Heater	3.15	MJ/kg diluent
Reactor	31.4	MJ/kg diluent
Hydrotreat pump	0.40	MJ/kg diluent
Compressor	0.32	MJ/kg diluent
Hydrotreat heater	1.58	MJ/kg diluent
Column-reboiler	0.07	MJ/kg diluent
Flash separator	0.11	MJ/kg diluent
Hydrotreater	7.85	MJ/kg diluent

Table 4. Energy requirements for the hydrothermal liquefaction (HTL) of algae

Operation	**Value** [70]	**Unit**
HTL Pump	0.36	MJ/kg diluent
Reactor	12.23	MJ/kg diluent
Hydrotreat pump	0.47	MJ/kg diluent
Hydrotreat compressor	0.25	MJ/kg diluent
Hydrotreater	0.64	MJ/kg diluent
Column reboiler	0.28	MJ/kg diluent

Table 5. Energy requirements for the supercritical water gasification (SCWG) of algae

Operation	**Value** [70]	**Unit**
SCWG pump	1.44	MJ/kg H_2
Heater	56.7	MJ/kg H_2
Selexol pump	1.66	MJ/kg H_2
Compressor	7.6	MJ/kg H_2
Gas purification pump	5.4	MJ/kg H_2

Table 6. Energy requirements for the thermal gasification of algae

Operation	**Value** [70]	**Unit**
Reactor	57.24	MJ/kg H_2
Dryer	5.51	MJ/kg H_2
Selexol pump	2.56	MJ/kg H_2
Compressor	12.89	MJ/kg H_2
Gas purification pump	6.62	MJ/kg H_2

Table 7. LCA of thermochemical technologies for diluent and hydrogen production via two alternative cultivation systems (open pond raceway [OPR] and photobioreactor [PBR]) and four different thermochemical production platforms (hydrothermal liquefaction [HTL] and pyrolysis for diluent production and supercritical water gasification [SCWG]) and thermal gasification [TG] for 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

Statement of Informed Consent, Human/Animal Rights

“No conflicts, informed consent, human or animal rights applicable”

Statement of Novelty

This work evaluates the environmental sustainability of open pond raceway and photobioreactor algae cultivation systems in a cold climate with downstream processing to hydrogen and diluent with commercial biomass production of 2000 T/day. This has not been investigated earlier and hence is a novel contribution in this area.

Appendix

Algae Biomas Production – CO_2 Emissions Calculations

Table A1 – Open pond raceway (OPR) calculations (kg CO_2e kg^{-1} biomass produced)

	+10% increase	**Calculated emissions**	**-10% Reduction**		**+10% increase**	**Normalized to zero**	**-10% Reduction**
Paddle Wheel	0.022	0.020	0.018		-0.002	0	0.002
Pumps	0.236	0.215	0.193		-0.021	0	0.021
Membrane Filtration	0.104	0.094	0.085		-0.009	0	0.009
Centrifuge	0.245	0.222	0.200		-0.022	0	0.022
Chiller	0.007	0.006	0.005		-0.001	0	0.001
Water	0.000	0.000	0.000		0.000	0	0.000
Diammonium phosphate (DAP)	0.052	0.048	0.043		-0.005	0	0.005
Ammonia (NH_3)	0.215	0.195	0.176		-0.020	0	0.020

Table A2 – Photobioreactor (PBR) calculations (kg CO_2e kg^{-1} biomass produced)

	+10% increase	**Calculated emissions**	**-10% Reduction**		**+10% increase**	**Normalized to zero**	**-10% Reduction**
Sparging	0.138	0.125	0.113		-0.013	0	0.013
Lights	0.579	0.526	0.474		-0.053	0	0.053
Membrane Filtration	0.019	0.017	0.015		-0.002	0	0.002
Centrifuge	0.044	0.040	0.036		-0.004	0	0.004
Chiller	0.007	0.006	0.005		-0.001	0	0.001
Water	0.000	0.000	0.000		0.000	0	0.000
Diammonium phosphate (DAP)	0.033	0.030	0.027		-0.003	0	0.003
Ammonia (NH_3)	0.211	0.192	0.173		-0.019	0	0.019