

Supporting Information

Life Cycle Energy and Carbon Footprints of Microalgal Biodiesel Production in Western Australia: A Comparison of Byproducts Utilization Strategies

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1. Review of Previous Life Cycle Analysis Studies

Table 1 in the main paper provides an overview on main considerations of previous life cycle analysis (LCA) studies. Most studies chose open raceway ponds as the algae cultivation system, using flue gas produced from fossil-fuel-fired power stations as the carbon source. Various harvesting and dewatering technologies, including flocculation, dissolved air flotation, centrifugation, and thermal drying, were considered to explore suitable technologies for concentrating microalgae slurry that is used in further downstream processes. Both dry and wet lipid extraction methods were investigated. One finding is that the dry lipid extraction consumes more energy than energy produced in biodiesel due to the energy-intensive drying process. The extracted lipid is mostly converted to biodiesel via transesterification. Anaerobic digestion was generally considered as a “standard” approach to recover energy and nutrients embedded in defatted microalgae after lipid extraction.

2. Model Overview

2.1 System Description

The system boundary is set as “Cradle-to-Gate”, considering the processes from microalgae cultivation to the production of biodiesel as a main product. In this study, the process chain refers to a conceptual system, considering the geographic and climate conditions in Western Australia (WA). Microalgae are cultivated in a race-way pond farm with an effective growth area of 100 ha on the coastal land in Karratha (~1500 km north of Perth in WA, see Figure S1). Karratha is selected as farm site for two main reasons. One is its long daily sunshine hours (10 hours, see Figure S2), which facilitates microalgae growth. The other is that there is a gas-fired power plant, Yurralyi Maya Power Station, nearby to provide CO₂. The microalgae is harvested and dewatered via a combination of auto-flocculation, dissolved air flotation, and centrifugation before being subjected to cell homogenization and wet lipid extraction. The extracted lipid (mainly triacylglycerols, TAG) is then converted to biodiesel via transesterification with methanol. Justifications and detailed description of each process are given in following sections.

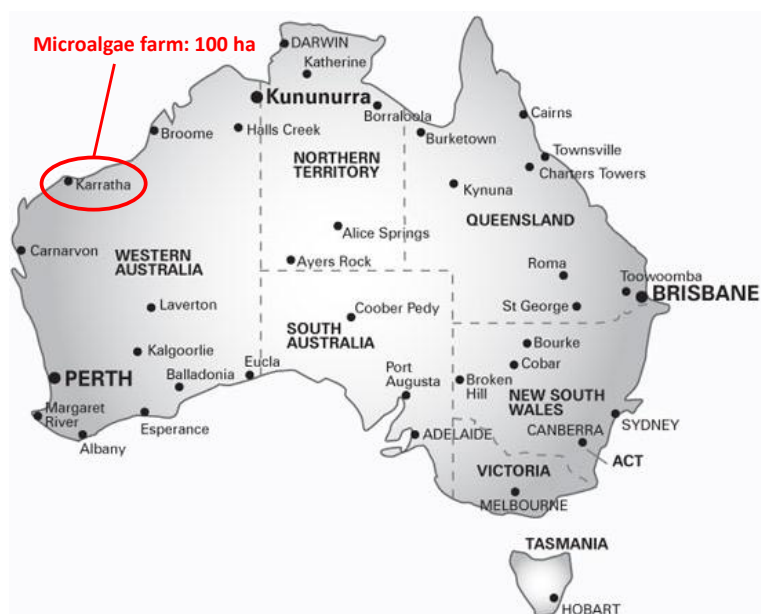


Figure S1. Location of microalgae farm studied (Karratha in Western Australia), with the map adapted from a website.¹

After transesterification, two main byproducts are produced, i.e., defatted microalgae and glycerol. While the main processes (including cultivation, harvesting and dewatering, lipid extraction, and transesterification) are identical, this study considers two scenarios for byproducts utilization in order to compare their ability in offsetting the overall life cycle energy and carbon footprints. One is byproducts utilization via anaerobic digestion (scenario A). The other is that via hydrothermal liquefaction (scenario B, see Figure 1 of the main paper). Scenario A anaerobically digests the defatted microalgae and glycerol to produce biogas for electricity and heat production. The anaerobic digestion supernatant rich in C, N, and P nutrients is recycled to the ponds for microalgae cultivation. Scenario B produces bio-oil, biochar, and aqueous phase via hydrothermal liquefaction of the defatted microalgae. The bio-oil is then mixed with the biochar and glycerol to produce a bioslurry fuel that is further transported and co-combusted in coal-fired power stations for electricity production. The aqueous phase rich in organic carbon and nutrients (N and P) is subjected to catalytic hydrothermal gasification for biogas production and nutrients recycling.

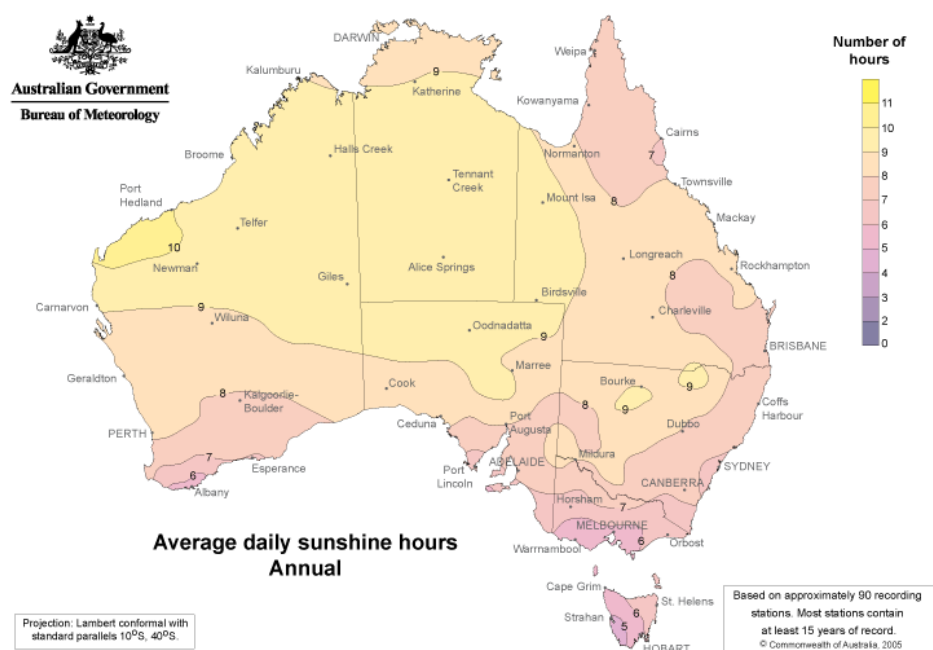


Figure S2. Average daily sunshine hours in Karratha (Port Hedland), Courtesy of Bureau of Meteorology, Commonwealth of Australia.²

2.2 Summary of Input Parameters

Input parameters (including those for the base, low and high cases) are determined based on the data available in the open literature and/or engineering calculations (see Table 2 of the main paper). The details are discussed in subsequent sections. Mass balance and energy flow diagrams for the main processes (from microalgae cultivation to transesterification) are given in Figures S3 and S4, respectively.

2.3 Functional Unit, Energy Footprint, and Carbon Footprint

The functional unit of this study is 1 MJ of biodiesel produced. The energy footprint is determined as total nonrenewable energy inputs per MJ of biodiesel produced (**MJ/MJ Biodiesel**). These nonrenewable energy inputs include direct energy inputs (e.g., process heat and electricity, etc.) and indirect energy inputs (e.g., fertilizers, process chemicals, and system infrastructure, etc.) involved in

the process chain. The carbon footprint is calculated based on the total direct and indirect greenhouse gases (GHG) emissions during biodiesel production. Three main GHGs (e.g., CO₂, CH₄, and N₂O) are considered in terms of their carbon dioxide equivalent (CO₂-eq), which is calculated by multiplying the estimated mass of emissions by their 100-year global warming potentials.³ The carbon footprint is thus expressed as **grams of CO₂-eq/MJ biodiesel**. It should be noted that CO₂ absorbed by microalgae cultivation is not considered as carbon credit because the amount of CO₂ will release to atmosphere after biodiesel combustion and byproducts utilization.⁴ The life cycle data used for calculating energy and carbon footprints are listed in Table S1.

The energy and carbon credits from byproducts utilization are calculated via substitution allocation method.⁵ Depending on the scenarios studied, co-products utilization can produce and thereby displace process heat, electricity and/or fertilizers. The energy and carbon credits from byproducts utilization are equal to the primary energy requirements and GHGs emissions associated with the production of the displaced process heat, electricity, and/or fertilizers.

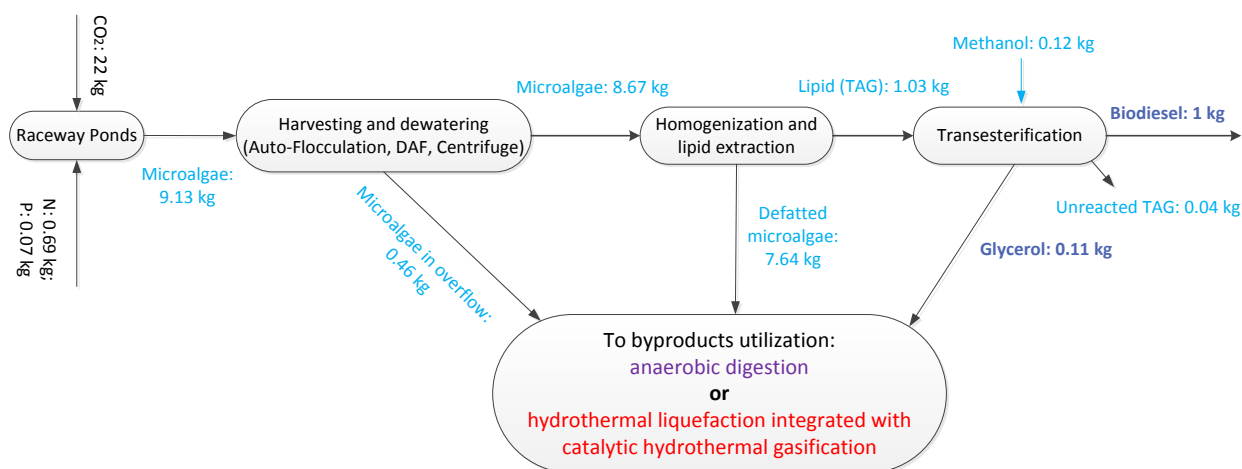


Figure S3. Mass balance of the main processes (from microalgae cultivation to transesterification) for producing 1 kg biodiesel (base case) at a net harvesting efficiency of 95% (resulting from the recycling microalgae in supernatant of auto-flocculation and DAF⁶)

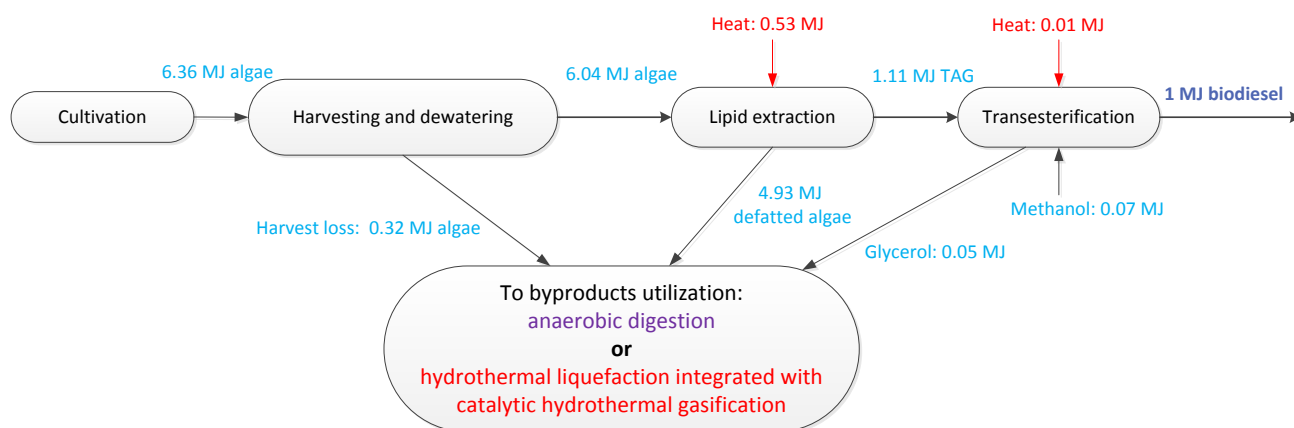


Figure S4. Process energy flow for producing 1 MJ biodiesel (base case).

Table S1. Energy and materials inputs data used to calculate the energy and carbon footprints in this study^a

Input items	Unit basis	Energy density ^b (MJ/Unit)	CO ₂ -eq emissions (kg CO ₂ -eq/Unit)
Electricity	kWh	10.37 ^c	0.78 ^c
Heat (from natural gas)	kWh	4.46 ^d	0.27 ^d
Diesel fuel (for transport)	Liter	47.76 ^e	3.49 ^e
Hexane	Kg	52.05	17.71
Methanol	Kg	39.67	0.65
KOH	Kg	42.33	0.69
NaOH	kg	42.33	0.69
H ₂ SO ₄	Kg	2.62	0.02
Process water	Kg	0.00925	0.00247
Al ₂ (SO ₄) ₃	kg	2.61	0.00051
Ammonium sulfate (as N)	Kg	41.8 ^d	2.69 ^d
Triple superphosphate (as P ₂ O ₅)	kg	25.7 ^d	2.01 ^d
Concrete	kg	0.95 ^f	0.13 ^f
Steel (recycle steel)	kg	31.3 ^f	2.07 ^f
Steel (stainless steel)	kg	34.21 ^f	2.21 ^f
High density polyethylene (HDPE)	kg	48.53 ^f	3.68 ^f
Polyvinyl chloride (PVC)	kg	47.2 ^g	2.0 ^g
Dollar-to-Energy or dolloar-to-carbon conversions	\$1 AUD-2009	4.58 ^h	0.419 ⁱ

^a Data taken from previous studies⁷⁻¹⁰ unless otherwise specified.

^b Energy density referring to the total accumulated nonrenewable energy embedded in a unit quantity of an item.

^c Based on the 2010-11 data on the normalized share of primary energy source (natural gas, coal etc.) for electricity generation in Western Australia¹¹ and the method described in GREET 1.8c.0 model.¹²

^d The data taken from Handler et al. (2012)¹³.

^e Data taken from Grant et al. (2008)¹⁴, considering the gross calorific value of diesel is 38.64 MJ/L.

^f Data taken from GREET 2.7 model.¹⁵

^g Data taken from Resurreccion et al. (2012).¹⁶

^h Based on a dollars-to-energy conversion factor for conversion of capital costs of process plant/equipment and labor costs into primary energy input as an indicator of Australian primary energy consumption per unit Gross Domestic Product (GDP) in 2009-10.¹⁷

ⁱ Estimated according to Australian net GHG emissions per unit Gross Domestic Product (GDP) in 2009-10.^{17, 18}

3. Microalgae Cultivation

3.1 Microalgae Strain, Productivity, and Properties

WA has a shortage of fresh water due to relatively dry climate⁴ whereas seawater is abundant. Therefore, marine microalgae strains are potential candidates for biodiesel production in WA. In this study, a marine microalgae, *Pleurochrysis carterae*, is selected for two reasons. One is its high total lipid yield of ~21.9 ton/ha/year¹⁹. The other is that it has been successfully cultivated by Moheimani and Borowitzka¹⁹ in outdoor raceway ponds in a semi-continuous mode in WA over a whole year.

Data on the areal growth rate ($\text{g/m}^2/\text{day}$, dry basis) and specific growth rate (day^{-1}) of the microalgae are taken from Moheimani and Borowitzka 2006¹⁹ and presented in Figure S5. In a semi-continuous cultivation mode, the areal growth rate determines the microalgae mass productivity while the corresponding specific growth rate determines its daily harvest ratio of pond volume. In order to harvest microalgae at exponential growth phase, 50% of the cultivation volume needs to be daily harvested at a rate equal to the specific growth rate.²⁰ For instance, a specific growth rate of 0.5/day requires a daily harvest rate of 25% ($50\% \times 0.5$) of the total pond volume.

In this study, an annual average areal growth rate of $22 \text{ g/m}^2/\text{day}$ is used as the base case value. The average of growth rate from April to September ($10 \text{ g/m}^2/\text{day}$, see Figure S5) is taken as the low case value while a high areal growth rate of $34 \text{ g/m}^2/\text{day}$ is used the high case value. The corresponding specific growth rates (base case: 0.38 day^{-1} ; low case: 0.2 day^{-1} ; high case: 0.58 day^{-1}) are used to determine the daily harvest rate at a given areal growth rate. The base case value of the daily harvest rate is thus calculated as 19% ($50\% \times 0.38$) of the total pond volume. Its low case and high case values are 10% ($50\% \times 0.2$) and 29% ($50\% \times 0.58$), respectively. Such daily harvest rates agree well with that ($\sim 15\text{-}33\%$) proposed by Benemann et al.²¹ Given the daily harvest rate (19% of the pond volume) and the corresponding areal productivity, it is estimated that the culture density during harvesting is $\sim 0.38 \text{ g/L}$, in consistence with the conditions achieved in ponds in WA.¹⁹

Table S2 lists the properties of *Pleurochrysis carterae* considered in this study. It should be noted that the lipid content reported by Moheimani et al. (2006) is the total lipid that includes both polar and neutral lipids. Practically, only the neutral lipid, which contains mainly triacylglycerols (TAG), can be suitably extracted and then converted to biodiesel via transesterification. Unfortunately, for marine microalgae that are considered to be most suitable for the conditions in Western Australia,¹⁹ there are no data reported on its lipid profile in open literature.

Therefore, a review was then carried out to collect information on the TAG contents in the total lipids of various microalgae in the literature. Williams and Laurens²² summarized the TAG contents reported in 46 studies. They reported that the TAG contents are in the range of 7-68 wt% of the total lipid. Chen et al.²³ found that $\sim 65\text{-}69 \text{ wt\%}$ of the total lipid is TAG. It was also reported that under special cultivation conditions, the TAG content can be as high as 80% of the total lipid.²⁴ Therefore, a mean value of 40% (average from 7 to 80%) is set as the value used in the base case, in consistence with that used by Murphy and Allen (2011).²⁰ In addition, it is also known that at a TAG fraction $< 30\%$ of the total lipid (equal to $36.5\% \times 30\% = 10.95\%$ of dry microalgae mass), the microalgae are no longer suitable for biodiesel production due to low productivity and poor economic performance.⁶ Therefore, a TAG content of 30% is set as the value in the low case in this study. Also, considering that further R&D may improve the TAG content in the total lipid, a TAG content of 90% is then set as the value used in the high case. In summary, the TAG contents used in this study are $36.5\% \times 40\% = 14.6\%$ (base case), $36.5\% \times 30\% = 11\%$ (low case) and $36.5\% \times 90\% = 33\%$ (high case), on a basis of the dry mass of microalgae.

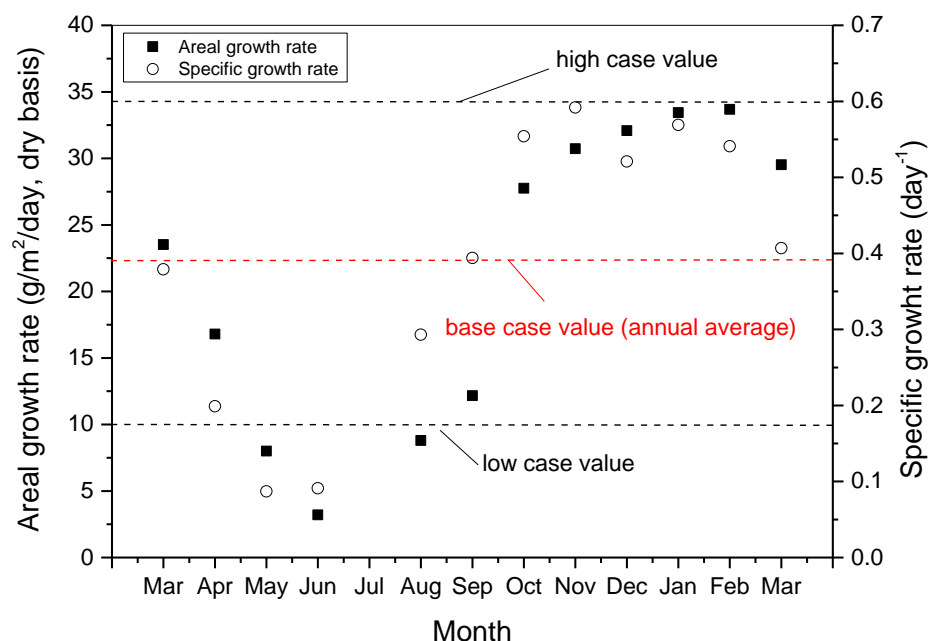


Figure S5. Areal and specific growth rates of *Pleurochrysis carterae*. Data are taken from Moheimani et al. (2006).¹⁹

Table S2. Properties of *Pleurochrysis carterae*

Composition	Value	Source
Ash content ^a , wt%, dry basis (db)	8.6	Moheimani et al. (2006) ¹⁹
Total Lipid (C ₄₀ H ₇₄ O ₅) ^b , wt%, db	36.5 ^c	Moheimani et al. (2006) ¹⁹
TAG content (wt% of total lipid)	40% (base case)	
Protein (C _{4.43} H ₇ O _{1.44} N _{1.16}) ^b , wt%, db	32.9 ^d	
Carbohydrate (C ₆ H ₁₂ O ₆) ^b , wt%, db	22.0 ^d	
Carbon (C) content ^e , wt%, db	54.0	
Hydrogen (H) content ^e , wt%, db	8.1	
Molar ratio of C:N:P	175:21:1	Williams et al. (2010) ²²
Higher heating value (HHV), MJ/kg (db)	25.9 ^f	

^aThe average mass percentage of calcium carbonate reported in Moheimani et al. (2006)¹⁹ is considered as ash content. ^b The formulas of lipid, protein, and carbohydrate are taken from Lardon et al. (2009)²⁵. ^c It is the average lipid content for a culture period of 12 months in WA, as reported in Moheimani et al. (2006)¹⁹. ^d The total amounts of protein and carbohydrate are calculated by difference, assuming the microalgae studied only contains ash, lipid, protein, and carbohydrate. The content of protein and carbohydrate is then estimated by assuming their mass ratio of 3:2. ^e C and H contents are calculated based on contents and formulas of lipid, protein, and carbohydrate. ^f HHV is calculated based on Dulong's formula: HHV (MJ/kg) = 0.338 × C + 1.428 × (H - O/8), where C, H, and O are mass percentage based on dry microalgae mass while O content is calculated by difference.

3.2 Cultivation System

Open raceway pond is selected as cultivation system in this study as it is more suitable for mass production of microalgae than photobioreactors (PBRs).^{26, 27} The cultivation system, including growth ponds and inoculation ponds, are designed based information reported by Lundquist et al.²⁸ Briefly, a single pond has a useful cultivation area of 4 ha (length: 690 m; width: 60 m) and is designed to hold cultivation water at a depth of 0.3 m. The whole farm consists of 25 cultivation ponds (4-ha scale), leading to a total cultivation area of 100 ha. The inoculation system is composed of three cultivation stages. The first stage is lab-scale photobioreactors that are excluded in this study as its life cycle burdens are small and can be neglected.²⁸ The second and final stages are open raceway ponds with cultivation areas of 1 ha (1% of the farm area) and 10 ha (10 % of the farm area), respectively. Both the inoculation ponds and growth ponds are built with earth berms and lined with high density polyethylene (HDPE). Detailed material required for ponds construction are given in Section 6.

3.3 Water Balance

3.3.1 Overview

Sea water is used to cultivate the microalgae. The water balance is calculated based on the approach reported by Murphy and Allen.²⁰ A schematic diagram of water movement is given in Figure S6, which is used to determine the amount water circulated among the cultivation ponds and settling ponds as well as new water taken from the sea. Table S3 summarizes the water balance for base case study. Detailed calculation methods are given in Section 3.3.2 and Section 3.3.3, respectively.

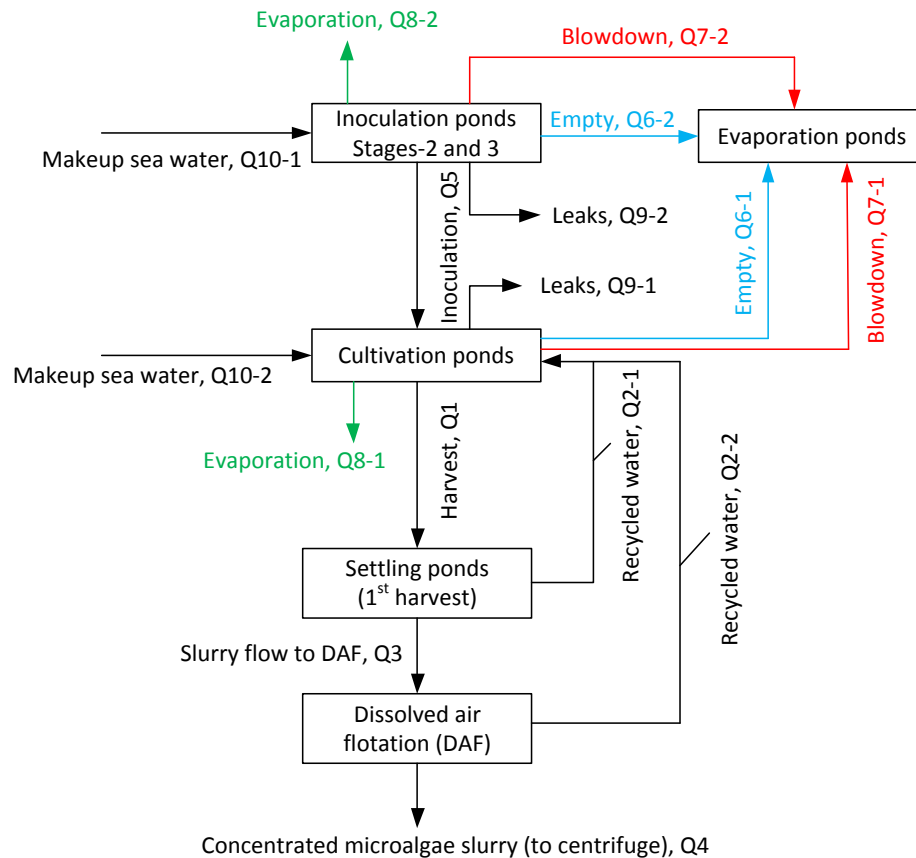


Figure S6. Schematic diagram of water movement.

Table S3. Water movement during microalgae cultivation and harvest (base case: daily harvest rate is 19% of the total pond volume, operating 330 days/year), calculated based on the approach reported by Murphy and Allen.²⁰

Water flow	Base case value (m ³ /m ² /year)	Water source
Daily harvest from cultivation ponds to settling ponds, Q1	18.81	On-site ponds
Recycled water from settling ponds to cultivation ponds, Q2-1	18.08	On-site ponds
Recycled water from DAF to cultivation ponds, Q2-2	0.60	On-site ponds
Slurry flow from settling ponds to DAF, Q3	0.73	On-site ponds
Slurry flow to centrifuge, Q4	0.12	On-site ponds
Water from inoculation ponds to cultivation ponds, Q5	1.88 ^a +0.19 ^b	On-site ponds
Flush cultivation ponds, Q6-1 (2 times/year)	0.60	On-site ponds
Refill cultivation ponds (2 times/year)	0.60	Off-site, from the sea
Flush inoculation ponds, Q6-2 (4 times/year)	0.12	On-site ponds
Re-fill inoculation ponds (4 times/year)	0.12	Off-site, from the sea
Blowdown flow from cultivation ponds, Q7-1	0.46	On-site ponds
Blowdown flow from inoculation ponds, Q7-2	0.05	On-site ponds
Evaporated water loss in cultivation ponds, Q8-1	3.30	
Evaporated water loss in inoculation ponds, Q8-2	0.33	
Water leaks from cultivation ponds, Q9-1	0.36	
Water leaks from inoculation ponds, Q9-2	0.04	
Makeup water to cultivation ponds, Q10-1	4.25	Off-site, from the sea
Makeup water to inoculation ponds, Q10-2	2.30	Off-site, from the sea

^a 10% of harvested volume (10% x Q1) is pumped from 3rd stage inoculation ponds to cultivation ponds. ^b 1% x Q1 of cultivation water is transported from the 2nd inoculation ponds to the 3rd ones, which is not shown in Figure S6.

3.3.2 On-site Water Circulation

As shown in Table S3, except the makeup water and refill water streams that are newly taken from the sea, all other water streams are circulated within the cultivation farm. In a semi-continuous operation mode, harvesting is generally arranged at night in order to maximize effective growth hours of microalgae.²⁰ The average sunshine time in Karratha (Pord Hedland) is 10 hours (see Figure S2). Thus, the harvesting time is set at 13 hours in total at night. Six hours are spent to pump water from the cultivation ponds to the settling (harvest) ponds. After settling in the harvest ponds for 1 hour, water is pumped back to the cultivation ponds in 6 hours while the concentrated microalgae flow is transported to the next dewatering stage. This study considers an operating time of 330 days/year. For the base case, 19% (Q1) of the pond volume ($Q_{\text{pond}} = 100 \text{ ha} \times 10000 \text{ m}^2 \times 0.3 \text{ m}$) is daily harvested based on the specific growth rate (see Section 3.1). The amount of water (Q2, including Q2-1 and Q2-2 in Figure S6) that can be recycled back to the cultivation ponds is determined by the concentration of the microalgae slurry after harvest and the harvest efficiency (see Section 4.1). The microalgae slurry flow rates after dissolved air flotation (Q3) and centrifuge (Q4) are calculated similarly.

According to Murphy and Allen,²⁰ the flow rate from inoculation ponds (3rd stage) is set as 10% of Q1. The flow rate from the 2nd stage of the inoculation ponds to the 3rd ones is 1% of Q1. Thus, the total flow rate (Q5) is 11% of Q1 (see Figure S6). The new water required by the inoculation ponds is taken from the sea. The cultivation ponds and inoculation ponds are also annually flushed 2 and 4 times, respectively, in order to control cultivation circumstance. After flushing, all the ponds are refilled by sea water that is transported from the sea off-site. For marine microalgae, purging a portion of cultivation media (blowdown) is required to control the salinity of the sea water. Salt accumulation in the cultivation media is mainly caused by evaporation loss. Therefore, according to Weissman and Goebel,¹ the blowdown flow rate (Q7, including Q7-1 and Q7-2) is 14% of evaporation loss (Q8, including Q8-1 and Q8-2) that is determined by pond surface area and local evaporation rate (0.01 m/day).² According to Murphy and Allen,²⁰ the water leak from the cultivation ponds and inoculation ponds is taken as $0.0011 \text{ m}^3/\text{m}^2/\text{day}$.

Once the total water flow rate (Q_{total}) that needs to be daily pumped is determined, the power required for water pumps (P, kW) can be calculated by Equation S1.

$$P = \frac{\frac{\rho g Q H_t}{\eta}}{1000} \text{ kW} \quad \text{Equation S1}$$

where ρ =density of sea water, $1025 \text{ kg}/\text{m}^3$

Q_{total} =water flow rate, m^3/s

H=water head loss, assumed to be 6 m.⁶

η =overall pump efficiency, 67.5%, considering pump efficiency of 75% and motor efficiency of 90%.

3.3.3 Off-site Water Supply from Sea to Microalgae Farm

Sea water is taken via a floating pontoon intake pump station and then transported to a store canal on microalgae farm via HDPE pipeline (ID: 0.88 m; Length: 5 km as base case value). The amount of sea water daily required is calculated as $Q_{10}+Q_6$, i.e., only makeup water and refill water streams are pumped from the sea off-site. The makeup water is estimated as $Q_{10}=Q_1-Q_2+Q_7+Q_8+Q_9$ (see Figure S6). For the base case of this study, the amount of sea water (Q_{sw}) to be transported from the sea to the farm is $22,009 \text{ m}^3/\text{day}$. The current design considers a pumping time of 6 hours, leading to a flow rate of $3,668 \text{ m}^3/\text{h}$ ($1 \text{ m}^3/\text{s}$).

During sea water transport, the total head loss is contributed by three main sources: (1) the elevation change from the sea level to the storage canals, taken as 5.2 m;²⁹ (2) the dynamic loss and loss in pump station, taken as 2 m;²⁹ and (3) the head loss in transport pipeline. Because the storage canal is designed at a higher level than the cultivation ponds, water can be distributed to the ponds via gravity, i.e., no further pumping is required once the sea water is transported to the storage canal.

The head loss in straight pipes can be estimated as:³⁰

$$H_L = \lambda \times \frac{L}{d} \times \frac{v^2}{2g} \quad \text{Equation S2}$$

where λ is the pipe friction factor; L is the length of pipeline, m; d is the inner diameter of pipeline, m; v is the velocity of water flow, m/s; and g is the acceleration of gravity, 9.8 m/s².

The pipe friction factor (λ) can be calculated via Equation S3:³⁰

$$\lambda = 0.309 / \left(\lg \frac{Re}{7} \right)^2 \quad \text{when } 2320 < Re < 10^8 \quad \text{Equation S3}$$

The Reynolds' number (Re) can be calculated by Equation S4:³⁰

$$Re = v \times d / \kappa \quad \text{Equation S4}$$

where κ is kinetic viscosity of water at 20 °C, 1×10^{-6} m²/s

The power required is calculated by Equation S1 at a pump efficiency of 67.5%.

3.4 Paddle Wheel Mixing

The power required for paddle wheel mixing is estimated based on a method described by Lundquist et al. (2010)²⁸. The hydraulic power requirement (W_{PW} , Watts) of the paddle wheel can be calculated via equation S5:

$$W_{PW} = 9.8 \times \left(\frac{Q\rho h}{\eta_{PW}} \right) \quad \text{Equation S5}$$

where, Q is the volumetric channel flow rate (m³/s), ρ is the density of sea water (1,025 kg/m³), h is the total head loss (m), and η_{PW} is the efficiency of paddle wheel (40%).

Three mixing head losses are considered in this study, i.e. the head loss in the 180° bends at both ends of the pond (h_b), head loss through the two counter-current carbonation sumps (h_s), and the channel straightway head loss due to friction of the pond bottom (h_c). All these head losses can be estimated with Manning's equations:³⁰

$$h_b = \frac{Kv^2}{2g} \quad \text{Equation S6}$$

$$h_c = v^2 n^2 \left(\frac{L}{R^{4/3}} \right) \quad \text{Equation S7}$$

$$h = h_b + h_s + h_c \quad \text{Equation S8}$$

where, v is the mean velocity of the cultivation media, 0.25 m/s; g is the acceleration of gravity, 9.8 m/s²; K is the kinetic loss coefficient for 180° bends (theoretical value is 2); n is Manning's

roughness coefficient, 0.01 for HDPE plastic surface; R is the hydraulic radius of channel (m); L is channel length (m). h_s is also calculated from Equation S6, which is 0.025 m in this study. At a mixing time of 24 h per day, the power requirement for paddle wheel mixing is 26.6 kWh/ha/day for the 100-ha system analyzed.

3.5 Carbon Dioxide

The amount of CO₂ required is estimated as ~2.4 kg CO₂/kg dry microalgae based on the carbon content of the microalgae, considering a CO₂ utilization efficiency of 82%. CO₂ is supplied from the Yurralyi Maya Power Station (180 MW, gas-fired) near the farm (at a distance of 5 km in the base case). A review by Rubin et al. (2007)³¹ suggested that CO₂ emitted from a typical gas-fired power plant is ~344-379 kg CO₂/MWh so that an average value (367 kg CO₂/MWh) is considered in this study. The daily CO₂ emission from the power plant is therefore ~1600 ton/day at 100% load. Given the microalga growth rate (22 g/m²/day) and CO₂ utilization efficiency, the farm (100 ha) in this study requires 53 ton CO₂/day. Therefore, the power plant can supply sufficient amount of CO₂ to the microalgae farm.

A low-pressure pipeline transport method is employed due to its lower energy cost compared to other methods such as pressurized pipelines, supercritical pipelines, and bottle CO₂ transport.⁶ The CO₂-containing flue gas is transported from the power station via HDPE pipelines to the farm site at an outlet pressure of 1 atm. It is recompressed via a compressor in order to be transferred into CO₂ sumps in the cultivation ponds. The CO₂ sump station is designed according to Lundquist et al.²⁸ The CO₂ concentration in the flue gas produced from a gas-fired power plant is ~8.7% after cooling and removing water in the flue gas.³² The power requirement to transport flue gas from the power station to farm site and to transfer flue gas into ponds is estimated based on a method presented in Frank et al. (2011).³³ It is briefly summarized as follows.

- **Overview**

The power requirements for delivering CO₂ can be estimated in three steps:

- (1) The amount of required flue gas is computed by considering CO₂ demands in ponds and the volume fraction of CO₂ in flue gas;
- (2) Given several key input data, the pressure drop of transporting flue gas can be estimated by Fanning equation; and
- (3) The power requirements for CO₂ delivery (i.e., transport from the power plant to the microalgae farm and transfer to cultivation ponds) are finally calculated based on the pressure drop and assumed efficiency of motor and compressor.

- **Input data**

- (1) Volume fraction of flue gas : 8.7%;³²
- (2) Density of flue gas: 1.3 kg/m³;³³
- (3) Distance between the gas-fired power station (CO₂ source) and the microalgae farm: 5 km (designed in the base case);
- (4) Pipeline inner diameter: 1 m (designed in the base case);
- (5) Pipeline absolute roughness coefficient: 0.0015 mm (HDPE plastic pipe).³⁴

- **Calculation of the pressure drop (ΔP) using Fanning equation**

The pressure drop during CO₂ transport in the pipeline can be estimated with the Fanning equation:

$$\Delta P = 4f(\rho v^2/2)(L/D)$$

Equation S9

where, f is Fanning friction factor; ρ is flue gas density, 1.3 kg/m³; v is the velocity of flue gas in the pipeline (m/s); L is the length of pipeline (m); D is pipeline diameter (m).

The Fanning friction factor can be calculated using the following equations:³⁵

$$f = 2 \left[\left(\frac{8}{Re} \right)^{12} + \left(\frac{1}{(A+B)^{3/2}} \right) \right]^{(\frac{1}{12})}$$

Equation S10

$$A = \left\{ 2.457 \ln \left[\frac{1}{\left(\frac{7}{Re} \right)^{0.9} + 0.27 \left(\frac{\varepsilon}{D} \right)} \right] \right\}^{16}$$

Equation S11

$$B = \left(\frac{37530}{Re} \right)^{16}$$

Equation S12

$$Re = \frac{\rho v D}{\mu}$$

Equation S13

where, Re is the Reynolds number; ε is the pipeline absolute roughness, 0.0015 m; μ is the dynamic viscosity of flue gas, 0.0000158 Pa·s.

- **Estimation of electricity requirements (P_{total}) for CO₂ delivery**

The total electricity requirements (P_{total}) for CO₂ delivery is computed with the following equation:

$$P_{total} = P_{transport} + P_{transfer}$$

Equation S14

where, $P_{transport}$ is the power requirement to transport CO₂ from the power plant to the microalgae farm cite; $P_{transfer}$ is the power requirement to transfer CO₂ into the cultivation ponds via CO₂ sumps.

$$P_{transport} = P_0 k / (k - 1) \left[\left(\frac{P_0 + \Delta P}{P_0} \right)^{\frac{k-1}{k}} - 1 \right] / \eta$$

Equation S15

where, P_0 is the outlet pressure of flue gas transport pipeline, 101,325 Pa; k is a ratio of specific heat of flue gas, which is 1.395; η is the combined efficiency (50%) of motor and compressor.

$P_{transfer}$ is also estimated using Equation S15, assuming the pressure drop of delivering CO₂ into the culture media is 1 m water equivalent.²⁸ The gas diffuser pressure drop is taken to be 6895 Pa.⁶ Finally, the total electricity requirement for CO₂ transport and transfer is estimated as 41.4 kWh/tonne CO₂, the majority of which is consumed for transferring CO₂ into the cultivation ponds. This power consumption is higher than that of transporting CO₂ from coal-fired power plants because the CO₂ concentration in the coal-fired flue gas is considerably higher (~15%).

The recycled carbon (gaseous CO₂ and/or carbon in digested liquid) is also introduced to the cultivation ponds to reduce the flue gas CO₂ demands. For the anaerobic digestion route, CO₂ in biogas and that produced from biogas combustion are injected into the cultivation ponds to save electricity consumed for transporting flue gas CO₂. After anaerobic digestion, the carbon dissolved in digested liquid (see Section 5.2) is also recycled to the cultivation ponds at a 100% utilization efficiency.¹ For the hydrothermal liquefaction route, the recycled carbon includes CO₂ produced from hydrothermal liquefaction and biogas combustion. The concentration of CO₂ in the gas phase during hydrothermal liquefaction is taken to be 100% (see Section 5.3). The CO₂ concentration in the flue gas after biogas combustion is taken to be same as that in flue gas from the power plant (i.e. 8.7 vol%). It should be noted that, with the presence of CO₂ in biogas, the CO₂ concentration in the recycled flue

gas should be higher. Overall, recycling part of carbon to the cultivation ponds reduces the demands of flue gas CO₂ from the power plant. This study does not consider the upstream burdens of flue gas CO₂. Based on the electricity consumed for flue gas delivery, the effect of carbon recycling on the overall life cycle performance is insignificant. The reason is that recycling carbon only saves electricity consumed for flue gas CO₂ transport (from the power plant to the farm), which contributes less to the total electricity consumed on CO₂ delivery.

3.6 Nutrients

Nutrients considered in this study are nitrogen (N) and phosphorus (P). The demands of nutrients during microalgae growth are stoichiometrically calculated via molar ratio of C:N:P (175:21:1) of microalgae,²² at a fertilizer utilization efficiency of 100%. The nutrient elements N and P are provided by ammonium sulfate and triple superphosphate which have lower energy and carbon footprints than other fertilizers.¹³ During byproducts utilization (i.e., anaerobic digestion and hydrothermal liquefaction), part of nutrients can be recovered, reducing fertilizer demands. This will be discussed in Section 5.

4. Downstream Processes

4.1 Harvesting and Dewatering

A three-step harvesting and dewatering process, including auto-flocculation, dissolved air flotation (DAF), and centrifugation, is considered in this study. Both dissolved air flotation³⁶ and centrifugation³⁷ are matured technologies for liquid-solid separation and are therefore selected in this study. The microalgae slurry from the ponds is firstly sent to settling ponds to concentrate to 10 g/L via auto-flocculation. It is further concentrated to 60 g/L via DAF before being subjected to the centrifugation that concentrates the microalgae slurry to 150 g/L.³⁸ The microalgae harvest efficiency of the auto-flocculation, DAF, and centrifugation is assumed to be 90%, 90%, and 95%.⁶ However, supernatants after the auto-flocculation and DAF are eventually recycled to the cultivation ponds. Thus, microalgae in the supernatants are not considered as loss. As suggested by Davis et al.⁶, this study also considers an overall microalgae harvest efficiency of 95% that is optimistic. The electricity consumption of the DAF is 0.07 kWh/m³ microalgae slurry.³⁹ The electricity consumption for centrifugation is calculated as follows. A self-cleaning disc-stack centrifuge (model: GEA Westfalia SSE 400), which has a maximum process capacity of 85 m³/h and a motor rating of 75 kW, is selected. At a process operation capacity of 80%, the slurry flow rate is 68 m³/h. The electricity consumption is thus 1.1 kWh/m³ of slurry.

4.2 Homogenization and Wet Lipid Extraction

Although wet lipid extraction process has not been demonstrated at an industrial scale, it has great potential and hence is considered in this study. A pressure homogenizer is firstly used to break microalgae cells to make the TAG accessible to solvent extraction. After two passes, a homogenization efficiency of 90% can be achieved.³⁸ The recovery rate of dry microalgae in the homogenization process is assumed to be 95 wt%.²⁷ The electricity demand for the homogenization process is 67 MJ/m³ of microalgae slurry treated per pass.²⁷

The solvent extraction process is adopted from a previous study.³⁸ Briefly, the disrupted microalgae cells are extracted with hexane using a liquid-liquid extraction column. The water and spent microalgae are then separated from the solvent and oil phase in a disc stack centrifuge, with 5% loss of lipid in the water phase. The solvent is recovered from lipid oil phase and recycled using a stripping

column.⁶ A gross solvent to biomass mass ratio of 5:1 is used to ensure proper mixing. A net solvent loss is estimated to be 5.2 g/kg of lipid extracted.³³ The process heat and electricity requirement for lipid extraction process are 3.09 and 0.069 kWh/kg of lipid extracted, respectively.⁶

4.3 Transesterification

The extracted lipid is mixed with methanol using KOH as a catalyst to produce biodiesel via transesterification. The biodiesel yield is calculated to be 972.6 kg/ ton of lipid, with a density of 0.88 kg/L.³⁶ The lower heating value of the biodiesel is 37.2 MJ/kg.²⁷ Crude glycerol is produced as a byproduct of the transesterification process, at an estimated yield of 104.3 kg/ton of lipid. A typical process of the designed transesterification plant is summarized in Table S4.

5. Byproducts Utilization

There are two main Byproducts from the whole process (from the microalgae cultivation to the biodiesel production). One is the defatted microalgae plus the raw microalgae lost during centrifugation and homogenization. This stream is referred as “spent microalgae” hereafter. Specifically, the defatted microalgae may include no-lipid fractions (i.e., protein, carbohydrate, and ash) and lipid in forms other than TAG. The other is the glycerol produced from transesterification. Its lower heating value is 17 MJ/kg.⁷ While the main stream processes remain unchanged, this study investigates two byproducts utilization scenarios, i.e., the anaerobic digestion and the hydrothermal liquefaction, to assess their ability in offsetting the total energy and carbon footprints. Details of each byproducts utilization scenario are discussed in Section 5.1 and Section 5.2, respectively.

Table S4. Typical process parameters of a microalgal lipid transesterification plant ^a

General parameters

Processing capacity: 2 ML of microalgal lipid/year

Plant operating days per year: 330 days/year

Plant’s service time: 30 years

Temperature of transesterification reaction: 60 °C

Product yields

Biodiesel: 972.6 kg biodiesel/ton microalgal lipid

Glycerol: 104.3 kg glycerol/ton microalgal lipid

Main chemicals consumed

Methanol: 119.5 kg/ton microalgal lipid

Potassium hydroxide (KOH): 10.0 kg/ton microalgal lipid

Sulfuric acid (H₂SO₄): 5.2 kg/ton microalgal lipid

Aluminium sulphate (Al₂(SO₄)₃): 0.02 kg/ton microalgal lipid

Energy consumed

Electricity: 35.8 kWh/ton microalgal lipid

Process heat: 378.1 MJ/ton microalgal lipid

^a Estimated based on a method adapted from that reported in a previous study.⁷

5.1 Properties of Byproducts Stream

Table S5 lists key properties of spent microalgae stream that is subjected to anaerobic digestion or hydrothermal liquefaction. For the anaerobic digestion route, all spent microalgae streams (including supernatant from centrifuge, lost microalgae from homogenization, and defatted microalgae) are directly mixed with glycerol, which results in an estimated total solid concentration of 5.0 wt%. The solid concentration is suitable for anaerobic digestion.⁶ With respect to the hydrothermal liquefaction route, the supernatant from centrifuge is concentrated again by centrifugation before being mixed with the other two streams. The resulted solid concentration is estimated as 11.5%, within the range of 10-20% that is considered to be suitable for hydrothermal liquefaction. This study considers no nutrients (N and P) loss during lipid extraction.

Table S5. Properties of spent microalgae stream for byproducts utilization (base case)

Items	Anaerobic Digestion ^a	Hydrothermal liquefaction
Stream volume, m ³ /day	366.7	146.3
Total dry solid mass flow rate, tonnes/day	19.8	19.5
Total solid concentration, wt%	5.0	11.5
Ash, tonnes/day	1.9	1.9
Carbon (C), tonnes/day	10.1 (51.1 wt% ^b)	10.0 (51.2 wt% ^b)
Hydrogen (H), tonnes/day	1.5 (7.6 wt% ^b)	1.5 (7.6 wt% ^b)
Nitrogen (N), tonnes/day	1.7 (8.4 wt% ^b)	1.7 (8.5 wt% ^b)
Phosphorus (P), tonnes/day	0.2 (0.9 wt% ^b)	0.2 (0.9 wt% ^b)
Higher heating value (HHV), MJ/kg (db)	24.1 ^c	24.1 ^c

^a Including co-digestion of glycerol. ^b on a dry basis. ^c Calculated based on Dulong's formula: HHV (MJ/kg) = 0.338 × C + 1.428 × (H-O/8), where C, H, and O are mass percentage based on dry microalgae mass and the O content is calculated by difference.

5.2 Anaerobic Digestion Scenario

In the anaerobic digestion scenario, the spent microalgae and glycerol are anaerobically co-digested at 35 °C with a retention time of 20 days.⁶ Glycerol co-digestion has potential benefits of achieving optimized C/N ratio in a digester for increasing biogas yield.⁴⁰

5.2.1 Methane (CH₄) Yield and Biogas Composition

A previous study estimated the theoretical CH₄ yield during anaerobic digestion.⁴¹ However, theoretical CH₄ yield is often higher than actual value because only part of organic carbon can be digested. Therefore, a practical approach is to statistically evaluate CH₄ yield reported in the literature. As shown in Figure S7, the CH₄ yields are generally in a range of 0.2-0.3 L CH₄/g total solid (TS). Therefore, a CH₄ yield of 0.3 L/g TS (in consistence with other studies^{6,38}) is used in the base case while a low case yield of 0.1 L/g TS and a high case yield of 0.4 L/g TS are used for sensitivity analysis. CH₄ yield of from glycerol digestion is estimated as 0.3 L CH₄/g glycerol.⁴²

A review on biogas composition suggests that average CH₄ volumetric fraction is 67 vol% (see Figure S8). To simplify the system studied, this study considers the biogas composition of 67 vol% CH₄ and 33 vol% CO₂. Based on methane yield, biogas composition, and carbon content in the TS, ~50% of carbon in the TS is converted to the biogas. The remaining carbon is evenly distributed between digested liquid and solid residue.¹ The carbon in digested liquid is recycled back to the cultivation ponds after solid-liquid separation (via centrifugation). A mass balance diagram is shown in Figure S9.

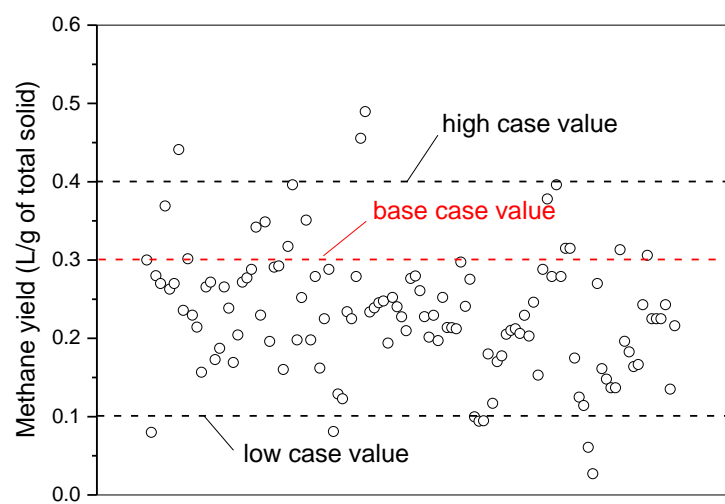


Figure S7. Methane yields at standard conditions (0 °C and 1 atm) reported in some previous studies,^{6, 28, 29, 40, 43-57} assuming 90% of total solids (TS) are volatile solids (VS)

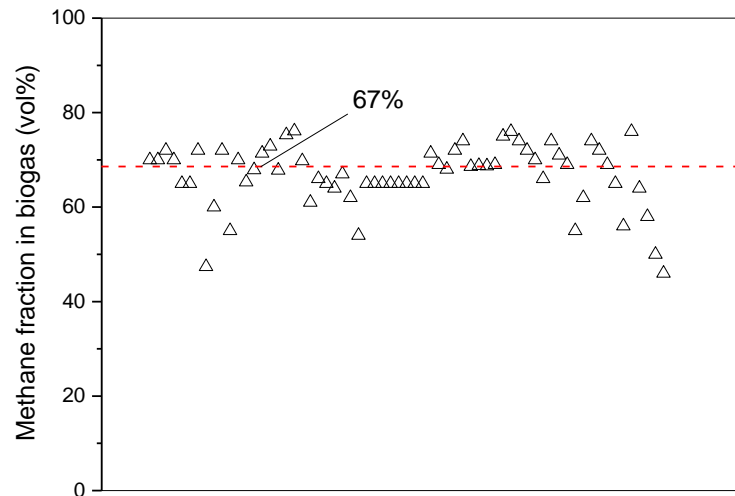


Figure S8. Volume fraction of methane in biogas reported in some previous studies.^{6, 28, 29, 40, 45-51, 58}

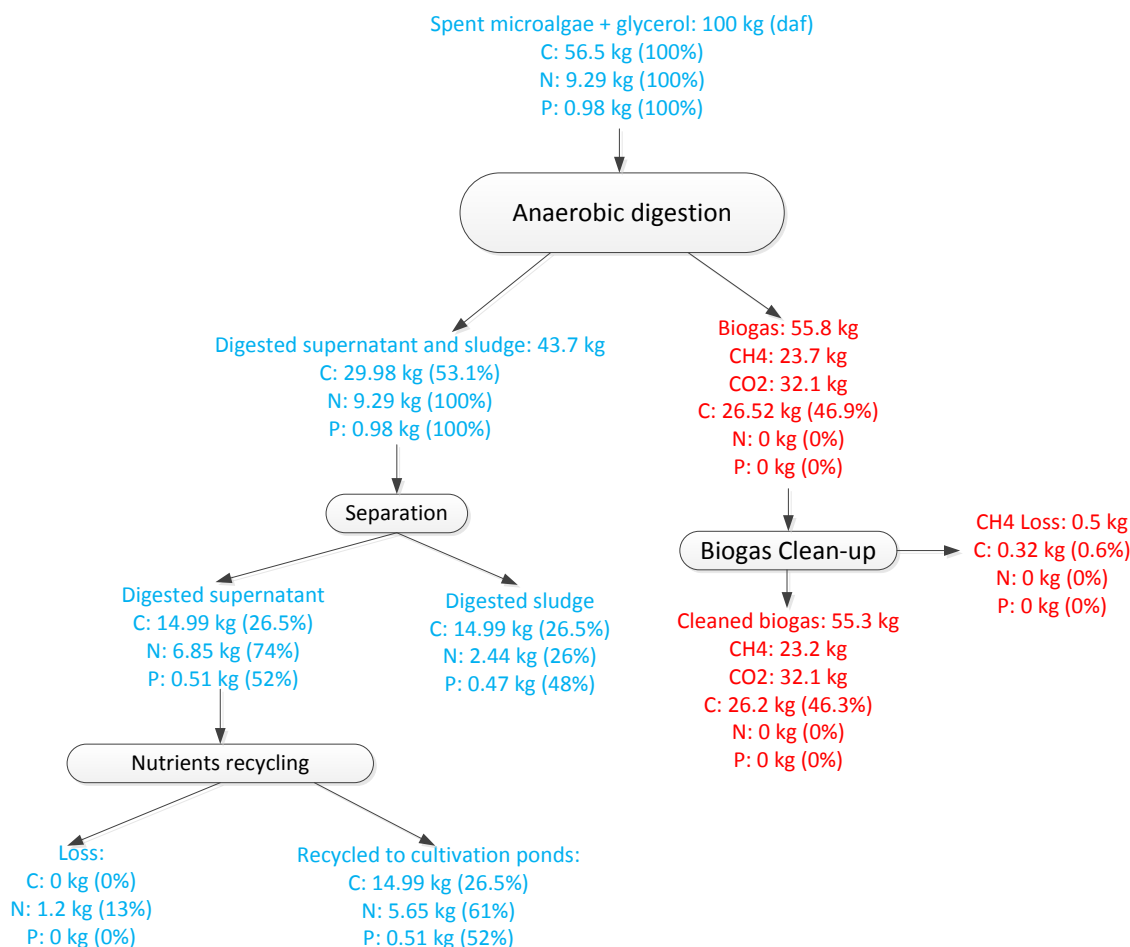


Figure S9. Mass balance of key nutrients during anaerobic digestion (base case).

5.2.2 Biogas Cleanup and Utilization

The raw biogas is cleaned to remove impurities (e.g. H_2S and dust) prior to combustion in a combined heat and power (CHP) unit.³³ The lower heating value of upgraded CH_4 is 50 MJ/kg. Based on the GREET 1 2012 model,⁵⁹ electrical efficiency is taken as 33%, with a total CHP efficiency of 76% for the base case scenario. A sensitivity analysis is conducted for electrical efficiency (28%-38%).

5.2.3 Energy Inputs

The process heat and electricity required for anaerobic digestion are 0.22 and 0.085 kWh/kg of total solid,⁶ respectively. The electricity consumption for biogas cleaning process is 0.25 kWh/m³ of raw biogas upgraded.³³ A process energy flow is given in Figure S10.

5.2.4 Nutrients Recovery

After anaerobic digestion, part of nutrients (C, N, and P) in the digested liquid can be recycled back to the cultivation ponds. As shown in Figure S9, all N and P are distributed between liquid and digested solid residue. N and P in the liquid are recycled into the cultivation ponds for nutrients recovery after solid-liquid separation via centrifugation, with 5-30% loss of N in the liquid.^{1, 46} Digested solid can be used as soil amendment (e.g., N-fertilizer), assuming 40% of N in solid is bioavailable.⁶

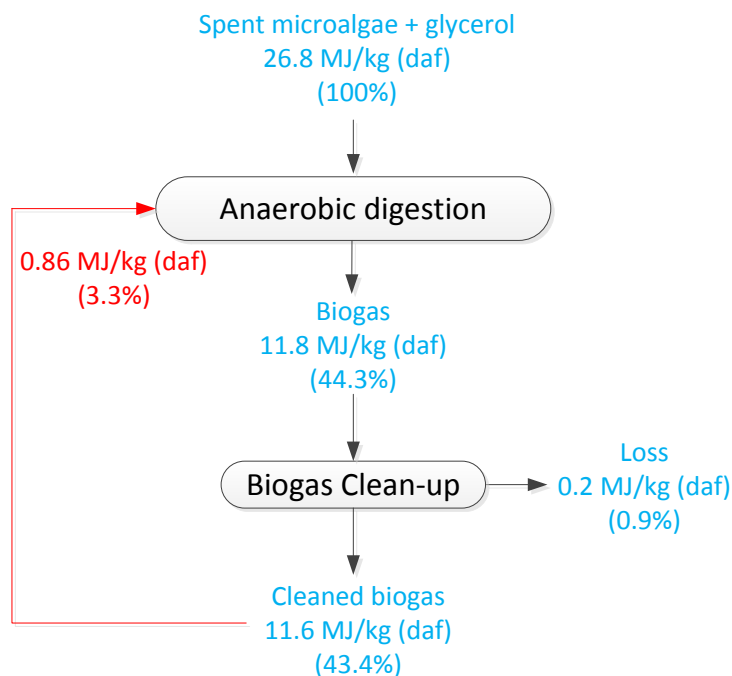


Figure S10. Process energy flow of anaerobic digestion (base case).

Table S6 summarizes the data on nutrients distribution based on the data reported in the literature. The base case values for the amount of N and P eventually recycled to cultivation ponds are then determined to be $74\% \times (1-17.5\%)=61\%$ N and 52% P. Briefly, from the data in previous studies reviewed in Table S6, mean values of 74% N and 52% P are used as base case values. An average (17.5%) of N loss values reported in two papers^{1, 46} is used to calculate base case N recycling ratio. The low case and high case values presented in Table S6 are used for sensitivity analysis. Similarly, for final nutrients recycled to the cultivation ponds, the low case values are estimated as $59\% \times (1-30\%) = 41\%$ for N and 20% for P while the high case values are estimated as $90\% \times (1-5\%) = 85.5\%$ for N and 89% for P, respectively.

5.3 Hydrothermal Liquefaction

5.3.1 System Overview

The hydrothermal liquefaction process is modeled according to the process described in a previous study.³⁸ The process consists of two major steps, i.e. hydrothermal liquefaction and catalytic hydrothermal gasification. The hydrothermal liquefaction converts the spent microalgae into bio-oil, aqueous phase, biochar, and gas at $300\text{ }^{\circ}\text{C}$ and $\sim 10\text{ MPa}$. The aqueous phase rich in organic carbon is subjected to the catalytic hydrothermal gasification ($350\text{ }^{\circ}\text{C}$ and 21 MPa as reported by Genifuel) that converts organic carbon into biogas. A mass balance and process energy flow of the hydrothermal liquefaction process are shown in Figure S11 and Figure S12, respectively, with detailed discussion given below.

5.3.2 Products Yields and Properties

Yields of bio-oil, biochar, aqueous phase, and gas are estimated based on Valdez et al.⁶⁰ because properties (e.g., elemental composition) of microalgae reported in this paper is close to the spent microalgae in this study. Reaction temperature is 300 °C, with a retention time of 60 minutes. We briefly list products yields and elemental composition in Table S7. Higher heating values (HHV) of bio-oil and aqueous phase are calculated by Dulong's formula. HHV of biochar is estimated using formula proposed by Sheng et al.⁶¹ It is reported that 13.6% of total carbon presents in aqueous phase as inorganic carbon.⁶⁰ Organic carbon content in aqueous phase is then estimated as ~32% of total carbon in feedstock. Organic carbon in aqueous phase can be converted to biogas (60% CH₄ and 40% CO₂) via catalytic hydrothermal gasification.³⁸ We conservatively assume that 90% of organic carbon will be converted. Further review on hydrothermal liquefaction of microalgae suggests that bio-oil yields are uniformly distributed between 30 to 50 wt%, dry ash free basis (daf), as shown in Figure S13. Therefore, bio-oil yields of 30% (daf) and 50% (daf) are subjected to sensitivity analysis.

Table S6. Nutrients (N and P) distribution in anaerobically digested liquid and solid

Nutrients in liquid (wt%) ^a		Nutrients loss during Recycling (wt%) ^b		Nutrients in solid (wt%) ^c		References
N	P	N	P	N	P	
75	50	30	0	25	50	Weissman et al. (1987) ¹
68				32		Ras et al. (2011) ⁵⁵
90			0	10		Collet et al. (2011) ⁴⁶
80	50	5	0	20	50	GREET 1 2012 ⁵⁹
59	89			41	11	Alcantara et al. (2013) ⁶²
70	77			30	23	Alcantara et al. (2013) ⁶²
	20					Wild et al. (1997) ⁶³
	25					Wild et al. (1997) ⁶³
74	52	17.5	0	26	48	Mean value
90	89	30		41	80	Maximum value
59	20	5		10	11	Minimum value
Final nutrients recycled to cultivation ponds ^d						
61 % of N	52 % of P	Baseline value				
41 % of N	20 % of P	Low value				
86 % of N	89 % of P	High value				

^a wt% of total N, P present in spent microalgae. ^b wt% of N, P in liquid. ^c wt% of N, P present in spent microalgae, calculated by difference, considering no N and P released to biogas. ^d Final N and P recovered after subtracting N and P loss during liquid recycling.

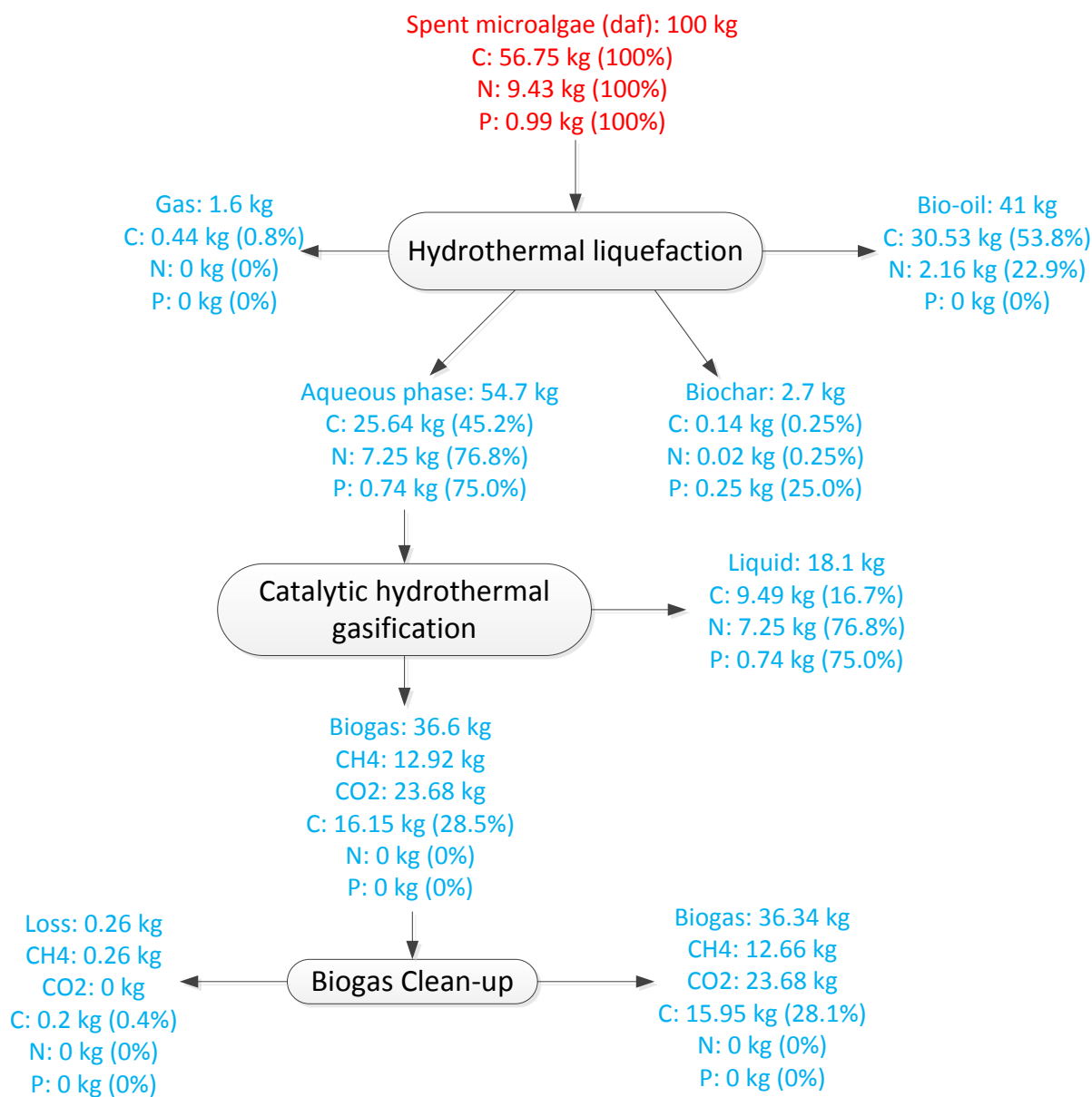


Figure S11. Mass balance of hydrothermal liquefaction integrated with catalytic hydrothermal gasification.

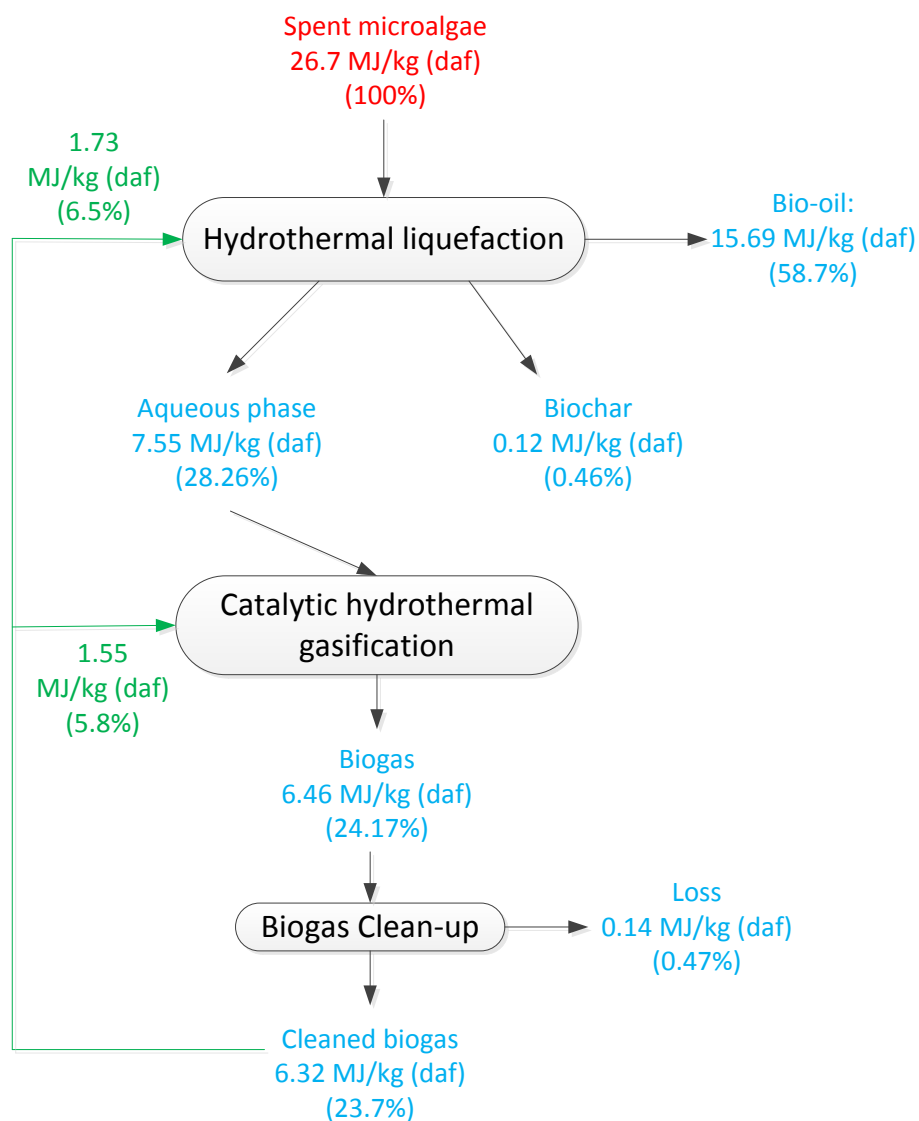


Figure S12. Process energy flow of hydrothermal liquefaction integrated with catalytic hydrothermal gasification.

Table S7. Yields and properties of products from hydrothermal liquefaction.

	Bio-oil	Biochar	Aqueous phase	Gas ^b
Yields, wt% (daf ^a)	41	2.7	54.7	1.6
Elemental composition, wt%				
C	74.5	5.2	42.8	
H	10.4	2.4	6.8	
O ^c	9.9	81.3	33.6	
N	5.3	0.9	15.3	
P	0	10.3	1.5	
HHV (MJ/kg)	38.3	4.5	11.2	

^a on a dry and ash free basis. ^b Considered to be CO₂. ^c Calculated by difference.

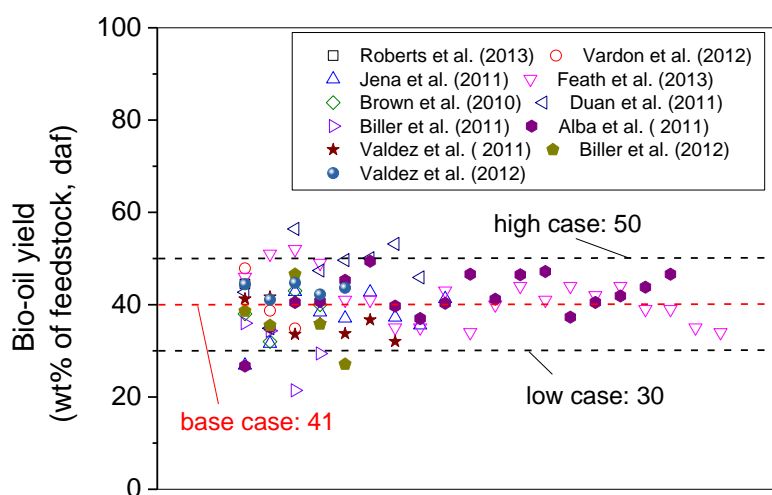


Figure S13. Yields of products from hydrothermal liquefaction reported in some studies: Robert et al. (2013)⁶⁴; Vardon et al. (2012)⁶⁵; Jene et al. (2011)⁶⁶; Feath et al. (2013)⁶⁷; Brown et al. (2010)⁶⁸; Duan et al. (2011)⁶⁹; Biller et al. (2011)⁷⁰; Alba et al. (2011)⁷¹; Valdez et al. (2011)⁷²; Biller et al. (2012)⁷³; and Valdez et al. (2012),⁶⁰ with reaction temperatures of 250-400 °C and reaction time of 10-60 minutes.

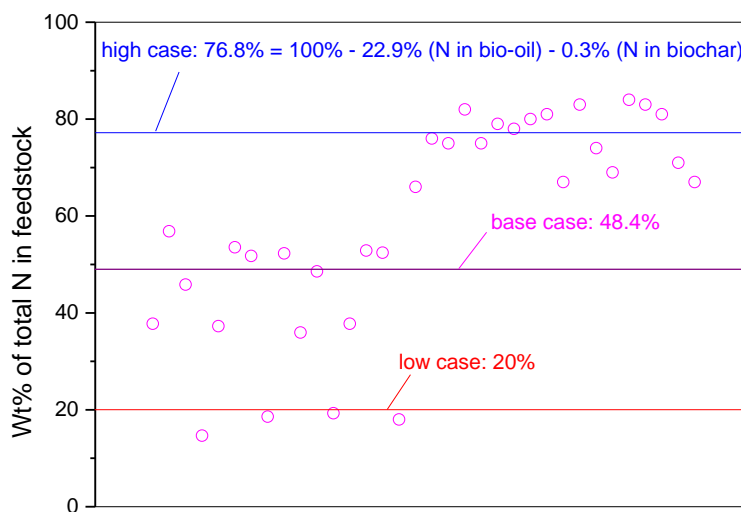


Figure S14. Percentage of N in feedstock retained in aqueous phase, reported by Valdez et al. (2012)⁶⁰ and Ross et al.⁷⁴

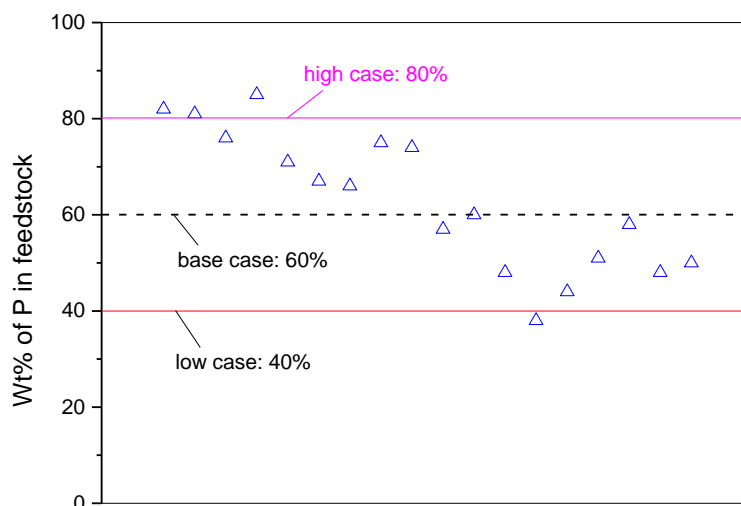


Figure S15. Percentage of P in feedstock present in aqueous phase, reported by Valdez et al. (2012).⁶⁰

5.3.3 Products Utilization

There are two main products produced from hydrothermal liquefaction and catalytic hydrothermal liquefaction, i.e., bio-oil and biogas (rich in CH₄). The bio-oil is mixed with biochar and glycerol to prepare a bioslurry. Glycerol has a higher heating value of 17 MJ/kg. The bioslurry is then transported and co-combusted in a coal fired power plant with an efficiency of 35% for electricity production. The base case distance between the microalgae farm and the coal-fired power plant is set as 50 km whereas the low case and high case values are 10 and 200 km, respectively. The transport method described in a previous study is employed.⁷ Biogas is cleaned following the same method for anaerobic digestion before combustion in a natural gas boiler (efficiency: 85%).

5.3.4 Nutrients Recovery

The nutrients (N and P) are recycled from the aqueous phase. N in the bio-oil and biochar is lost because the bioslurry is co-fired in the coal-based power plant. While substantial work was done on the characterization of bio-oil from hydrothermal liquefaction of microalgae, little has been done for the contents of N and P in the aqueous phase. Therefore, this study determines the N in aqueous phase based on the estimated N distribution in bio-oil and biochar. The N retention in bio-oil in base case of this study is 22.9% of total N in feedstock, estimated based on the bio-oil yield, N content in bio-oil, and N content in the feedstock (spent microalgae). Similarly, it is estimated that 0.3% of total N in the feedstock is present in the biochar. The gas phase is considered to be pure CO₂ and contains no N. This leads to the maximum N content in the aqueous phase to be 76.8 % (i.e. 100%-22.9%-0.3%) of the total N in feedstock. This value is taken as high case value of N in aqueous phase for sensitivity analysis in this study. A further review shows that the minimum amount of N in aqueous phase is ~20% (see Figure S14). The average value can then be calculated as $(76.8+20)/2 \times 100\% = 48.4\%$ of total N in feedstock and used as base case value of N in the aqueous phase. While a previous study⁶⁰ showed ~50% of N in aqueous phase is ammonia and can be recycled, the GREET 1 2012 model⁵⁹ assumes 95% of N in aqueous phase can be recycled. Therefore, in this study, an average value of 72.5% is used as the base case value. Therefore, the values of final N recycled into the cultivation ponds for the base, low, and high cases are set as 35% (i.e. $48.4\% \times 72.5\%$), 10% (i.e. $20\% \times 50\%$) and 73% (i.e. $76.8\% \times 95\%$), respectively.

With respect to P recycling, based on literature data⁶⁰ (see Figure S15), 40-80% of P is in the aqueous phase. A mean value of 60% is then taken as the base-case value. According to the GREET 1 2012 model,⁵⁹ 90% of P in aqueous phase can be recovered. Therefore, the values used for P recycled for microalgae cultivation are set as 54% (60% x 90%), 36% (40% x 90%), and 72% (80% x 90%) for the base, low and high cases, respectively.

5.3.5 Energy Inputs

- Electricity required for hydrothermal liquefaction and catalytic hydrothermal gasification

The electricity demand for pumping microalgae slurry into a hydrothermal liquefaction reactor is estimated to be 0.006 kWh/kg slurry at a reactor pressure of 10 MPa and a pump efficiency of 50%, based on a method described in a previous study.³⁸ The electricity demand for catalytic hydrothermal gasification process is taken from literature³⁸, i.e., 3.1×10^{-4} kWh/g of CH₄ produced. Therefore, for base case scenario, the electricity consumptions for the hydrothermal liquefaction and catalytic hydrothermal gasification can be calculated as 864 and 740 kWh/day, respectively.

- Heat required for hydrothermal liquefaction and catalytic hydrothermal gasification

Using a heat exchanger with an effectiveness of 85%, the cold stream (20 °C) of microalgae slurry is heated to 258 °C by the hot flow from the reactor outlet (reactor temperature: 300 °C). The specific heat (C_p , kJ/kg/K) of water at 258 °C is determined using an equation shown in Figure S16. Therefore, the additional heat required for the hydrothermal liquefaction is determined as 0.06 kWh/kg slurry based on the equation $Q = M \times C_p \times (300 - 258)^\circ\text{C}$, where M is the microalgae slurry flow rate.

The heat demand (Q_{CHG}) for the catalytic hydrothermal gasification is calculated as 0.05 kWh/kg slurry using a method presented in another study³⁸, considering a temperature rise of 30 °C after catalytic hydrothermal gasification heat exchanger. Therefore, in the base case scenario, the heat demands for hydrothermal liquefaction and catalytic hydrothermal gasification are calculated as 8451 and 7454 kWh/day, respectively.

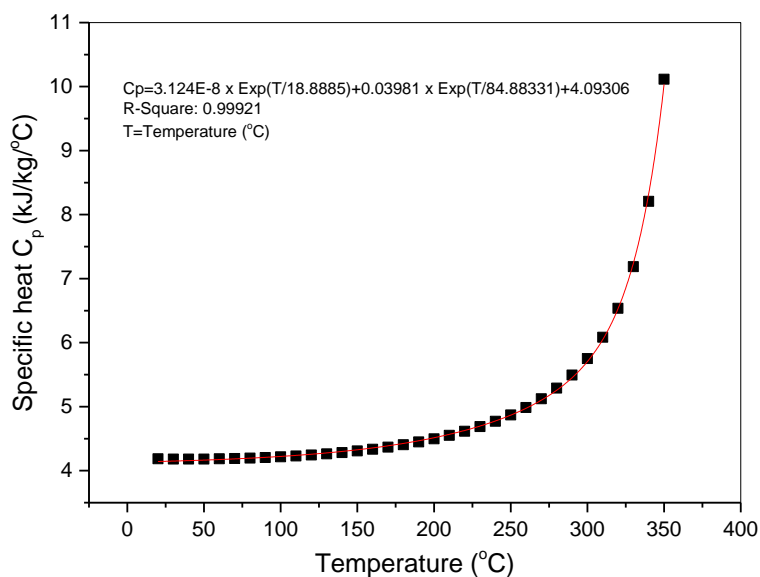


Figure S16. Fitting specific heat of hot compressed water with temperature (20–350 °C), based on data from: <http://webbook.nist.gov/chemistry/fluid> (last access in March 2013).

6. System Infrastructure

The life cycle energy and carbon burdens associated with the construction of cultivation, harvesting and dewatering, lipid extraction, and transesterification system are estimated based on the construction materials consumed. The life cycle burdens of the hydrothermal liquefaction and anaerobic digestion systems are calculated using dollar-to-energy and dollar-to-carbon methods based on the capital costs of these systems. Unless otherwise specified, the designed life time of these systems is 30 years.

6.1 Cultivation System

- Cultivation ponds

The cultivation ponds are constructed using earth berms that are lined with HDPE liners. Concrete and recycled steel are also required to build supporting base for paddle wheels and CO₂ sumps. Therefore, the materials for ponds construction include HDPE, concrete, and recycled steel. Based on the methods described by Murphy and Allen²⁰ and the GREET 1 2012 model,⁵⁹ the materials for ponds construction are calculated and briefly summarize as follows.

Figure S17 and Table S8 illustrate the pond layout and dimensions. The pond bottom and inner surface are covered by 2 mm thick HDPE liners. The total mass (25 ponds) of HDPE for bottom and inner surface is 2,315,764 and 139,177 kg, respectively, considering the actual mass being 1.2 times of theoretical mass.²⁰ The life time of the bottom liner and inner surface liner is 10 years. Therefore, the total HDPE required for the cultivation ponds is 245,494 kg/year.

According to the GREET 2012 model,⁵⁹ 53 m³ of concrete is required for one pond. The total concrete mass required for 25 ponds is therefore 3,153,500 kg at a concrete density of 2,380 kg/m³. The total recycled steel required is 46,231 kg. Therefore, the annual concrete and recycled steel required are 105,117 (i.e. 3,153,500/30) and 1,541 (i.e. 46,231/30) kg/year, respectively.

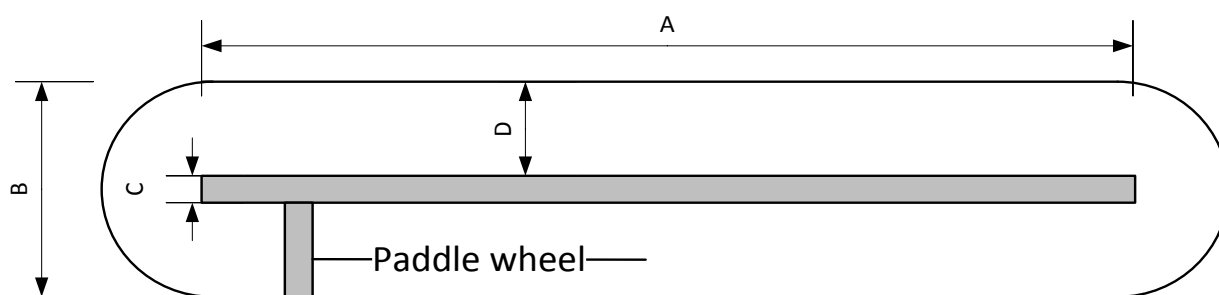


Figure S17. Layout of a 4-ha cultivation pond (carbon sumps are not shown).

Table S8. Pond dimensions, estimated based on GREET 1 2012⁵⁹

Length of straight part (A), m	630
Width (B), m	60
Separating earth berm width (C), m	2.25
Distance between separating berm and pond edge (D), m	28.9
Berm height, m	0.9

- Inoculum ponds

The inoculum ponds are designed in a similar way with the cultivation ponds. Therefore, the environmental (energy and carbon) burdens of the inoculum ponds are calculated as 11% of those for cultivation ponds, because the inoculation ponds' area is 11% of total cultivation ponds area.²⁰

- Evaporation ponds

The evaporation ponds are constructed with a compacted base made of natural materials found on site. The maximum permeability is 10^{-7} m/s. The energy and carbon associated with materials for the evaporation ponds are excluded.

- Pumps

As discussed in Section 3.1, the maximum daily harvest rate is 29% of total pond volume. Considering the time spent to pump water from the cultivation ponds to the harvest ponds (6 hours, see Section 3.2), total water flow rate is calculated as $9.8 \text{ m}^3/\text{s}$. Given a pump flow rate of $0.3 \text{ m}^3/\text{s}$ (KBS Elite E250-32), 33 ($9.8/0.3$) water pumps are required. Each pump is made of 311 kg steel⁷⁵ so that the whole farm requires 10,263 kg (i.e. $33 \times 311 \text{ kg}$) steel. Given 30 years' life time, this is equivalent to 342 kg steel per year. For gas pumps, the energy and carbon footprints are estimated to be 90 MJ/year and 3 kg CO₂-eq/year, respectively, following an approach detailed in a previous study.¹⁶

- Pipes

The water and gas pipelines are made of HDPE pipe. Their specification is listed in Table S9, based on the base case design in this study and data reported in a previous study.¹⁶

- Paddle wheels

The paddle wheels are constructed from PVC. The amount of PVC required is estimated according to a method in a previous study.¹⁶ Given a 30-year plant life, the annual share is 216,500 kg/year.

Table S9. Materials required for pipelines ^a

Items	Water pipe	Gas pipe
Length (m)	7,050 (5,000+2,050)	5,000 ^b
Outer diameter (m)	0.89	1.008
Inner diameter (m)	0.88	1
Volume of HDPE (m ³)	67	54
Total mass of HDPE (kg) ^c	63,893	51,344
Life time, years	30	30
Annual share, kg/year	2,130	1,711

^a Length and specification of pipeline for water and gas are estimated based on the base case design in this study and the data reported in a previous study.¹⁶ ^b Only the gas pipeline between the gas-fired power plant and the microalgae farm is considered. ^c Typical density of HDPE is 950 kg/m^3 .²⁰

6.2 Downstream Conversion System

For the downstream conversion system, the materials required are estimated based on the GREET 1 2012 model⁵⁹ and Zhang et al.,⁷⁶ which are briefly summarized in Table S10.

Table S10. Materials requirement for downstream conversion systems (at a 30-year plant life)

System (material)	Total requirement	Amortized over life time
Settling ponds (concrete) ^a	26,775,000 kg	892,500 kg/year
DAF (concrete) ^a	270,903 kg	9,030 kg/year
DAF (recycled steel) ^a	2,442 kg	81 kg/year
Centrifuge (steel) ^a	15,750 kg	525 kg/year
Pressure homogenizer (steel) ^a	14,700 kg	490 kg/year
Liquid-liquid extraction column (steel) ^a	4,613 kg	154 kg/year
Extraction centrifuge (steel) ^a	3,200 kg	107 kg/year
Extraction centrifuge (Concrete) ^a	21,670 kg	722 kg/year
Stripping column (steel) ^a	2,278 kg	76 kg/year
Transesterification (steel) ^b	1,657 kg	55 kg/year

^a Estimated based on the GREET 1 2012 model⁵⁹. ^b Estimated based on Zhang et al.⁷⁶

6.3 Byproducts Utilization System

In the literature, there is little information available on the materials required for the construction of hydrothermal liquefaction plant. Therefore, this study adopts the dollar-to-energy and dollar-to-carbon methods for determining the energy and carbon footprints. The same method is also applied to the anaerobic digestion system. The capital cost of anaerobic digestion system and hydrothermal liquefaction system are scaled from those reported in previous studies^{6, 77} according to the power law:

$C_s = C_0 \left(\frac{P_s}{P_0} \right)^n$, where C_0 is the capital cost for a plant with capacity P_0 and n is scale factor (a value of 0.6 used in this study). The energy and carbon footprints are then calculated from the life inventory data in Table S1 at a 30-year plant life. It is estimated that the energy inputs and GHG emission are 154,354 MJ/year and 14,137 kg CO₂-e/year for the anaerobic digestion system and 1,601,039 MJ/year and 146,645 kg CO₂-e/year for the hydrothermal liquefaction system, respectively.

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