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# Microalgae Oil Production: A Downstream Approach to Energy Requirements for the Minamisoma Pilot Plant

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**Abstract:** This study investigates the potential of microalgae oil production as an alternative renewable energy source, in a pilot project located at Minamisoma City in the Fukushima Prefecture of Japan. The algal communities used in this research were the locally mixed species, which were mainly composed of *Desmodesmus* collected from the Minamisoma pilot project. The microalgae oil-production processes in Minamisoma consisted of three stages: cultivation, dewatering, and extraction. The estimated theoretical input-energy requirement for extracting oil was 137.25 MJ to process 50 m<sup>3</sup> of microalgae, which was divided into cultivation 15.40 MJ, centrifuge 13.39 MJ, drum filter 14.17 MJ, and hydrothermal liquefaction (HTL) 94.29 MJ. The energy profit ratio (EPR) was 1.41. The total energy requirement was highest in the HTL process (68%) followed by cultivation (11%) and the drum filter (10%). The EPR value increased along with the yield in the cultivation process. Using HTL, the microalgae biomass could be converted to bio-crude oil to increase the oil yield in the extraction process. Therefore, in the long run, the HTL process could help lower production costs, due to the lack of chemical additions, for extracting oil in the downstream estimation of the energy requirements for microalgae oil production.

**Keywords:** microalgae; energy requirement; hydrothermal liquefaction; energy profit ratio

## 1. Introduction

Energy plays a vital role in modern society. For years, conventional energy sources, based on oil, coal, and natural gas, have been drivers for economic advancements [1]. Fossil fuel has long been used as the primary energy source in transportation. Coal and natural gas are used as fuel for electricity generation. Without fossil fuel and electricity to fuel a country, economic activity would be interrupted.

The issue of fossil-fuel depletion has recently come into debate and the rise of crude oil prices has encouraged many countries to develop alternative renewable energy sources. For example, Indonesia produces palm oil-based biodiesel because it is the most prominent producer of palm oil. Brazil produces ethanol from sugarcane as does the United States with its corn [2]. This scenario is good but can also become a problem because food crop-based biofuel can affect food availability and price, especially in developing countries [3].

Recently, algal biomass feedstock has been selected to avoid the confrontation of food vs. fuel and land-use changes [4–6]. Microalgae also have an advantage compared to other feedstock, with a higher oil yield/hectare. The oil palm has the highest yield of perennial crops, with 5950 L/ha, while microalgae with 30% oil (by weight) in biomass can generate 58,700 L/ha [6]. Because the land requirement for algae is one-tenth that of the oil palm, the microalgae can theoretically produce 10 times more oil than the oil palm in a same area.

Considering the advantages of microalgae, Japan has started to develop them as an energy feedstock at Minamisoma City, Fukushima Prefecture. The project location was selected in a risk-prone area after a major earthquake occurred in 2011. Because of the radioactive residue from the nuclear incident, Minamisoma may not be suitable for rehabilitation as an agricultural area. Developing microalgae as a biofuel feedstock can help restore the city as an industrial area.

### 1.1. Microalgae Production

Conventional microalgae oil extraction typically involves using a solvent. Therefore, only oil is used as a biofuel feedstock. However, recently, hydrothermal liquefaction (HTL) has gained more attention for its ability to process wet-algae biomass [7]. With HTL, almost all of the microalgae biomass can be converted to bio-crude oil [7,8]. The Minamisoma pilot plant is a research-based pilot plant. Its initial objective was to test a method of producing microalgae oil using HTL. The microalgae oil production started from microalgae cultivation using a raceway pond with native algal communities, with *Desmodesmus* as the main species with other species including *Scenedesmus acumunatus*, *Klebsormidium* sp., *Dictyosphaerium* sp., and other various species with small percentage. *Desmodesmus* as the main species proportion vary according to season but can reaches up to 24% of the total organism. The microalgae were harvested and sent to a centrifuge for the dewatering process, and a drum dryer for a second dewatering process before undergoing the HTL treatment.

The HTL process does not need to add chemicals to extract the oil; therefore, in the long run, chemical costs can be avoided. Reducing the operational costs will help lower the production cost, which is beneficial economically. The Minamisoma pilot plant uses HTL, which requires high-temperature and high-pressure systems and is expected to consume considerable energy. However, this energy requirement is expected to be offset by the increase in yield from the biomass conversion, and the omission of the energy required to dry the biomass thoroughly.

### 1.2. Energy Requirements

Microalgae has high potential; however, the main drawback is its size. Microalgae are small organisms; thus, to get much feedstock, water removal or drying is crucial. Drying can account for more than 80% of the energy consumption [9]. Previous researchers reported the mass balance and life-cycle assessment of microalgae; for example, using an open raceway pond for the cultivation [10–12] or using a photobioreactor for the cultivation stage [13]. Using the total biomass enables the utilization of fast-growing species because there is no need to wait for lipid production [14], and the HTL process utilizes biomass more efficiently than lipid extraction [15]. Minamisoma sometimes faces clogging problems in the HTL process. In the future, they must adopt a method that can resolve the clogging issue, which will successfully prolong the process time [16]. Other problems, for example, nitrogen content in the oil [17], can be resolved using two-stage HTL. In two-stage HTL, Stage 1 was pre-treatment (<200 °C) and stage 2 was the main treatment (250–350 °C). Stage 1 resulted the input nitrogen flow to the aqueous phase; following stage 2, the nitrogen reduction was up to 55% relative to direct HTL [18].

The advantages of processing various strains of microalgae are especially apparent if we consider the geographical constraints. If an area cannot grow high-lipid microalgae but is very suitable for growing high-biomass microalgae, it can still develop microalgae fuel by utilizing HTL technology. This was because HTL can process whole biomass and not only the oil in microalgae [7,8], therefore low-lipid, high-biomass microalgae still have prospects to be developed. Therefore, the HTL process

in Minamisoma is projected to be developed into an industrial-sized algae oil plant. However, the energy requirement is a significant issue that must be addressed before moving from the pilot scale to the industrial scale.

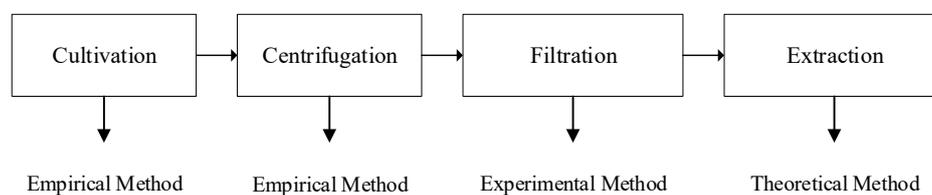
Opinions are split between negative and positive energy balances, and there is still no agreement on an accurate energy balance [8]. Some studies have resulted in an energy loss [8,18] while others have resulted in an energy profit [19,20]. Energy profit ratio (EPR) is the ratio between energy produced and energy consumed, thus a positive value is preferred. Therefore, a downstream process to analyze the EPR is required for the Minamisoma project to accurately determine the energy balance through the EPR, before further establishing the plant on an industrial scale.

### 1.3. Objective

The objective of this research is to find the EPR, based on the energy requirements for microalgae production, involving all the stages from cultivation to extraction, to determine the feasibility of recommending an industrial-scale production from the pilot project. In this proposed analysis, the Minamisoma pilot plant was used as the ground base of development for microalgae oil production. Its potential to contribute in the rehabilitation area would be beneficial environmentally and socially.

## 2. Methodology

This research was based on experimental, empirical, and theoretical models. The model from [21] was mainly used in the cultivation process, while the model from [22] was mainly used in the centrifugation process. The filtration was mainly based on experimental results from [23], and the extraction was mainly based on a theoretical model from the law of thermodynamics. Figure 1 shows the analytical process of this research.



**Figure 1.** Research analytical process for four stages of microalgae production at Minamisoma.

### 2.1. Cultivation

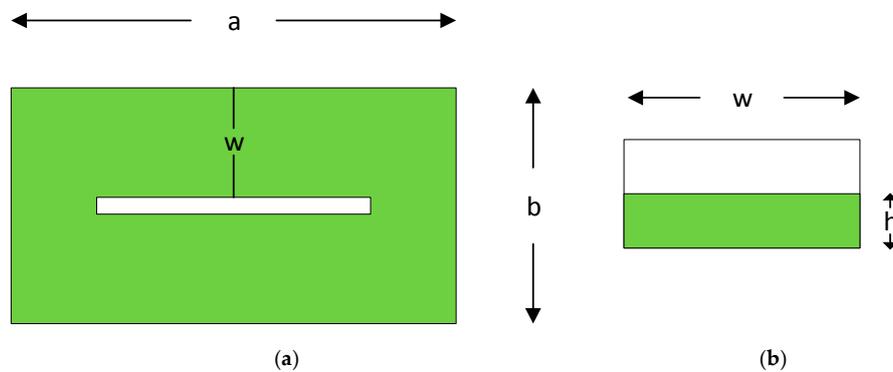
The production process in this study was based on the production-process layout in the Minamisoma pilot plant, which consisted primarily of four stations. Those stations were cultivation, centrifugation, drum filtration, and extraction. The cultivation station utilized an open raceway pond (ORP) with a paddlewheel acting as the mixer. The theoretical power required for a paddlewheel in cultivation was estimated using the following equation from [21]:

$$P = \frac{1.59\rho g u^3 L_r (w + 2h) f_M^2}{e d_h^{0.33}}, \quad (1)$$

where  $L_r$  (m) is the channel length of the pond,  $w$  is the channel width,  $h$  is the culture depth,  $\rho$  ( $\text{kg}/\text{m}^3$ ) is the density of the culture broth,  $g$  ( $9.81 \text{ m}/\text{s}^2$ ) is the gravitational acceleration,  $d_h$  is the hydraulic diameter of the flow channel,  $f_M$  is the Manning channel roughness factor, and  $e$  is the efficiency of the motor, drive, and paddlewheel. A typical  $f_M$  value for trowel-finished concrete is 0.013 [24]. For a paddlewheel located in a channel with a flat bottom, the  $e$  value is about 0.17 [25].

The microalgae concentration in cultivation is low. In Minamisoma, the harvest concentration was around 0.34 g/L. Therefore, the microalgae-cultivation properties, such as density and viscosity, were typically selected to closely resemble water properties at the operating temperature [21].

These parameters were later used in Equation (1) to calculate the power required for cultivation. Figure 2 shows the open-raceway pond dimensions of the Minamisoma pilot plant, where  $a$  is the length of the pond,  $b$  is the width of the pond,  $h$  is the depth of the culture, and  $w$  is the channel width.



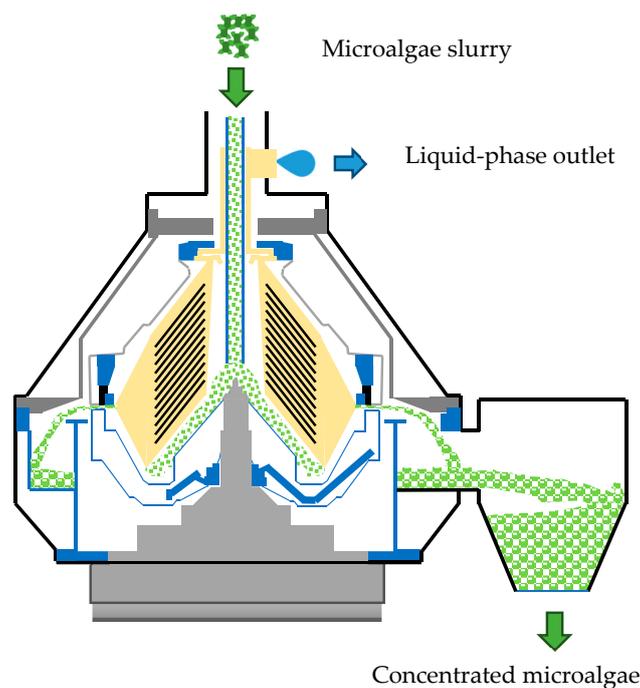
**Figure 2.** Open raceway pond: (a) top view of the open raceway pond; (b) flow channel of the open raceway pond.

Before the power calculation, the hydraulic diameter ( $d_h$ ) must be calculated, using the following equation from [21], where  $w$  is the width of the channel and  $h$  is the average depth of the liquid in it.

$$d_h = \frac{2wh}{w+h} \quad (2)$$

## 2.2. Centrifuge

The centrifuge uses centrifugal force to separate the microalgae cells from the water. The centrifuge equipment is smaller than a settling tank. The centrifuge primarily increases the gravity to accelerate the separation process. Figure 3 illustrates the disk stack centrifuge used for the experiment at the Minamisoma pilot plant.



**Figure 3.** Disk-stack centrifuge used at the Minamisoma pilot plant.

The centrifuge accelerates the settling rate by increasing the gravity (G-force). The settling equation follows Stokes' Law to calculate the terminal settling velocity (TSV). Stokes' terminal settling velocity in gravity (1 g) can be calculated using Equation (3) from [26], where  $u_o$  is the settling velocity,  $\rho_p$  is the particle density,  $\rho_f$  is the water density,  $g$  is the gravity acceleration, and  $d$  is the particle diameter. The volumetric flow rate ( $Q$ ) can be calculated using Equation (4), where  $V$  is the volume and  $t$  is time.

$$u_o = \frac{(\rho_p - \rho_f)gd^2}{18\mu} \quad (3)$$

$$Q = \frac{V}{t} \quad (4)$$

The power is calculated using Equation (5) from [22], where  $P_{acc}$  is the power for the feed acceleration,  $sg$  is the specific gravity of the feed slurry,  $Q$  is the volumetric flow rate of the feed,  $\omega$  is the speed, and  $r_p$  is the radius of the bucket.

$$P_{acc} = 5.984(10^{-10})sgQ(\omega r_p)^2 \quad (5)$$

### 2.3. Drum Filtration

The drum-filtration energy is calculated based on the expression:

$$Energy = power \times time. \quad (6)$$

Figure 4 illustrates the drum filter used in the Minamisoma pilot plant.

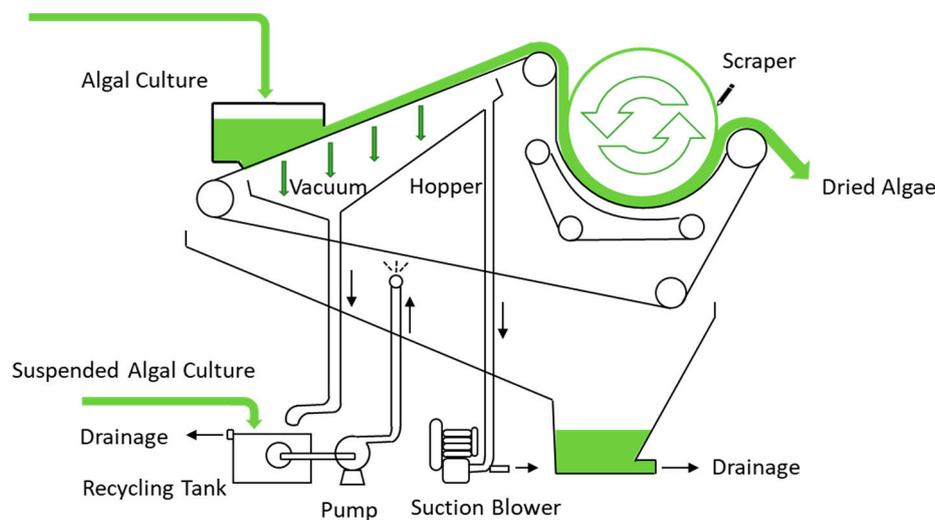


Figure 4. Drum filter installed at the Minamisoma pilot plant.

### 2.4. HTL

Hydrothermal liquefaction processes biomass in water at high/subcritical temperatures (below 374 °C) and high pressure (above water vapor pressure) with or without a catalyst [19,27]. HTL can process 5–20% algae concentration as input [27]; in the Minamisoma pilot plant, microalgae concentration more than 20% introduces a clogging problem. In the HTL process, microalgae biomass is broken down in water to small molecules which then can repolymerize into oily compounds. HTL therefore allows wet conversion of biomass, thus reducing the energy consumption in drying process [19,28]. In the HTL process, the primary data was obtained from the Minamisoma pilot plant,

especially from [23] and from the literature review. The specific heat ( $C_p$ ) for the microalgae can be determined utilizing Equation (7) from [29].

$$C_p \text{ microalgae} = \sum \% \text{ properties} \times C_p \text{ properties} \quad (7)$$

The basic equation to calculate the heat requirement for microalgae and water is as shown in equation, where  $m$  is the mass and  $\Delta T$  is the temperature difference (8).

$$Q = m \times C_p \times \Delta T \quad (8)$$

### 2.5. Energy Profit Ratio (EPR)

The final part is the energy profit ratio (EPR) calculation, which is the ratio of the energy produced to the energy consumed by an energy-production method. The EPR value can be calculated using Equation (9) as in [30].

$$EPR = \frac{\text{Output energy}}{\text{Input energy}} \quad (9)$$

## 3. Results and Discussion

### 3.1. Baseline

The Minamisoma pilot plant in Fukushima Prefecture, Japan was selected for its collected algal communities. The technology was implemented using four stations from cultivation to extraction. The cultivation process was carried out using an open raceway pond (ORP). The dewatering process consisted of two sub-processes: centrifugation for the first phase and a drum filter for the second phase. The last primary process was extraction, which used hydrothermal liquefaction (HTL) methods. Figure 5 shows the mass balance of the microalgae oil production at Minamisoma, SS is suspended solid and  $dW$  is dry weight.

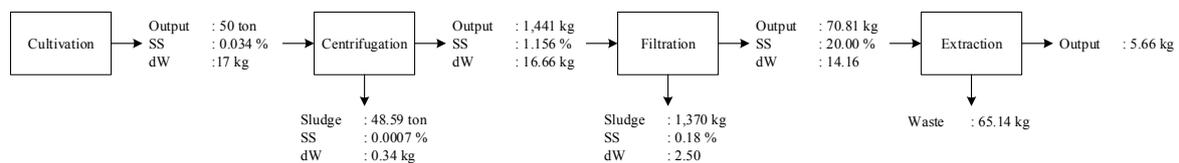


Figure 5. Mass balance of microalgae oil production at the Minamisoma pilot plant.

### 3.2. Cultivation

The pilot project in Minamisoma used an ORP to cultivate microalgae. The ORP dimensions were 20 m in width and 50 m in length (1000 m<sup>2</sup> area). The cultivation depth was 0.2 m, which made the volume 200 m<sup>3</sup> or 200,000 L. The ORP was constructed from concrete.

The main microalgae species cultivated in Minamisoma is *Desmodesmus*. The microalgae cultivation had a hydraulic retention time (HRT) of four days with an average harvest concentration of 0.034%. The harvesting volume per day was 50 m<sup>3</sup>. Therefore, the everyday cultivation had a yield of 17 kg of microalgae (dry weight) or 0.34 g/L. The primary equipment in this cultivation station was the raceway pond, which utilized an electric motor to drive the paddlewheel. Table 1 shows the parameters and value for ORP at Minamisoma pilot plant

**Table 1.** Open raceway pond parameters for the pilot plant at Minamisoma.

Parameter	Value	Unit
Length ( $a$ )	50	m
Width ( $b$ )	20	m
Channel width ( $w$ )	10	m
Height ( $h$ )	0.2	m
Area	1000	m <sup>2</sup>
Volume	200	m <sup>3</sup>
HRT	4	days
Harvest	50	m <sup>3</sup> /d

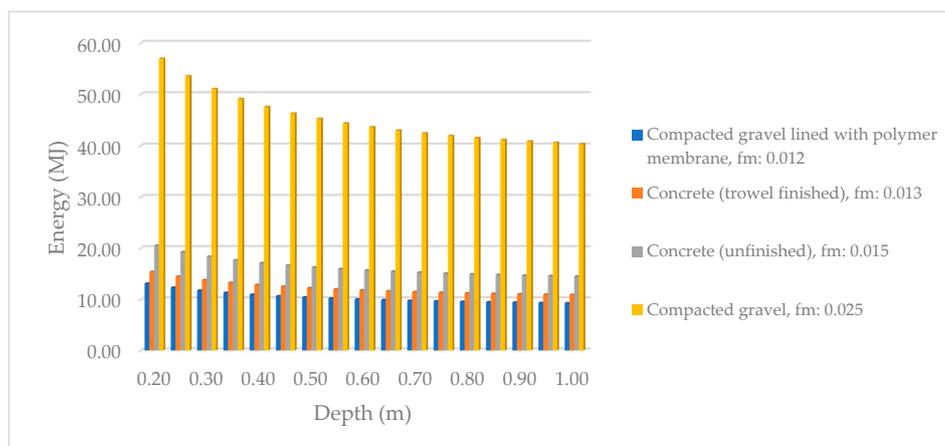
Nagappan and Verma [31] used the same species, *Desmodesmus* sp., but the highest yield obtained from their laboratory was 77.73 mg/L or 0.08 g/L. The biomass yield obtained in this research was similar to the result from Ji et al., in which the biomass yield was 0.385 g/L [32]. The yield in this research can be increased by adding anaerobically digested wastewater (ADW), where the yield reached 1.039 g/L, or a more-than-250% increase in biomass; therefore, in the future, the yield potential can still be increased.

Using Equation (2), the calculated  $d_h$  value was 0.77 m and, using Equation (1), the power for the paddlewheel was 0.86 MJ. The paddlewheel was operated for 24 h a day, and the energy consumption was 20.53 MJ. In addition, we could reduce the paddlewheel speed at night, when there is no photosynthesis, to further reduce the energy consumption to 15.40 MJ. Table 2 shows the energy consumption for the two scenarios.

**Table 2.** Energy consumption by the paddlewheel.

Scenario	Day	Night	Total	Energy	Remarks
	h	h		MJ	
24 h run	12	12	24	20.53	Running 24 h
18 h run	12	6	18	15.40	At night, speed reduced to half

By using calculation based on Equation (1), the power consumption decreases with the increased culture depth. The power consumption is also decreased by lowering the Manning coefficient. The Manning value is related to the pond materials; a smooth surface gives a lower Manning value because the friction is lower, thereby reducing the overall power consumption. Figure 6 shows the power-consumption changes by depth and material changes.

**Figure 6.** Energy requirements for operating the paddlewheel with different culture depths and pond materials (18 h).

Additional energy is required if we consider the nutrients used in the cultivation. With an initial weight of 5 kg and a harvest weight of 17 kg, approximately 12 kg of biomass was produced. Using stoichiometry from [23,33], we can estimate the nutrients needed for cultivation. The calculation based on the stoichiometry can be seen in Appendix A, and Table 3 shows the energy for the nutrients. The energy demand was estimated using the Simapro<sup>®</sup> Cumulative Energy Demand Methods, version 1.09.

**Table 3.** Nutrients' energy demand.

Component	Weight (kg)	MJ/kg	Total (MJ)
CO <sub>2</sub>	22.51	8.89	200.09
HNO <sub>3</sub>	4.77	14.80	70.59
H <sub>2</sub> SO <sub>4</sub>	0.70	7.23	5.08
H <sub>3</sub> PO <sub>4</sub>	0.60	25.70	15.46
			291.21

The nutrients' energy demand is very high if we rely on the fertilizer. Alternatively, we can integrate the microalgae cultivation with other industries to supply nutrients for the microalgae [32,34–36]. If we could replace the CO<sub>2</sub> and other nutrients, it would be beneficial for the final EPR value.

### 3.3. Centrifugation

A centrifuge was used to accelerate the harvesting time for microalgae cultivation compared to gravity sedimentation. With a 360-L volume and a 270-s residence time, we calculated the volumetric flow rate of 1.33 L/s. The total time to process 50 m<sup>3</sup> input using Equation (4) results in 10.42 h. With a volumetric flow rate of 1.33 L/s, we can compare this value to the typical centrifuge setting to obtain the speed of the centrifuge and the radius of the bucket/bowl from [33]. The typical setting for a 1.33 L/s input uses a 10,000-rpm speed and a bucket radius of 0.25 m. The later power can be calculated using Equation (5), which results in a value of 4.99 HP or 13.39 MJ.

The calculated theoretical value for the centrifugal action was 13.39 MJ or 0.07 kWh/m<sup>3</sup>. This theoretical value was lower than the application in practice because of influences such as machine efficiency. A field measurement of around 1 kWh/m<sup>3</sup> was reported; this value is the same as [37], which also gave a value of 1 kWh/m<sup>3</sup>, but higher than the value from the Alva Laval in [38], which gave a value of 0.53 kWh/m<sup>3</sup>. The parameters to calculate the centrifuge power can be seen in Table 4.

**Table 4.** Energy required in the centrifuge process.

Parameter	Definition	Value	Unit
<i>P<sub>acc</sub></i>	Horsepower for feed acceleration	4.99	HP
		13.39	MJ
<i>sg</i>	Specific gravity feed slurry	1000.02	kg/m <sup>3</sup>
<i>Q</i>	Volumetric flow rate of feed	1.33	L/s
<i>ω</i>	Speed	10,000.00	rpm
<i>rp</i>	Radius of the bucket	0.25	m

### 3.4. Filtration

According to the specification's energy requirement, the drum filter equipment's power was 1.42 kW, with a feed capacity of 520 kg/h to produce 20% microalgae. The input feed was 1441 kg, which required 2.77 h of processing time. The total energy consumption for the filtration was 14.17 MJ. This value is equal to 2.73 kWh/m<sup>3</sup>, which was slightly lower than the value obtained by [38] and Mohn in [39], both of which gave a value of 3 kWh/m<sup>3</sup>.

### 3.5. Extraction

The native microalgae communities cultivated in Minamisoma were mainly *Desmodesmus*. Theoretically, solvent extraction can only extract from fatty-acid content, which is only 13% of the total biomass. This fatty-acid value was lower than the protein and polysaccharide values, which were 45.7% and 21.1%, respectively. Hydrothermal liquefaction (HTL), on the other hand, could convert almost all the biomass into crude oil. Therefore, the yield is expected to be higher than for only oil extraction. Because the purpose is to produce energy, a higher yield is preferable. Table 5 shows the properties of the algal communities in Minamisoma [40].

**Table 5.** Properties of the algal communities at the Minamisoma pilot plant.

Property	Percentage
Water	5.7%
Fatty acids	13.0%
Protein	45.7%
Polysaccharide	21.1%
Ash	14.5%

A previous study showed a base for calculating the specific heat of the algal communities [29]. Table 6 shows the parameters used to calculate the specific heat of the algal communities with *Desmodesmus* as the main species.

**Table 6.** Specific heat assumption.

Property	Specific Heat	
Water	4.18	kJ/(kg·°C)
Fatty acids	2.30	kJ/(kg·°C)
Protein	1.47	kJ/(kg·°C)
Polysaccharides	1.26	kJ/(kg·°C)
Ash	0.73	kJ/(kg·°C)

The specific heat of the microalgae was calculated using the composition given in Tables 5 and 6. Using Equation (7), the specific heat ( $C_p$ ) of the microalgae was 1.58 kJ/(kg·°C).

The HTL input was a microalgae slurry with a microalgae concentration of 20%; therefore, for 70.81 kg of input, 56.64 kg was water and 14.16 kg was microalgae. Here, we used the average value required to heat the water from 25 °C to 350 °C. The energy required to heat 56.64 kg of water from 25 °C to 350 °C, according to Equation (8), was 87.02 MJ, and the energy required to heat 14.16 kg of microalgae from 25 °C to 350 °C was 7.28 MJ. Thus, the total energy to heat 70.81 kg of microalgae slurry from 25 °C to 350 °C was 94.29 MJ. The microalgae specific heat ( $C_p$ ) value was 1.58 kJ/(kg·°C). This microalgae specific heat value was categorized as average, as [29] stated that the specific heat for microalgae ranged from 1.2–2 kJ/(kg·°C). Table 7 shows the parameters used in the theoretical calculation of the energy requirement.

**Table 7.** Parameters used in the hydrothermal liquefaction (HTL) energy requirement.

Parameter	Value	Unit
Mass	70.81	kg
Microalgae concentration	20	%
Water concentration	80	%
$C_p$ microalgae	1.58	kJ/(kg·°C)
$C_p$ water (average)	4.73	kJ/(kg·°C)
Initial temperature	25	°C
Final temperature	350	°C
Microalgae energy requirement	7.28	MJ
Water energy requirement	87.02	MJ
Total energy requirement	94.29	MJ

### 3.6. Energy Profit Ratio (EPR)

The EPR (Energy Profit Ratio) is the ratio of the energy produced to the energy consumed by an energy-production method [30]. The highest energy demand came from the nutrients, followed by the HTL process, with around 68% and 22%, respectively. Carbon dioxide from flue gas could be used as a CO<sub>2</sub> source in microalgae cultivation [41]. If we could obtain CO<sub>2</sub> from another industry, the nutrient percentage would decrease to around 40% of the total energy demand. Further, if we could completely substitute the nutrients, the highest energy consumption would be the HTL process with around a 68% share.

Without the nutrients, the HTL energy consumption was the highest, with 94.29 MJ or slightly more than 68%, followed by cultivation with 15.40 MJ or slightly more than 11%. The drum filtration and centrifuge contributed 14.17 MJ and 13.39 MJ or around 10% and 9%, respectively. With a microalgae-oil energy content of 193.27 MJ, the energy profit ratio was found to be 1.41.

Figure 7 shows the EPR value with nutrients, with nutrients but without CO<sub>2</sub>, and without nutrients. It was observed that with nutrients, the EPR was very low at only 0.45; the EPR value increased to 0.85 if we excluded the CO<sub>2</sub> from the system. The EPR value would rise more if we could substitute all the needed nutrients. Therefore, an integrated system for microalgae cultivation or overall microalgae oil production is preferable. An integrated microalgae cultivation system was partially designed and a study reported on a photo-bioreactor using wastewater, which resulted in an increased yield [39,40]. We expect that the EPR value can be increased with the increased yield.

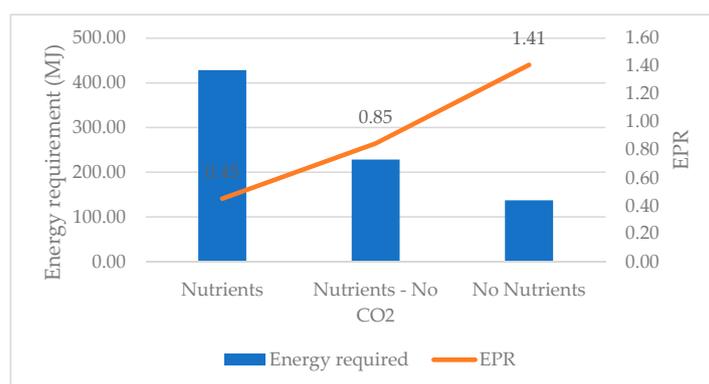


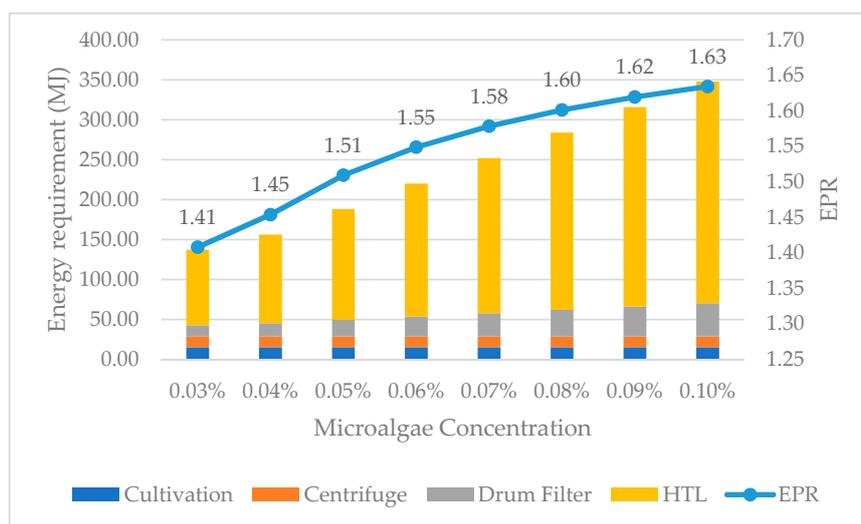
Figure 7. Energy profit ratio with nutrients and nutrients removed.

To determine the EPR value from the increase in biomass yield, we calculated different scenarios, from the existing 0.03% to a concentration of 0.1%. The other parameters are the same, with the paddlewheel running for 18 h and a culture depth of 0.2 m. The energy requirement for cultivation was mostly the same because of the constant paddlewheel operation, and the increased yield produced more energy, thereby helping to increase the EPR value. A similar scenario occurred in a centrifuge, which further increased the EPR value. The results are shown in Table 8.

Table 8. Energy profit ratio from scenarios with a culture depth of 0.2 m.

Microalgae Concentration	0.03%	0.04%	0.05%	0.06%	0.07%	0.08%	0.09%	0.10%
Cultivation (MJ)	15.40	15.40	15.40	15.40	15.40	15.40	15.40	15.40
Centrifuge (MJ)	13.39	13.39	13.39	13.39	13.39	13.39	13.39	13.39
Drum Filter (MJ)	14.17	16.67	20.84	25.00	29.17	33.34	37.50	41.67
HTL (MJ)	94.29	110.93	138.66	166.40	194.13	221.86	249.60	277.33
Energy required	137.25	156.39	188.29	220.19	252.09	283.99	315.89	347.79
Energy produced	193.27	227.38	284.22	341.06	397.91	454.75	511.60	568.44
EPR	1.41	1.45	1.51	1.55	1.58	1.60	1.62	1.63

The theoretical EPR value can reach more than 1, which indicates a positive energy balance; however, the field applications were typically lower than the theoretical value. Therefore, equipment optimization or an increased yield is still needed. The increasing yields in the scenarios showed an increase in the EPR. *Desmodium* yields reached 0.8 g/L in our experiment and [42] also achieved a yield of 0.758 g/L; several other studies were also included [34–36]. Figure 8 shows the EPR value increase with different yield scenarios.



**Figure 8.** Energy profit ratio (EPR) for different microalgae concentrations.

Increasing the concentration in the HTL input yielded a higher EPR; however, the HTL equipment design needs further improvement. A higher concentration in the HTL input means more microalgae and less water. Because the energy required to heat water is higher compared to heating microalgae, the energy requirement is expected to decrease. However, the higher the input concentration, the more likely the equipment is to clog and disrupt the HTL process. The HTL equipment in Minamisoma sometimes clogged with a higher input concentration. Therefore, an input concentration higher than 30% in HTL equipment was suggested for future research. Another aspect that needs to be considered is the use of a heat exchanger. The pilot project in Minamisoma did not utilize a heat exchanger; therefore, the energy requirement was higher. By incorporating a heat exchanger, the energy requirement is expected to decrease.

The EPR value in the system for a 0.03% microalgae concentration was 1.41. If we incorporate a heat exchanger, the EPR is expected to increase. The heat exchanger effectiveness was reported to vary between 0.6 and 1 [43]. We simulated the decreased energy requirement and assumed 10% to 50% energy reductions. Figure 9 shows the EPR by energy reduction in the four stages for the Minamisoma pilot plant.

Before being used as a biofuel feedstock, microalgae was mostly commercially produced for its nutritional value [7]. This type of cultivation did not pose problems for energy balance because the product was mostly for food (supplements), feed, or cosmetics. When the purpose was changed to energy production, the EPR was brought into serious consideration. We need to input less energy than the energy produced to make it a sustainable option.

The disadvantage of microalgae is its small size and high water content. These constraints should be overcome through developing equipment and reducing the processing time. On the other hand, the dewatering process requires higher energy if we utilize a centrifuge and filtration, compared to gravity sedimentation. Extraction using HTL also requires higher energy, which, in turn, results in a lower EPR for the overall product line. However, in a gravity-sedimentation system, the required time is longer, and the area is significantly more extensive.

Cultivating microalgae for energy production could be optimized by using traditional methods such as gravity sedimentation to harvest the microalgae; however, the trade-off is the processing time. Time and area could be a trade-off with the energy requirement. The EPR is the decision-making benchmark for the feasibility of converting pilot-type plants to industrial-scale or integrated microalgae production systems. The EPR of this research indicates that the current level of microalgae-cultivation technology for producing bioenergy is still on the border of being feasible. More research on productivity and machine efficiency are still needed.

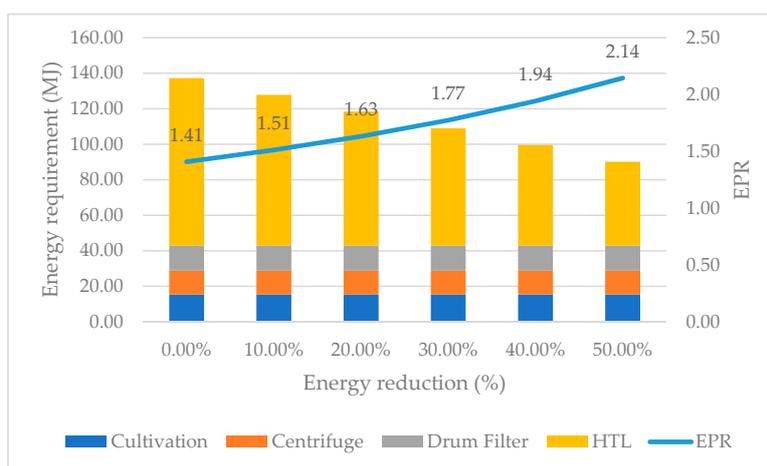


Figure 9. EPR status by energy reduction in the HTL process.

#### 4. Conclusions

The EPR result from the calculated energy requirement using a downstream approach for four stages in the Minamisoma pilot plant was more than 1, which means that the amount of energy produced was higher than the energy required in the four stages of oil extraction. The EPR was found to be more than 1 with a nutrient replacement, which indicated the potential of the Minamisoma pilot plant to move to the industrial scale. On the other hand, in the scenario without nutrient replacement, the EPR was lower than 1. In such a case, integrated microalgae production systems were recommended. A supply of nutrients from external sources (e.g., waste) could help mitigate the nutrient requirement, thereby reducing the energy requirement for nutrients.

An option to switch to more gravitation settling processes could help increase the EPR; however, the trade-off was a longer processing time. The other disadvantage was the area required, which is typically larger. The EPR could be increased by increasing the yield in the cultivation station or by changing the processing method to use technology with lower energy requirements.

Another option was to increase the machine efficiency by, for example, increasing the HTL equipment input concentration or incorporating a heat exchanger. Even though increasing the concentration of the HTL input was expected to yield a higher EPR, the HTL equipment design needs to be improved accordingly, because the higher input concentration makes it more likely for clogging to occur and disrupt the HTL process. The clogging problem in the HTL process has been successfully solved by other researchers, which makes the HTL process more promising and increases the possibility for expansion to a larger scale.

By knowing the EPR value, we can determine which process needs more attention, and take the necessary precautions to minimize the energy requirements for oil extraction. Therefore, this research recommends scaling up the Minamisoma pilot project to an industrial scale, based on the EPR, as preparation for a bigger picture of ensuring energy security.

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## Nomenclature

Parameters	Value	Unit
Open raceway pond		
Length ( $a$ )	50	m
Width ( $b$ )	20	m
Channel width ( $w$ )	10	m
Height ( $h$ )	0.2	m
Area	1000	m <sup>2</sup>
Volume	200	m <sup>3</sup>
HRT	4	days
Harvest	50	m <sup>3</sup> /d
Paddlewheel running time	18	h
Centrifugation		
Horsepower for feed acceleration ( $P_{acc}$ )	4.99	HP
	13.39	MJ
Specific gravity feed slurry ( $sg$ )	1000.02	kg/m <sup>3</sup>
Volumetric flow rate of feed ( $Q$ )	1.33	L/s
Angular speed ( $\omega$ )	10,000.00	rpm
Radius of the bucket ( $rp$ )	0.25	m
Filtration		
Feed capacity	520	kg/hr
Running time	2.77	hr
Extraction		
<i>Desmodesmus</i> sp. Properties		
Water	5.70	%
Fatty acids	13.00	%
Protein	45.70	%
Polysaccharide	21.10	%
Ash	14.50	%
Specific heat		
Water	4.18	kJ/(kg·°C)
Fatty acids	2.30	kJ/(kg·°C)
Protein	1.47	kJ/(kg·°C)
Polysaccharides	1.26	kJ/(kg·°C)
Ash	0.73	kJ/(kg·°C)
HTL equipment		
Mass	70.81	Kg
Microalgae concentration	20	%
Water concentration	80	%
$C_p$ microalgae	1.58	kJ/(kg·°C)
$C_p$ water (average)	4.73	kJ/(kg·°C)
Initial temperature	25	°C
Final temperature	350	°C

**Appendix A. Microalgae Biomass Stoichiometry**

		CO <sub>2</sub>	+	0.148 HNO <sub>3</sub>	+	0.014 H <sub>2</sub> SO <sub>4</sub>	+	0.012 H <sub>3</sub> PO <sub>4</sub>	+	0.751 H <sub>2</sub> O	→	CH <sub>1.715</sub> O <sub>0.427</sub> N <sub>0.148</sub> S <sub>0.014</sub> P <sub>0.012</sub>	+	1.437 O <sub>2</sub>
MW	g/mol	44.01		63.01		98.08		98.00		18.02		23.47		32.00
#mol	mol	511.39		75.69		7.16		6.14		384.06		511.39		734.87
Mass	g	22,506.89		4769.36		702.17		601.38		6919.14		12,000.00		23,515.83
	kg	22.51		4.77		0.70		0.60						

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