

Article

An Evaluation Study of Energy Consumption and Efficiency of Algal Hydrothermal Liquefaction Processes

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Abstract

Hydrothermal liquefaction (HTL) has been widely investigated as a suitable process method for the preparation of alternative fuels from algae, due to its mild reaction conditions and environmentally benign reaction medium. HTL requires heat input to a large amount of aqueous phase medium, which accounts for most of the heat consumption in the bio-crude preparation stage; in addition, co-processing requires bio-crude as a feedstock for the fuel refinery system. Therefore, energy consumption in the preparation stage of bio-crude is important for industrial cost control. In this paper, HTL from different types of algae and process methods is evaluated from the perspective of energy consumption. One-step HTL, two-step HTL, and co-solvent system HTL were modelled and calculated using the chemical simulation software Aspen Plus. Five algal species with lipid contents ranging from 6.15 wt% to 47.80 wt% were evaluated. The results showed that both process method and algal species had a significant effect on the energy consumption of the HTL process. The co-solvent system HTL using a methanol:water ratio of 1:19 (*v/v*) and an ethanol:water ratio of 3:97 (*v/v*) consumed less heat (based on fatty acids and fatty acid esters (FAFES)) than one-step HTL while obtaining high quality bio-crude. Two-step HTL has about 20% higher process heat consumption, although there are advantages in bio-crude quality and by-products over one-step HTL.

Keywords: algae; bio-crude; hydrothermal liquefaction (HTL); energy consumption



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1. Introduction

Algal biofuels can achieve negative carbon emissions over their entire lifecycle [1]. Consequently, the use of algal biofuels is emerging as a significant means of reducing carbon emissions in aviation. It has been shown that algae-based biomass is more suitable for use in the hydrothermal liquefaction (HTL) process due to its high water content [2], which avoids high energy consumption compared to the drying step required by other conversion technologies [3]. HTL has been experimentally studied by a large number of research teams as an ideal process for the production of hydrocarbon fuels from microalgae due to its environmental friendliness and mild conditions.

The key mechanisms and detailed reaction pathways of HTL are complex because microalgal biomass contains a complex mixture of proteins, carbohydrates and lipids, but

the HTL process involves three key steps: depolymerization, catabolism, and recombination [4]. By controlling the experimental conditions, the rate and direction of conversion of the key steps can be directionally regulated.

Based on the compositional properties of algae, carbohydrates typically hydrolyse first during HTL, starting at 120 °C. Hemicellulose is hydrolysed to 85% at 180 °C, while cellulose achieves full conversion by 280 °C [5,6]. Their hydrolysis products, such as 5-HMF and furfural, can further condense with reducing sugars above 200 °C to form solid humins, which contribute to solid residue formation. To suppress these by-products, two-step HTL has been proposed [7]. Two-step HTL ensures a high bio-crude yield with a lower solid residue yield, which is positive for microalgae HTL. In addition, the bio-crude produced by the two-step process has a relatively low nitrogen (N) content [8].

Proteins begin to hydrolyse at around 140 °C, with yields peaking at 260 °C and continuing up to 400 °C [9]. The resulting amino acids may undergo deamidation, self-condensation, or react with reducing sugars via the Maillard reaction above 140 °C to form N-heterocycles [10]. Additionally, amino acids can generate hydrocarbons and oxygenates through deamino-decarboxylation, enhancing bio-crude yield.

Lipids, present as triglycerides and others, hydrolyse between 180 and 350 °C into fatty acids and glycerol [11]. In alcohol–water co-solvents, fatty acid esters form instead [12]. While fatty acids can also react with ammonia from protein deamination to produce amides, adding methanol/ethanol significantly suppresses amide formation by altering product selectivity [13]. In a study by Chen et al. [14], it was noted that the highest yield of bio-crude was achieved when 40% (*v/v*) ethanol/water co-solvent was used as the medium. The ethylhexadecanoate in the bio-crude increased with increasing ethanol content. Contrary to the use of water, the added organic solvent needs to be distilled out after HTL; otherwise, some of the fatty acids will enter the organic phase and negatively affect the bio-crude yield.

Energy consumption has been found to be a major cost of many energy-intensive chemical processes due to the need for a negative entropy flow input during biofuel production [15]. The conversion of resources into useful products generates work, heat and material inputs [16]. In the industrial application of algal biomass for the preparation of biofuels, the energy input of the chemical production process is an issue that needs to be taken into account, which is related to the cost of production of the product as well as the energy saving and emission reduction. Biomass fuels in the production process need to strictly control the process of fire loss and the input of negative entropy flow, in order to effectively convert the energy in its biomass into effective energy.

For the biofuel production process from oil-bearing crops, exergy analysis and energy analysis studies have been carried out by researchers. Peralta et al. [17] carried out exergy analysis of material and energy flows for biodiesel production from *Chlorella* (100,000 t/a) through Aspen Plus software and affirmed the potential of third-generation biomass for biofuel production. Talens et al. [18] evaluated and compared the production of 1 t of biodiesel from waste grease and rapeseed crops. The energy consumption, total investment, and environmental restoration costs of the waste oil and grease production process were lower than those of rapeseed crops. Sorguven et al. [19] concluded that the algae–biodiesel–CO₂ cycle provided positive useful work, with nearly three-quarters of the energy used for production and environmental restoration. Some studies have introduced alternative definitions of energy efficiency to measure the conversion rate of input energy into the target product or the overall output efficiency of energy. This can be used to conduct a comprehensive evaluation of processes in relation to system energy consumption [16].

Algal biomass typically has a natural moisture content exceeding 90% [20]. In the HTL process, the aqueous phase constitutes over 90% of the total feed mass, and this entire feed stream must be heated uniformly. In contrast, the subsequent production of hydrocarbon

fuels involves removing water with its high heat capacity, requiring heating only for the remaining oil phase [21]. Therefore, the heat input during the HTL stage represents the dominant energy-consuming phase in the overall biofuel production pathway. Meanwhile, the feasibility of the co-refinery process for the preparation of hydrocarbon fuels and the effective reduction in the cost of biomass fuel preparation have been proposed [22–25]. Therefore, it is significant to explore the energy consumption analysis of the HTL stage of biomass for the industrial application of biomass fuel preparation.

Currently, there are relatively few studies on the energy consumption analysis of different HTL process methods. Industrial modelling based on experimental processes can provide a theoretical basis for industrial applications. There have been some previous findings on the yield and chemical composition of biomass HTL products. In this paper, the HTL process with different types of algae and process methods will be evaluated from the perspective of energy consumption. Numerical calculations have been carried out using Aspen Plus to simulate the HTL process, aiming to identify the main energy consumption units and to provide a theoretical basis for optimizing this key step in the conversion of wet algal biomass.

2. Materials and Methods

2.1. Raw Materials and HTL Products

Based on their varying lipid contents, five representative algal species (*Spirulina* spp., *Chlorella* spp., *Nannochloropsis* spp., *Schizochytrium* spp., and *Chlorella protothecoides*) were selected for this study. These species have been extensively employed by numerous researchers in investigations related to bio-crude production. Relevant experimental results from HTL studies have been previously published. The compositional differences among these five algal species are presented in Table 1 (normalization).

Table 1. Biochemical components of algae [26].

Biological Component	<i>Spirulina</i> spp.	<i>Chlorella</i> spp.	<i>Nannochloropsis</i> spp.	<i>Schizochytrium</i> spp.	<i>Chlorella protothecoides</i>
Protein/wt%	64.27	57.81	40.82	16.92	12.87
Lipid/wt%	6.15	14.37	20.70	42.94	47.80
Carbohydrate/wt%	17.74	20.51	29.03	32.90	31.64
Ash/wt%	11.84	7.31	9.45	7.23	7.69

The yields of different products and the quality of the bio-crude were varied by one-step, two-step, and co-solvent system HTL processes. Generally, higher fatty acids and fatty acid esters (FAFEs) in bio-crude correlates with higher quality, as these components readily convert to alkanes via hydrodeoxygenation compared to other constituents. Table 2 lists the product information from the three HTL processes for *Nannochloropsis* spp. The elemental analysis results of raw materials and bio-curde are shown in Table A1.

Table 2. Summary of product yields and FAFE content in bio-crude from one-step, two-step, and co-solvent system HTL processes.

Process Conditions	Yield (g/100 g) ¹				FAFEs in Bio-Crude (%)
	Bio-Crude	Solid Residue	Gas	Aqueous Phase	
One-step HTL					
240 °C, 3 min	26.69	12.30	6.81	54.19	61.39
260 °C, 3 min	28.11	8.89	8.02	54.98	63.37
280 °C, 3 min	28.74	8.56	9.20	53.50	63.21

Table 2. Cont.

Process Conditions	Yield (g/100 g) ¹				FAFEs in Bio-Crude (%)
	Bio-Crude	Solid Residue	Gas	Aqueous Phase	
300 °C, 3 min	28.99	6.16	9.53	55.32	65.14
240 °C, 30 min	26.46	12.18	6.81	54.55	69.59
260 °C, 30 min	26.03	7.34	8.02	58.61	61.18
280 °C, 30 min	27.22	4.19	9.20	59.39	60.54
300 °C, 30 min	26.36	3.41	9.53	60.70	56.44
Two-step HTL (HTL 1: 180 °C, 30 min)					
HTL 2: 240 °C, 30 min	25.79	3.80	6.81	63.60	70.28
HTL 2: 260 °C, 30 min	24.71	2.70	8.02	64.57	58.7
HTL 2: 280 °C, 30 min	22.58	1.30	9.20	66.92	50.44
HTL 2: 300 °C, 30 min	21.71	1.76	9.53	67.00	51.86
Co-solvent system HTL (MeOH:H ₂ O) ¹					
4:6 (v:v), 240 °C, 30 min	31.41	5.84	6.82	55.94	87.03
4:6 (v:v), 250 °C, 30 min	34.64	4.44	7.42	53.50	86.37
4:6 (v:v), 260 °C, 30 min	32.08	3.62	8.02	56.28	86.30
4:6 (v:v), 270 °C, 30 min	28.22	3.75	8.59	59.44	85.67
3:97 (v:v), 250 °C, 30 min	31.63	5.40	7.42	55.55	67.73
1:19 (v:v), 250 °C, 30 min	32.08	4.71	7.42	55.79	74.01
1:9 (v:v), 250 °C, 30 min	31.64	4.96	7.42	55.98	79.47
1:4 (v:v), 250 °C, 30 min	32.37	4.56	7.42	55.65	84.24
3:7 (v:v), 250 °C, 30 min	32.17	4.66	7.42	55.75	86.57
Co-solvent system HTL (EtOH:H ₂ O) ¹					
4:6 (v:v), 240 °C, 30 min	33.75	5.56	6.82	53.87	80.10
4:6 (v:v), 250 °C, 30 min	35.88	4.55	7.42	52.15	81.22
4:6 (v:v), 260 °C, 30 min	34.20	3.57	8.02	54.21	81.61
4:6 (v:v), 270 °C, 30 min	32.52	4.28	8.59	54.61	79.45
3:97 (v:v), 250 °C, 30 min	31.32	5.51	7.42	55.75	66.72
1:19 (v:v), 250 °C, 30 min	31.69	4.44	7.42	56.45	64.04
1:9 (v:v), 250 °C, 30 min	32.04	4.79	7.42	55.75	75.55
1:4 (v:v), 250 °C, 30 min	31.85	4.77	7.42	55.96	79.23
3:7 (v:v), 250 °C, 30 min	32.36	5.24	7.42	54.98	77.13

¹ The aqueous phase yield was obtained by the difference method, ensuring that bio-crude + solid + gas + aqueous = 100 g/100 g. To evaluate the trade-off between yield and energy consumption, we focused on ratios at or below this optimum, as high alcohol content increases process energy demand [13].

On the other hand, to investigate the impact of different species of algae, other types of algal biomass were primarily processed using the one-step HTL method. The relevant results can be found in reference [26].

2.2. Process Model Classification

In this paper, based on real experimental data and the calculation method of the chemical simulation software Aspen Plus V11, the material flow, heat consumption of each unit, and electricity consumption of the equipment of HTL are effectively simulated according to the accurate model setting and boundary conditions.

In the case of algal biomass, the type of raw material and the process method have a great influence on the yield and quality of the product. It was found that the two-step method and HTL with alcohol–water co-solvent as the liquid phase environment resulted in higher-quality bio-crude relative to one-step methods. The addition of methanol and ethanol and the setting of the HTL unit in the second step resulted in differences in the process models of the different process methods. In order to more accurately simulate the

process energy consumption of HTL of algae, the process is divided into one-step HTL, two-step HTL, and co-solvent system HTL in this paper. One-step HTL, two-step HTL, and co-solvent system HTL process models are shown in Figure 1a–c.

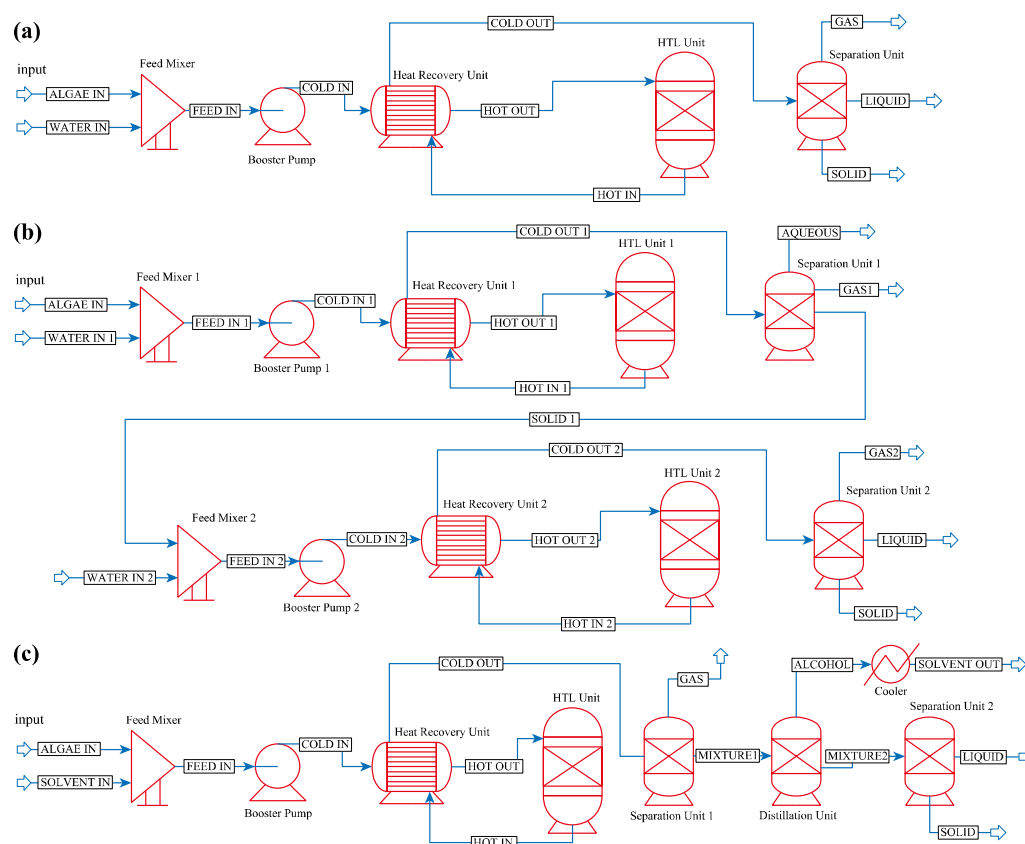


Figure 1. Algae HTL process model of (a) one-step HTL, (b) two-step HTL, and (c) co-solvent system HTL.

2.3. Process Simulation and Calculation Parameters

Accurate modelling of the process is a necessary step to ensure that accurate calculation results are obtained. During the modelling process, the appropriate module must be selected for the different reaction conditions and known boundary conditions. The study employs product composition and reaction conditions as the boundary conditions for simulation. In the reactor model, the RYIELD module is suitable for reaction units with known product information and is suitable for application in this simulation. In the separator model, the SEP module is suitable for material separation units, which are mainly used for solid–liquid separation or solid–liquid–gas separation in this simulation. In the heat exchanger model, the HEATX module is used to handle hot flow in and out and cold flow in and out, and could be used to recover the waste heat from the main energy consuming units. Typically, heat recovery efficiency can exceed 80% in industrial steam boiler systems [27]. Therefore, the heat recovery efficiency of the main energy consumption unit in this paper is set to 80%. The parameter settings for each module in the model are described in Table 3. In this case, the HTL product information is based on experimental data previously performed by the authors [13,26]. Gas product information is based on Tang et al. [28]. The yield of protein hydrolysis to amino acids is based on Hanna et al. [9]. The ambient temperature of the simulated process was set to 25 °C and the pressure to 1 atm. The feed rate was uniformly set at 100 kg/h of biomass feedstock.

Table 3. Parameters setting of the main modules in the process model.

Unit Name	Module Selection	Parameters Setting	Mass
One-step HTL [9,13,26,28]			
Input ¹	Material Flow Unit	Algae: 100 kg/h Water: 1000 L/h 25 °C, 1 atm	Algae:water = 1:10
Feed Mixer	Mixer		Algae:water = 1:10
Booster Pump	PUMP	Saturation pressure + 5 atm	Algae:water = 1:10
Heat Recovery Unit	HeatX	80% of HTL unit heat load	Algae hydrolysate, water
HTL Unit	RYield	180–300 °C, saturation pressure + 5 atm	Algae hydrolysate, water GAS: gas product
Separation Unit	Sep	Solid–liquid–gas separation	LIQUID: by-product in water SOLID: bio-crude, solid residue
Two-step HTL [9,13,28]			
Input 1 ¹	Material Flow Unit	Algae: 100 kg/h Water: 1000 L/h 25 °C, 1 atm	Algae:water = 1:10
Input 2 ¹	Material Flow Unit	Water: 535 kg/h 25 °C, 1 atm	
Feed Mixer 1	Mixer		Algae:water = 1:10
Booster Pump 1	PUMP	15 atm	Algae:water = 1:10
Heat Recovery Unit 1	HeatX	80% of HTL unit heat load	Bio-char, by-product in water
HTL Unit 1	RYield	180 °C, 15 atm	Bio-char, by-product in water SOLID1: bio-char
Separation Unit 1	Sep	Solid–liquid separation	AQUEOUS: by-product in water
Feed Mixer 2	Mixer		Algae:water = 1:10
Booster Pump 2	PUMP	Saturation pressure + 5 atm	Algae:water = 1:10
Heat Recovery Unit 2	HeatX	80% of HTL unit heat load	Algae hydrolysate, water
HTL Unit 2	RYield	240–300 °C, saturation pressure + 5 atm	Algae hydrolysate, water GAS: gas product
Separation Unit 2	Sep	Solid–liquid–gas separation	LIQUID: by-product in water SOLID: bio-crude, Solid residue
Co-solvent system HTL [9,13,28]			
Input ¹	Material Flow Unit	Algae: 100 kg/h Water–alcohol: 1000 L/h 25 °C, 1 atm	Algae:methanol solution = 1:10
Feed Mixer	Mixer		Algae:water = 1:10
Booster Pump	PUMP	Saturation pressure + 5 atm	Algae:water = 1:10
Heat Recovery Unit	HeatX	80% of HTL unit heat load	Algae hydrolysate, methanol solution
HTL Unit	RYield	240–270 °C, saturation pressure + 5 atm	Algae hydrolysate, methanol solution GAS: gas product
Separation Unit 1	Sep	Liquid–gas separation	MIXTURE1: algae hydrolysate, methanol, water
Distillation Unit	Sep	MeOH: 0.2 atm, 29 °C EtOH: 0.1 atm, 30 °C	ALCOHOL: methanol MIXTURE2: algae hydrolysate, water
Separation Unit 2	Sep	Solid–liquid separation	LIQUID: by-product in water SOLID: bio-crude, solid residue

¹ The material is input at a solid–liquid ratio of 1/10.

In order to improve the accuracy of the simulation results, it is necessary to set the boundary conditions accurately. Since the compounds in the biomass raw material and HTL products are complex in composition, it is necessary to find model compounds with similar properties to replace them in the simulation. In this paper, proteins, lipids, sugars, and ash in the raw material are replaced by dipeptides (C₄H₁₀N₂O₃), triglycerides (C₅₁H₉₈O₆), glucose (C₆H₁₂O₆), and potassium carbonate (K₂CO₃), respectively. Solid residues in the products are replaced by humins (C₁₄H₁₅N₃O₂). Fatty acids, fatty acid esters, and fatty acid amides in the bio-crude are replaced by the content of the highest hexadecanoic acid, hexadecanoic acid ester, and hexadecanamide, respectively. N heterocyclic compounds

were expressed as methyl indole (C_9H_9N). In order to ensure the reliability of the energy consumption comparison analysis, all models have been substituted with the same model compound to replace complex mixtures. It should be acknowledged that representing complex bio-crude fractions by single model compounds introduces simplifications, particularly for distillation and solvent recovery simulations. This simplification is justified for the comparative scope of the present study, as the same representative compounds are applied uniformly across all simulated cases and similar practices have been adopted in previous HTL energy and exergy assessments [16]. While a more detailed composition-based model would be advisable for future industrial design, the current approach remains reliable for the comparative purposes of this work. The HTL processes simulated were conducted under subcritical water conditions. In the Aspen Plus simulation, the pressure for all relevant units was uniformly set to 5 atm above the saturation pressure of water at the corresponding reaction temperature. This ensures the water remains in a liquid (subcritical) state throughout the process.

The Non-Random Two-Liquid (NRTL) model is widely used for handling binary and multi-liquid mixtures, capable of accurately simulating phase equilibrium, phase separation, and other thermodynamic properties of liquid mixtures [29–31]. In this study, since the primary environment involves polar liquids and some processes involve liquid–liquid phase equilibrium of methanol/ethanol–water co-solvents, the NRTL property method [32] is used to predict the activity coefficients of components in the liquid phase. However, NRTL is not suitable for thermodynamic calculations under high-pressure conditions. Therefore, the SR-POLAR property method was selected as a supplement for the high-pressure hydrothermal unit in the process [33]. The SR-POLAR method was consistently applied to all high-pressure units (HTL reactor, heat exchangers, and pumps) for enthalpy and heat balance calculations, while NRTL was used only for low-pressure liquid–liquid equilibrium calculations. Consequently, the calculated energy consumption values are thermodynamically valid for the subcritical water conditions, and the results are used for comparative analysis of energy efficiency across different process configurations.

2.4. Evaluation Indicators

In order to include the yield and quality of bio-crude in the evaluation system of process energy consumption, the results of energy consumption calculations will be presented in two standards: based on the bio-crude and based on the fatty acids and fatty acid esters (FAFES), respectively.

HC_b is defined as the amount of heat energy consumed to produce 1 kg of bio-crude. EC_b is defined as the electrical energy consumed to produce 1 kg of bio-crude. HC_f is defined as the heat energy consumed to produce 1 kg of FAFES. EC_f is defined as the electrical energy consumed to produce 1 kg of FAFES.

In order to evaluate and compare the energy utilization efficiency of biomass conversion to bio-crude through HTL under different process models, some indicators were identified as defined below:

(a) Energy efficiency of bio-crude (η_b)

The η_b is used to measure the extent to which the total input energy to the production system is converted into bio-crude, as shown in Equation (1).

$$\eta_b = \frac{E_{bio-crude}}{E_{input}} = \frac{m_{bio-crude} \times HHV_{bio-crude}}{m_{algae} \times HHV_{algae} + m_{solvent} \times HHV_{solvent} + E_{heat+electricity}} \quad (1)$$

where $E_{bio-crude}$ is calculated based on the higher heating value (HHV) of bio-crude; E_{input} is the total input energy to the system per kilogram of bio-crude, including biomass, heat,

and electricity; and η_b measures the degree of conversion of input energy within the system to the target product (bio-crude).

(b) Energy efficiency of the system (η_s)

The η_s is used to measure the degree of energy utilization of the system, as shown in Equation (2).

$$\eta_s = \frac{E_{\text{system}}}{E_{\text{input}}} = \frac{E_{\text{all input}} - Q_{\text{loss}}}{E_{\text{all input}}} \quad (2)$$

where E_{system} is the total energy outputs of the products, including bio-crude, gas products, and other by-products; Q_{loss} is the heat loss of the system; and η_s measures the output efficiency of total energy (including by-products), thereby indicating the extent of energy losses within the system.

(c) Recovery energy efficiency (η_r)

The η_r is used to measure the recovery efficiency of the process, as shown in Equation (3).

$$\eta_r = \frac{E_r}{E_{\text{input}}} = \frac{E_{\text{bio-crude}} + E_{\text{solvent}}}{E_{\text{input}}} \quad (3)$$

where E_r denotes substances within the process that can be directly recovered. This primarily applies to co-solvent processes, where methanol and ethanol can be directly recovered, thereby enhancing the recovery efficiency of the system.

The energy of gaseous products in the system is obtained by multiplying the mass of combustible material in the gases by HHV. The energy of solid residues is calculated by the difference method.

3. Results

3.1. Energy Consumption of Different Processes

Nannochloropsis spp. possess the advantages of rapid growth, low cultivation costs, and high lipid content [34]. Furthermore, the bio-crude produced through its HTL process is rich in C16 compounds, making it suitable for subsequent hydrogenation into sustainable aviation fuel (SAF) [26]. Consequently, it was selected as the model feedstock. The effects of the HTL process conditions of *Nannochloropsis* spp. have been explored relatively comprehensively in previous studies [13]. In this section, three process models will be analysed for energy consumption.

3.1.1. One-Step HTL

The one-step HTL model is shown in Figure 1a. Energy consumption analysis was conducted on the HTL process using deionized water as the medium. Figure 2a,b show the heat and electrical energy consumption for the preparation of 1 kg of bio-crude and FAFEs, respectively. The process retention times were 3 min and 30 min.

Based on the energy consumption results, it is evident that as the reaction temperature exceeds 240 °C, the heat and electrical energy consumption of the preparation process gradually increases. Furthermore, when the reaction temperature is higher than 260 °C, the energy consumption per unit mass of bio-crude and FAFEs produced is lower at a retention time of 3 min compared to 30 min at the same temperature. However, the process conditions with the lowest energy consumption are listed in the results for the one-step process at 240 °C for 30 min. Under these conditions, the heat and electrical energy consumption for producing 1 kg of bio-crude are 9.31 MJ/kg and 0.55 MJ/kg, respectively, while the heat and electrical energy consumption for producing 1 kg of FAFEs are 13.38 MJ/kg and 0.79 MJ/kg, respectively. It is evident that heat consumption increases gradually with rising temperature because heating the raw materials and aqueous phase

to higher temperatures requires more heat energy input. The primary reason for the increase in electrical energy consumption with rising temperature is that the saturated vapour pressure of water increases with temperature. To maintain normal flow of the hydrothermal process in subcritical water, pressure pumps must compress the material to higher pressures under higher temperature conditions.

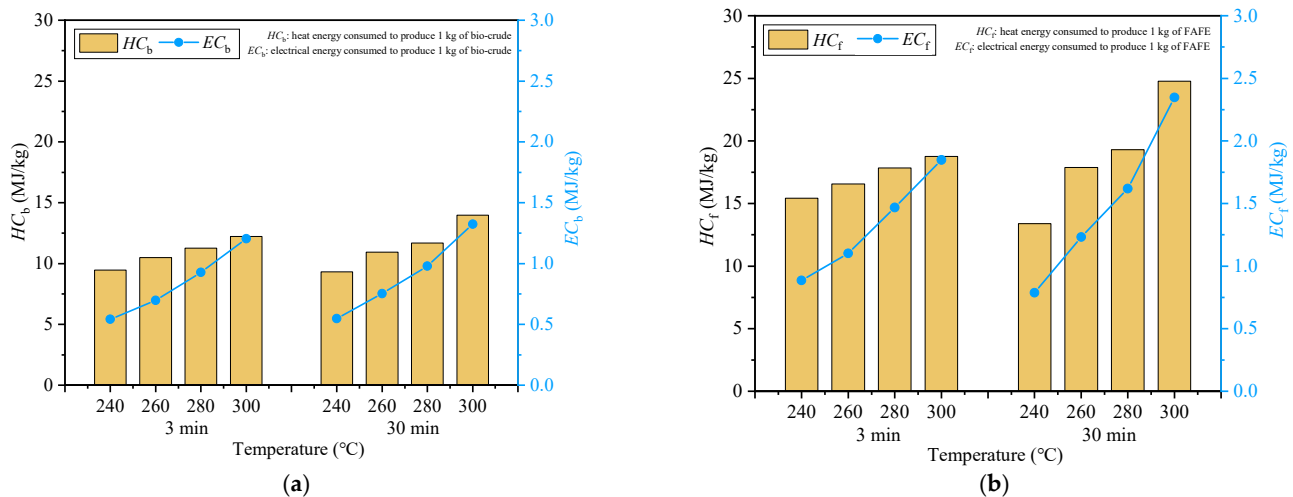


Figure 2. Energy consumption of one-step HTL of *Nannochloropsis* spp. (a) based on bio-crude and (b) based on FAFEs.

3.1.2. Two-Step HTL

The bio-crude produced by the two-step HTL not only has lower nitrogen content but also generates less solid residue during the process. The process model of two-step HTL is shown in Figure 1b.

Figure 3 compares the one-step and two-step HTL processes under different temperature conditions. In the two-step process, the low-temperature hydrothermal condition is 180 °C for 30 min, and the second hydrothermal step also uses a retention time of 30 min. The one-step process uses a retention time of 30 min as a control. Under various temperature conditions, the heat consumption of the two-step HTL is 18.1–29.2% higher than that of the one-step HTL at the same temperature. Among these, the two-step process has the lowest energy consumption at a second-step temperature of 240 °C, with a heat consumption of 11.26 MJ/kg per unit mass of bio-crude, which is 20.9% higher than that of the one-step process at the same temperature. Under these conditions, the heat consumption per unit mass of FAFEs was 16.02 MJ/kg, approximately 19.7% higher than that of the one-step method at the same temperature. Although the two-step method has higher heat consumption than the one-step method, it still holds application potential for improving the quality of bio-crude and the graded utilization of biomass energy.

3.1.3. Co-Solvent System HTL

The HTL process with *Nannochloropsis* spp. as the raw material and methanol/ethanol–water co-solvent as the liquid-phase medium requires the addition of a distillation unit to fractionate methanol/ethanol after the HTL unit, for two reasons: (1) unfractionated methanol/ethanol leads to part of the fatty acids being dissolved in organic solvent–water co-solvent, which affects the recovery of the bio-crude; and (2) fractionation of methanol/ethanol increases the recycling of organic solvents in the system and decreases the cost of production. The process model for the co-solvent system HTL is shown in Figure 1c. In this case, the distillation unit is carried out under negative pressure to reduce the process heat consumption, so it is necessary to equip the distillation unit with a vacuum

pump. In this simulation, the vacuum degree of the methanol distillation unit is set to 0.8 atm, and the vacuum degree of the ethanol distillation unit is set to 0.9 atm to ensure that the distillation unit can normally separate methanol/ethanol from the system at a temperature of around 30 °C. According to the feed amount of biomass (100 kg/h) and alcohol–water co-solvent (1000 L/h), the electric power of the vacuum pumps for the two types of distillation units is set to 1 kW and 1.5 kW, respectively, in order to ensure the vacuum conditions in the distillation unit.

The results of the effect of temperature on the heat consumption of the co-solvent system HTL with alcohol/water = 40% (v/v) are shown in Figure 4. It is clear that both methanol/water and ethanol/water co-solvents have the lowest heat consumption at 250 °C, and the energy consumption increases gradually with increasing temperature. The process heat consumption for production per unit mass of bio-crude at 250 °C was 17.40 MJ/kg and 14.40 MJ/kg bio-crude, respectively. For the production of FAFEs per unit mass, the process heat consumption was 20.14 MJ/kg and 17.73 MJ/kg of FAFEs, respectively. This is related to the fact that *Nannochloropsis* spp. achieve the highest bio-crude yield in an alcohol–water co-solvent medium at 250 °C [19].

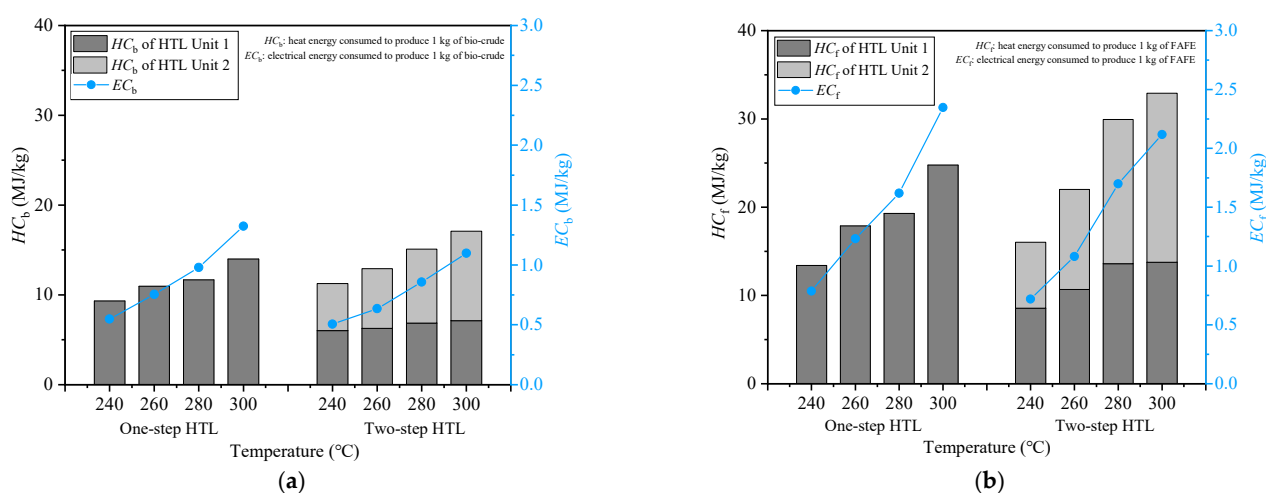


Figure 3. Energy consumption of two-step HTL of *Nannochloropsis* spp. (a) based on bio-crude and (b) based on FAFEs.

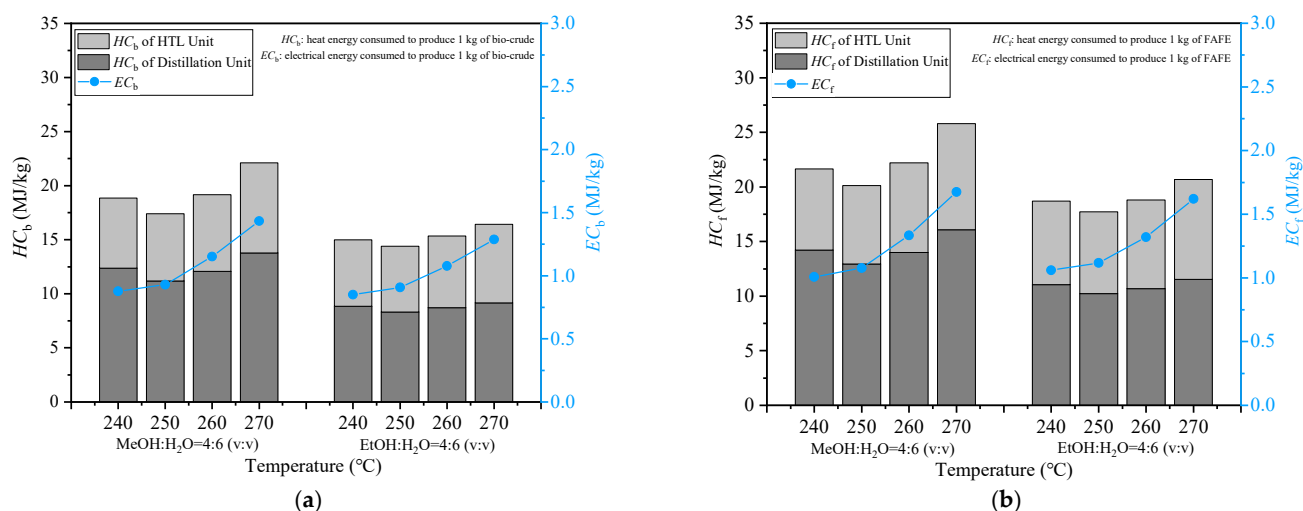


Figure 4. Energy consumption of co-solvent system HTL of *Nannochloropsis* spp. with 40% (v/v) alcohol–water co-solvent (a) based on bio-crude and (b) based on FAFEs.

In the analysis of the co-solvent system with a liquid phase medium of alcohol:water = 4:6 (v:v), it was clearly observed that the process heat consumption of the co-solvent system was generally higher than that of the one-step process. According to the results of the above analysis, the heat consumption of methanol/ethanol:water = 4:6 (v:v) co-solvents to produce a unit mass of bio-crude was 86.8% and 54.6% higher than that of one-step HTL at 240 °C for 30 min, respectively. Similarly, under the same process conditions, the heat consumption for producing a unit mass of FAFEs using methanol/ethanol:water = 4:6 (v:v) as a co-solvent is also 50.5% and 32.4% higher than that of one-step HTL.

Obviously, the latent heat of vaporization of alcohols elevates the energy consumption of the HTL process, which will lead to a challenging industrial application of the co-solvent system HTL. Addressing this challenge, reducing the concentration of organic solvents in the co-solvent has become a key strategy for lowering the energy consumption of this process model. Figure 5a,b further illustrate the impact of different methanol/ethanol concentrations in the co-solvent on the energy consumption of the co-solvent system HTL.

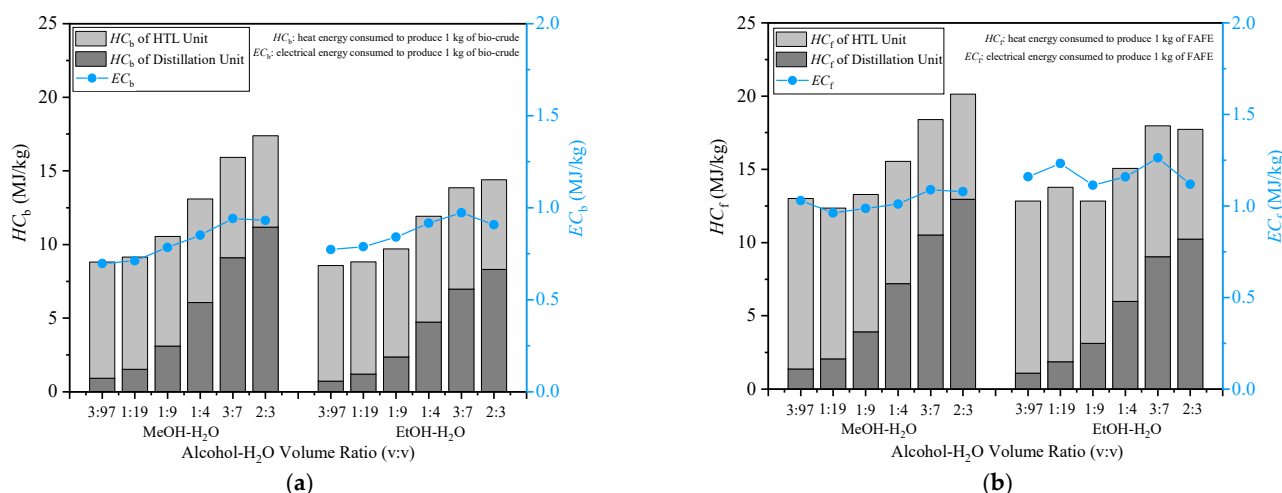


Figure 5. Energy consumption of co-solvent system HTL of *Nannochloropsis* spp. with different concentrations of co-solvents (a) based on bio-crude and (b) based on FAFEs.

This study selected an alcohol–water co-solvent system HTL with a retention time of 30 min at 250 °C. The ratio of methanol or ethanol to water in the co-solvent was increased from 3:97 (v:v) to 4:6 (v:v). The heat consumption for producing a unit mass of bio-crude showed an upward trend with the increase in alcohol content in the co-solvent. For the preparation of FAFEs per unit mass, the heat and electricity consumption of methanol–water and ethanol–water co-solvents reached their minimum values at methanol:water = 1:19 (v:v) and ethanol:water = 3:97 (v:v), respectively, with heat consumption values of 12.36 MJ/kg and 12.83 MJ/kg of FAFEs, respectively, which are 7.6% and 4.1% lower than the one-step process at 240 °C for 30 min. The electricity consumption for the two processes is 0.96 MJ/kg and 1.16 MJ/kg of FAFEs, respectively, slightly higher than the 0.79 MJ/kg of FAFEs for the one-step process at 240 °C for 30 min. The higher electricity consumption of this process compared to the one-step process is primarily due to the higher saturated vapour pressure of the co-solvent compared to water, which requires a pressure pump to compress the material to a higher pressure. Additionally, the vacuum pump in the vacuum distillation unit also consumes a certain amount of electricity. This result highlights the significant impact of the content of different organic solvents in the co-solvent system on the energy consumption of the HTL process.

The statistics on alcohol consumption for different processes in the alcohol–water co-solvent system HTL are shown in Figure 6. Under identical conditions, ethanol consumption is generally lower than that of methanol. This difference can likely be attributed to the more complete progression of the esterification reaction for methanol under the given system parameters. Furthermore, as the alcohol content increases, methanol consumption rises significantly. In contrast, ethanol consumption plateaus and stabilizes once the alcohol-to-water ratio exceeds 1:4 (v:v).

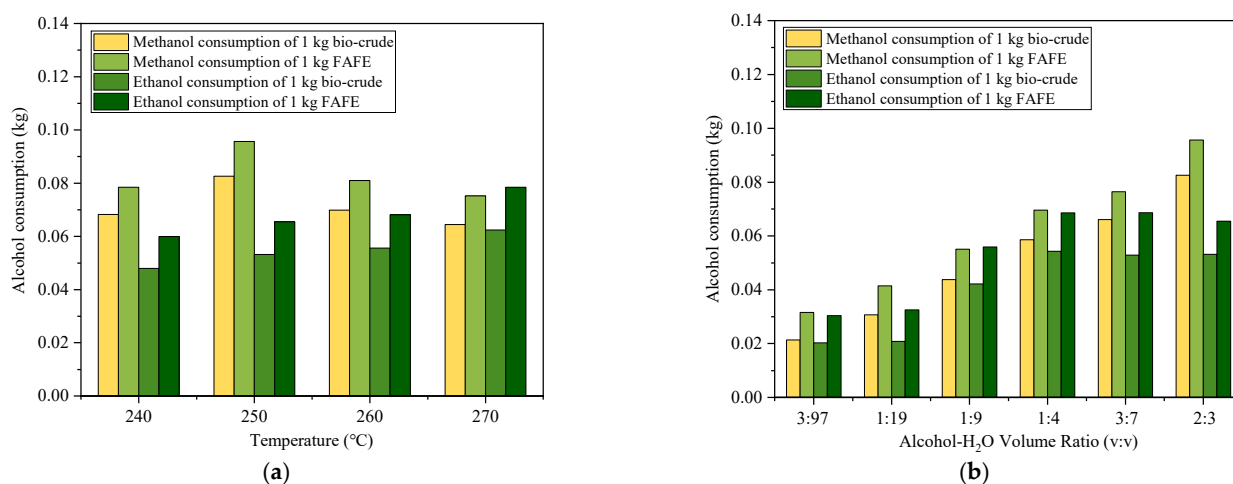


Figure 6. Alcohol consumption of co-solvent system HTL in *Nannochloropsis* spp. under different conditions: (a) alcohol–water = 2:3 (v:v); (b) 250 °C for 30 min.

The preceding section calculated and analysed the consumption of heat and electricity for the three process models under different conditions. Through a comparison of the conclusions, it was found that, compared to the one-step process, the two-step process consumes approximately 20% more heat energy than the one-step process when producing the same unit mass of bio-crude at the same temperature. For the HTL process using an alcohol–water co-solvent system, when preparing a unit mass of FAFEs at a temperature of 250 °C for 30 min, with methanol:water = 1:9 (v:v) and ethanol:water = 3:97 (v:v), the process heat consumption is even lower than that of the one-step process, while electricity consumption increases. In contrast, the quality of bio-crude produced by the alcohol–water co-solvent process is significantly improved. This result indicates that the alcohol–water co-solvent process holds great potential for future applications in the algal biomass industry.

3.2. Energy Consumption of Different Algae

Previous work investigated the effect of temperature on HTL of microalgae with different lipid contents [26]. From the results, it can be concluded that the raw material type and the reaction temperature have a great influence on the yield and quality of the bio-crude.

The calculated energy consumption of the HTL process for the five algal species is shown in Figure 7. It is obvious that the heat consumption for producing a unit mass of bio-crude and FAFEs from different algae is generally negatively correlated with the lipid content of the raw material. There is a significant difference in the variation pattern of energy consumption with temperature for HTL of each algal species.

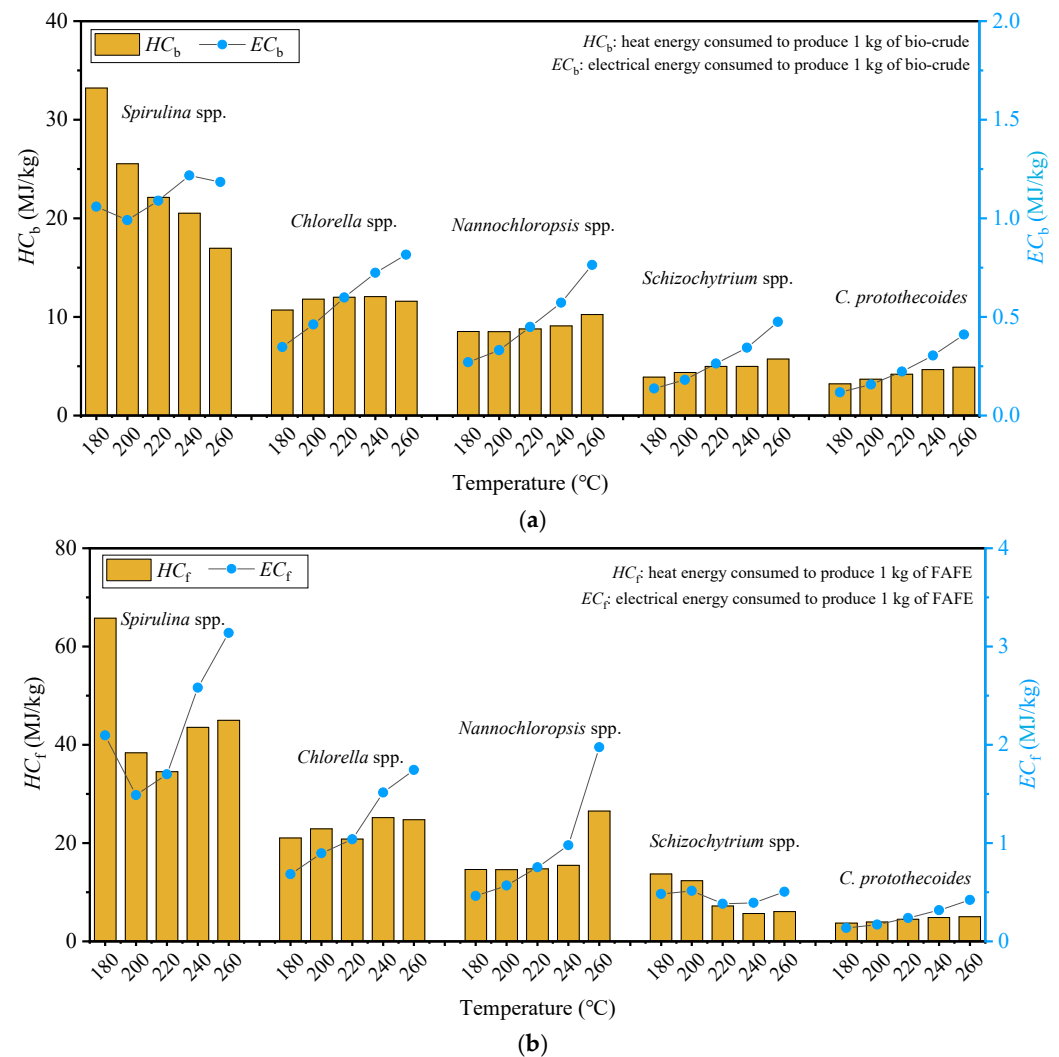


Figure 7. Energy consumption of HTL processes of different algal species (a) based on bio-crude and (b) based on FAFEs.

For the production of bio-crude per unit mass, as shown in Figure 7a, the heat consumption of *Spirulina* spp. gradually decreased with increasing temperature, and the lowest heat consumption of 16.97 MJ/kg of bio-crude was achieved at 260 °C. On the other hand, the heat consumption of *Nannochloropsis* spp., *Schizochytrium* spp. and *Chlorella protothecoides* (*C. protothecoides*) increased with increasing temperature, and the lowest heat consumption of three algae for HTL was achieved at 180 °C, which was 8.53 MJ/kg, 3.90 MJ/kg and 3.21 MJ/kg of bio-crude, respectively. *Chlorella* spp. showed an increasing and then decreasing trend with increasing temperature, and the lowest was achieved at 180 °C, which was 10.70 MJ/kg of bio-crude.

For the preparation of FAFEs per unit mass, the results are shown in Figure 7b. It can be concluded that the difference in process energy consumption between different biomasses is obvious, whether based on bio-crude or FAFEs, and the heat consumption of the HTL process at the same temperature of algae decreases significantly with the increase in its lipid content. At the same time, there are differences in the pattern of change in heat consumption with temperature for different algae processes.

4. Discussion

4.1. Energy Flow Analysis

Based on the results of the energy consumption calculations above, the most energy-advantageous process conditions among the three process models were taken for energy flow analysis and summarized in Table 4.

Table 4. List of process conditions with energy advantages.

Cases	Process Model	Process Condition
Case 1	One-step HTL	HTL temperature: 240 °C Retention time: 30 min Liquid medium: water
Case 2	Two-step HTL	HTL temperature: Unit 1: 180 °C; Unit 2: 240 °C Retention time: 30 min Liquid medium: water
Case 3	Co-solvent system HTL	HTL temperature: 250 °C Retention time: 30 min Liquid medium: methanol–water = 1:19 (v:v) co-solvent

In the energy flow analysis of the three processes, each flow stream corresponds to its respective energy flow information. The system inputs include: energy from feedstock input, electrical power input (to pressurize the flow stream to the set pressure or provide a vacuum environment), and heat input (to elevate the flow stream temperature to the designated level). The system outputs comprise: gas product energy, bio-crude energy, recovered solvent energy, system by-product energy, and energy losses within each unit. As the aqueous phase products in HTL are defined by the difference method, the system ensures mass balance. The energy of the by-product stream is calculated via the difference method, whilst heat loss to the environment is treated as a separate term and not double-counted, thereby guaranteeing energy balance.

The energy flow information for Case 1 is shown in Figure 8a. The primary source of electricity consumption is the PUMP unit. The primary source of heat consumption is the HTL unit, with the heat recovery unit transferring 80% of the residual heat from the heat flow stream of the HTL unit to the cold flow stream. The energy input streams for Case 1 (based on a biomass input of 100 kg) include: microalgae 2265 MJ, electricity input 15 MJ, and heat energy input 246 MJ; the energy output stream includes: gas products 82 MJ, bio-crude 934 MJ, and by-products 1301 MJ. A certain amount of energy loss occurs during the process of cooling the stream to ambient temperature, primarily in the form of heat energy loss. Additionally, the pump in the simulation incurs electricity loss. The total energy loss in Case 1 is 209 MJ.

The energy flow information for Case 2 is shown in Figure 8b. The electricity consumption primarily originates from two PUMP units, which provide sufficient pressure to HTL Unit 1 and HTL Unit 2 to ensure normal circulation. The heat input also primarily originates from the two-stage HTL units. Both two-stage HTL units recover 80% of the unit heat through heat exchangers for heating the low-temperature flow stream. The energy input flow streams for Case 2 (based on a biomass input of 100 kg) include: microalgae 2265 MJ, electricity input 13 MJ, HTL Unit 1 heat input 155 MJ, and HTL Unit 2 heat input 135 MJ. The lower heat input in HTL Unit 2 is primarily due to the fact that the outlet stream from HTL Unit 1 has already been heated to a higher temperature by the heat exchanger, resulting in a smaller temperature rise in HTL Unit 2. The energy output streams include: gas products 82 MJ, bio-crude 951 MJ, HTL Unit 1 by-products 838 MJ, and HTL Unit 2 by-products 430 MJ. Due to the two-stage heating involved in the two-step process, energy

losses are relatively high, with total energy losses for the two-step process amounting to 267 MJ.

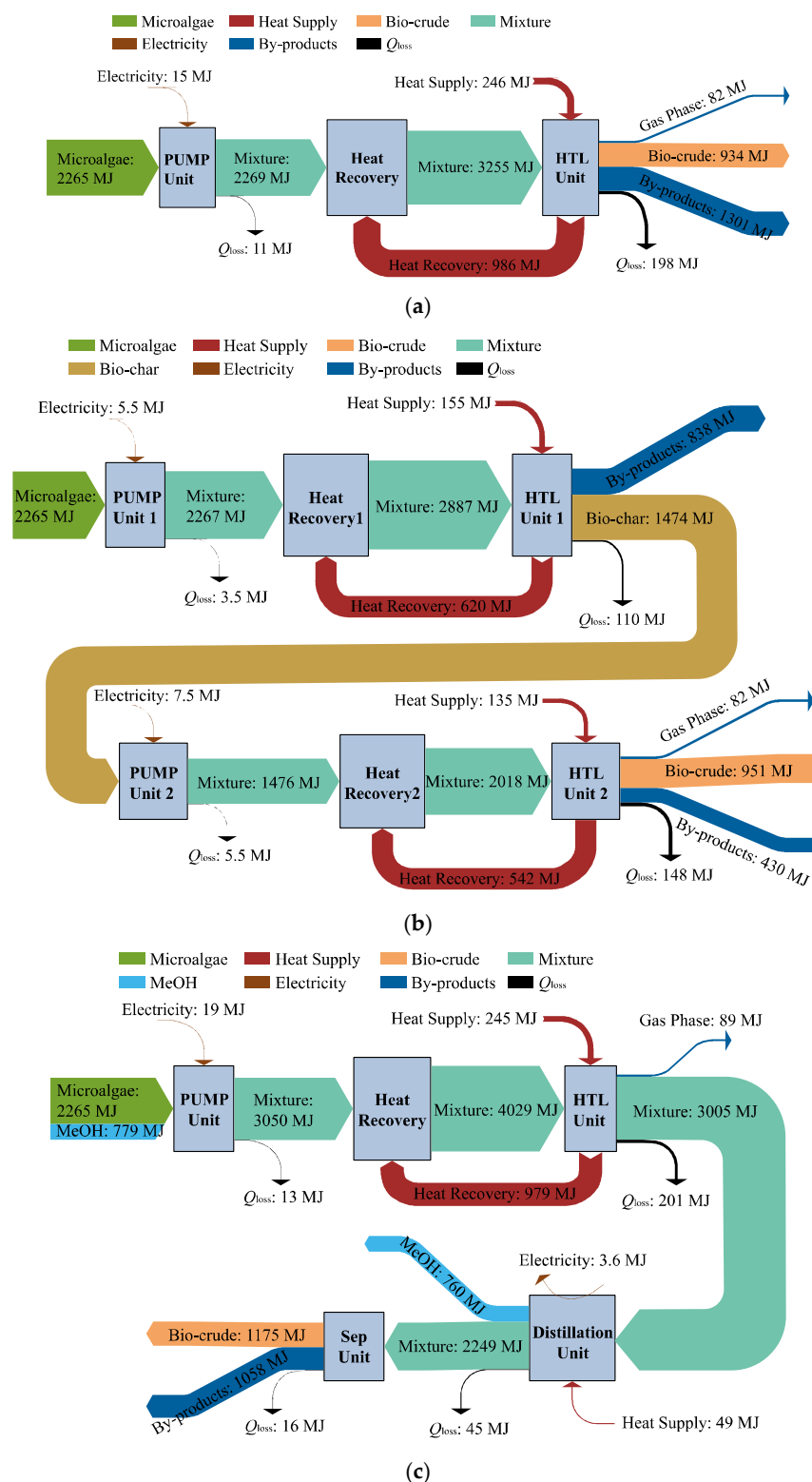


Figure 8. Energy flow information for (a) the Case 1 model, (b) the Case 2 model and (c) the Case 3 model.

The energy flow information for Case 3 is shown in Figure 8c. The primary electricity consumption occurs in the PUMP unit and the vacuum pump of the distillation unit. The electricity consumed by the vacuum pump is used to maintain negative pressure within

the distillation unit, thereby reducing heat consumption during the distillation process. Distillation enables the recovery of methanol from the system, thereby lowering the cost of organic solvent consumption. The primary heat consumption of the process stems from the HTL unit and the distillation unit. The energy input streams for Case 3 (based on a biomass input of 100 kg) include: microalgae 2265 MJ, methanol 779 MJ, electricity input 19 MJ, heat input to the HTL unit 245 MJ, and heat input to the distillation unit 49 MJ; the energy output streams include: gas products 89 MJ, bio-crude 1175 MJ, methanol stream 760 MJ, and by-products 1058 MJ. Energy losses occur in the HTL unit, distillation unit, Sep unit, and PUMP unit, totalling 275 MJ. The detailed flow stream information of Case 1, Case 2, and Case 3 can be found in Tables A2–A4.

Energy flow information for the one-step HTL process at different temperatures for different algal biomasses is summarized in Figure 9, and the specific distribution of the energy flow strands can be found in energy flow information in Table 3. The calculations lead to the following results: at the same input of biomass feedstock, the lipid content of the feedstock is positively correlated with the $E_{\text{bio-crude}}$ of the process, and with the increase in the reaction temperature, the E_{input} and the Q_{loss} are in an upward trend, and the E_{system} shows a decreasing trend.

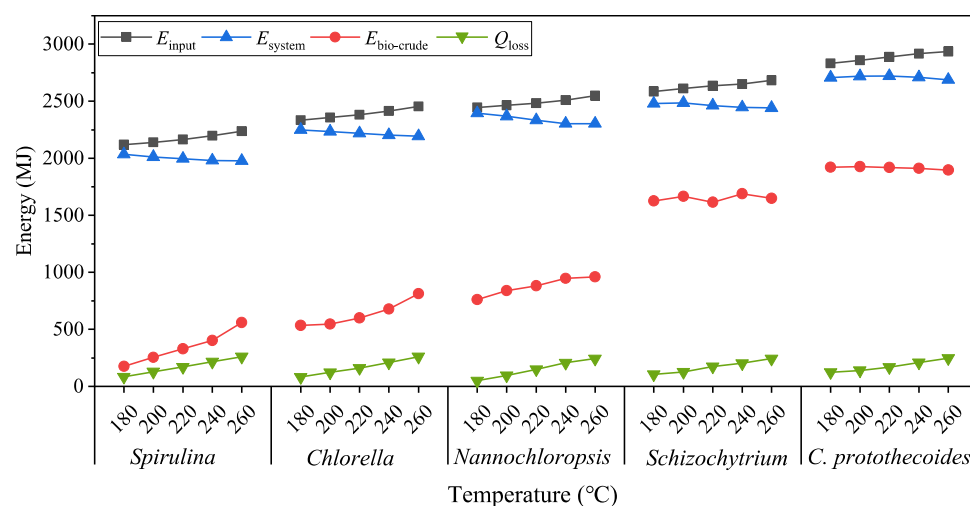


Figure 9. Energy flow information of HTL processes for different algal biomasses (100 kg of algae feed).

4.2. Energy Efficiency Analysis

The bio-crude energy efficiency (η_b), system energy efficiency (η_s), and recovery energy efficiency (η_r) under the three optimal process conditions are shown in Figure 10. The η_b in Case 3 is the lowest among the three cases. This is because the addition of methanol increases the total energy input of the system, while the output methanol is not accounted for in the energy output [35]. The η_b in Case 2 is the highest among the three processes, reaching 37.0%. Concurrently, as the η_r accounts for the recovery of organic solvents, the η_r for Case 3 is markedly higher than the other two processes, reaching 57.6%. However, in Case 3, the η_s reached 91.8% by setting up a distillation unit to recover and reuse methanol in the system, making it the process with the highest η_s among the three cases. These results also indicate that, from the perspective of overall system energy loss, the co-solvent system process has a more significant advantage. The two-step HTL in Case 2 has the lowest η_s at 89.6% due to the significant energy loss in the two-stage HTL units. When evaluating the energy utilization efficiency of a process, both parameters must be considered comprehensively.

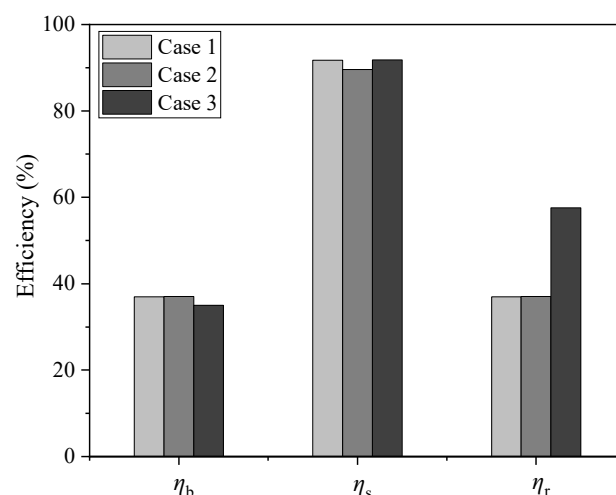


Figure 10. Efficiency of three optimal process models.

The η_b and η_s statistics for the five algal species are shown in Figure 11. At the same reaction temperature, the η_b of different algae was positively correlated with the lipid content of the feedstock. The η_b of the process was greatly affected by the bio-crude yield, so three low-lipid algae achieved the maximum value at 260 °C process condition, while the two high-lipid algae were less affected by the temperature, and the difference in η_b between different biomasses was obvious. In addition, the heat loss of the one-step HTL at the same temperature did not differ much for different algae at the same feed amount, resulting in insignificant differences in η_s between different feedstocks. In contrast, for the HTL process for the same algal species, the η_s tended to decrease with increasing temperature, due to the higher energy losses resulting from the high-temperature HTL unit.

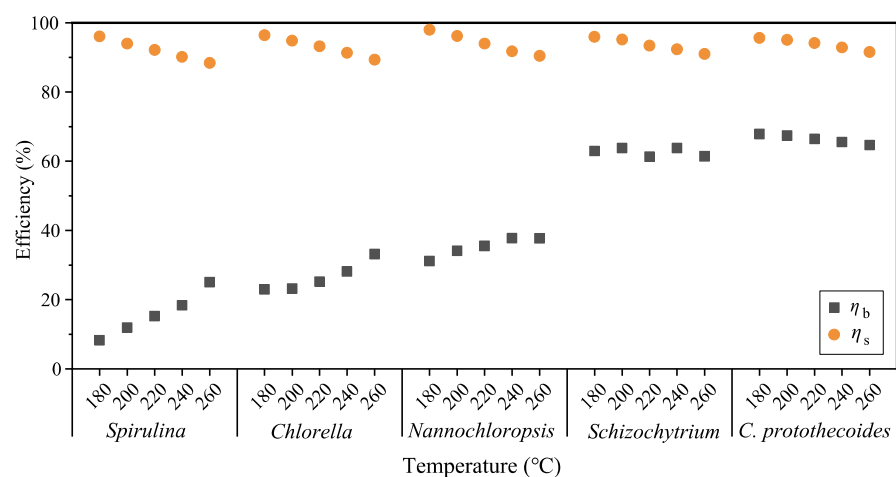


Figure 11. Energy efficiency of HTL processes for different algal biomasses (100 kg of algae feed).

The energy consumption for the preparation of bio-crude by HTL of different algae varies widely. However, the cultivation costs and growth cycles of these algae are also different. Therefore, determining a suitable algal feedstock for biofuel production requires a comprehensive evaluation from a life cycle assessment perspective, which represents an important direction for future research and analysis. Furthermore, future work should focus on developing process scale-up models to provide more accurate simulation data for the practical industrial application of algae.

5. Conclusions

Based on experimental results of algal HTL under different feedstock types and process conditions, this study designed three algal HTL process models: one-step HTL, two-step HTL, and co-solvent system HTL. Energy consumption analysis of different process models shows that the heat input of two-step HTL is generally about 20% higher than that of one-step HTL at the same temperature. Preparation of FAFEs per unit mass, with methanol:water = 1:19 (v:v) and ethanol:water = 3:97 (v:v) co-solvent system HTL, yields heat consumption values of 12.36 MJ/kg and 12.83 MJ/kg of FAFEs, respectively, which are 7.6% and 4.1% lower than one-step HTL at 240 °C for 30 min. This highlights the promising application of the HTL process by the alcohol–water co-solvent system method. The analysis of the energy consumption of different algal species of HTL concluded that the lipid content of algae generally exhibits a negative correlation with process energy consumption, whilst temperature effects demonstrate specific characteristics. These results provide a critical basis for industrial scale-up, and future work should focus on pilot-scale validation and systems integration.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data will be made available on request.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

HC_b	Heat energy consumed per unit mass of bio-crude produced (MJ)
EC_b	Electrical energy consumed per unit mass of bio-crude produced (MJ)
HC_f	Heat energy consumed per unit mass of fatty acids and esters produced (MJ)
EC_f	Electrical energy consumed per unit mass of fatty acids and esters produced (MJ)
η_b	Energy efficiency of bio-crude (%)
η_s	Energy efficiency of the system (%)
η_r	Recovery energy efficiency (%)
$E_{\text{bio-crude}}$	Energy of exported bio-crude (MJ)
E_{input}	Total input energy to the system per kilogram of bio-crude (MJ)
E_{system}	Total energy outputs of the products (MJ)
Q_{loss}	Heat loss of the system (MJ)

Appendix A

Table A1. Elemental analysis of bio-crude.

Condition	Element Analysis/wt%				HHV/ MJ·kg ⁻¹	Recovery (%)		
	C	H	O	N		CR	HR	ER
<i>Spirulina</i> , 260 °C	72.51	8.99	12.81	5.69	34.88	26.9	21.6	29.3
<i>Chlorella</i> , 260 °C	72.69	8.60	13.66	5.05	34.36	36.5	30.0	38.9
<i>Schizochytrium</i> , 180 °C	79.42	10.25	10.29	0.04	38.70	64.0	59.5	71.7
<i>Schizochytrium</i> , 240 °C	78.13	10.28	11.16	0.43	38.20	66.3	62.8	74.5
<i>C.protothecoides</i> , 180 °C	76.22	11.37	12.31	0.10	38.65	67.6	68.2	74.7
<i>C.protothecoides</i> , 240 °C	74.73	11.17	13.66	0.44	37.77	67.5	68.3	74.4
<i>Nannochloropsis</i> , 240 °C	72.62	9.57	14.33	3.48	35.29	0.390	0.348	42
<i>Nannochloropsis</i> , 260 °C	75.52	10.21	10.92	3.35	37.42	39.4	36.1	43.6
<i>Nannochloropsis</i> , 250 °C, 30 min MeOH/H ₂ O = 2:3 (v:v)	74.52	9.99	11.92	3.57	36.71	0.513	0.454	55
<i>Nannochloropsis</i> , 250 °C, 30 min EtOH/H ₂ O = 1:4 (v:v)	74.42	9.91	12.04	3.63	36.58	0.472	0.420	51
<i>Nannochloropsis</i> , 250 °C, 30 min EtOH/H ₂ O = 2:3 (v:v)	74.29	9.99	11.98	3.74	36.64	0.530	0.476	58
<i>Nannochloropsis</i> , Two-step HTL, 240 °C	74.71	10.18	12.41	2.7	36.89	0.391	0.361	43

Appendix B

Table A2. Material flow stream information for Case 1.

	ALGAE IN	WATER IN	FEED IN	COLD IN	COLD OUT	HOT IN	HOT OUT	LIQUID	SOLID	GAS
Temperature, °C	25.00	25.00	25.00	28.35	63.32	240.00	219.76	25.00	25.00	25.00
Pressure, atm	1.00	1.00	1.00	38.00	38.00	38.00	38.00	1.00	1.00	1.00
Mass flow, kg/h	100.00	1000.00	1100.00	1100.00	1100.00	1100.00	1100.00	1054.64	38.64	6.72
Protein, kg/h	40.82	0.00	40.82	40.82	22.58	22.58	40.82	22.58	0.00	0.00
Glucose, kg/h	29.03	0.00	29.03	29.03	1.86	1.86	29.03	1.86	0.00	0.00
Lipid, kg/h	20.70	0.00	20.70	20.70	0.00	0.00	20.70	0.00	0.00	0.00
Ash, kg/h	9.45	0.00	9.45	9.45	9.45	9.45	9.45	9.45	0.00	0.00
Water, kg/h	0.00	1000.00	1000.00	1000.00	999.59	999.59	1000.00	999.59	0.00	0.00
CO ₂ , kg/h	0.00	0.00	0.00	0.00	6.14	6.14	0.00	0.00	0.00	6.14
H ₂ , kg/h	0.00	0.00	0.00	0.00	0.58	0.58	0.00	0.00	0.00	0.58
Fatty acids, kg/h	0.00	0.00	0.00	0.00	17.93	17.93	0.00	0.00	17.93	0.00
Fatty acid esters, kg/h	0.00	0.00	0.00	0.00	0.48	0.48	0.00	0.00	0.48	0.00
Fatty acid amides, kg/h	0.00	0.00	0.00	0.00	2.85	2.85	0.00	0.00	2.85	0.00

Table A2. *Cont.*

	ALGAE IN	WATER IN	FEED IN	COLD IN	COLD OUT	HOT IN	HOT OUT	LIQUID	SOLID	GAS
N-heterocyclic, kg/h	0.00	0.00	0.00	0.00	1.00	1.00	0.00	0.00	1.00	0.00
Cholesterol, kg/h	0.00	0.00	0.00	0.00	1.00	1.00	0.00	0.00	1.00	0.00
Oxygen compound, kg/h	0.00	0.00	0.00	0.00	0.78	0.78	0.00	0.00	0.78	0.00
Alkane, kg/h	0.00	0.00	0.00	0.00	1.67	1.67	0.00	0.00	1.67	0.00
Vitamin E, kg/h	0.00	0.00	0.00	0.00	0.06	0.06	0.00	0.00	0.06	0.00
Amine, kg/h	0.00	0.00	0.00	0.00	0.69	0.69	0.00	0.00	0.69	0.00
Glycerol, kg/h	0.00	0.00	0.00	0.00	2.46	2.46	0.00	2.46	0.00	0.00
Levulinic acid, kg/h	0.00	0.00	0.00	0.00	0.46	0.46	0.00	0.46	0.00	0.00
Humins, kg/h	0.00	0.00	0.00	0.00	12.18	12.18	0.00	0.00	12.18	0.00
Amino acids, kg/h	0.00	0.00	0.00	0.00	18.24	18.24	0.00	18.24	0.00	0.00

Table A3. Material flow stream information for Case 2.

	ALGAE IN	WATER IN 1	FEED IN 1	COLD IN 1	COLD OUT 1	HOT IN 1	HOT OUT 1	AQENOUS	SOLID1	GAS 1	WATER IN 2	FEED IN 2	COLD IN 2	HOT OUT 2	HOT IN 2	COLD OUT 2	SOLID	GAS2	LIQUID
Temperature, °C	25.00	25.00	25.00	26.27	45.09	180.00	156.38	25.00	50.76	25.00	25.00	26.30	29.54	224.27	240.00	81.49	25.00	25.00	25.00
Pressure, atm	1.00	1.00	1.00	15.00	15.00	15.00	15.00	1.00	15.00	1.00	1.00	1.00	38.00	38.00	38.00	38.00	1.00	1.00	1.00
Mass flow, kg/h	100.00	1000.00	1100.00	1100.00	1100.00	1100.00	1100.00	1046.41	53.50	0.09	535.00	588.50	588.50	588.50	588.50	588.50	29.59	6.72	552.19
Protein, kg/h	40.82	0.00	40.82	40.82	40.82	40.82	40.82	16.12	24.70	0.00	0.00	24.70	24.70	24.70	8.95	8.95	0.00	0.00	8.95
Glucose, kg/h	29.03	0.00	29.03	29.03	8.46	8.46	29.03	0.00	8.46	0.00	0.00	8.46	8.46	8.46	0.00	0.00	0.00	0.00	0.00
Lipid, kg/h	20.70	0.00	20.70	20.70	0.00	0.00	20.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ash, kg/h	9.45	0.00	9.45	9.45	9.45	9.45	9.45	9.45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Water, kg/h	0.00	1000.00	1000.00	1000.00	1000.00	1000.00	1000.00	1000.00	0.00	0.00	535.00	535.00	535.00	535.00	535.00	535.00	0.00	0.00	535.00
CO ₂ , kg/h	0.00	0.00	0.00	0.00	0.08	0.08	0.00	0.00	0.00	0.08	0.00	0.00	0.00	0.00	6.14	6.14	0.00	6.14	0.00
H ₂ , kg/h	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.58	0.58	0.00	0.58	0.00
Fatty acids, kg/h	0.00	0.00	0.00	0.00	9.44	9.44	0.00	0.00	9.44	0.00	0.00	9.44	9.44	9.44	17.47	17.47	17.47	0.00	0.00
Fatty acid esters, kg/h	0.00	0.00	0.00	0.00	2.43	2.43	0.00	0.00	2.43	0.00	0.00	2.43	2.43	2.43	0.66	0.66	0.66	0.00	0.00
Fatty acid amides, kg/h	0.00	0.00	0.00	0.00	0.34	0.34	0.00	0.00	0.34	0.00	0.00	0.34	0.34	0.34	3.28	3.28	3.28	0.00	0.00
N- heterocyclic, kg/h	0.00	0.00	0.00	0.00	0.31	0.31	0.00	0.00	0.31	0.00	0.00	0.31	0.31	0.31	1.06	1.06	1.06	0.00	0.00
Phytosterol, kg/h	0.00	0.00	0.00	0.00	2.01	2.01	0.00	0.00	2.01	0.00	0.00	2.01	2.01	2.01	0.00	0.00	0.00	0.00	0.00
Cholesterol, kg/h	0.00	0.00	0.00	0.00	2.42	2.42	0.00	0.00	2.42	0.00	0.00	2.42	2.42	2.42	1.01	1.01	1.01	0.00	0.00
Oxygen compound, kg/h	0.00	0.00	0.00	0.00	1.66	1.66	0.00	0.00	1.66	0.00	0.00	1.66	1.66	1.66	0.84	0.84	0.84	0.00	0.00

Table A3. *Cont.*

	ALGAE IN	WATER IN 1	FEED IN 1	COLD IN 1	COLD OUT 1	HOT IN 1	HOT OUT 1	AQENOUS	SOLID1	GAS 1	WATER IN 2	FEED IN 2	COLD IN 2	HOT OUT 2	HOT IN 2	COLD OUT 2	SOLID	GAS2	LIQUID
Alkane, kg/h	0.00	0.00	0.00	0.00	0.92	0.92	0.00	0.00	0.92	0.00	0.00	0.92	0.92	0.92	1.48	1.48	1.48	0.00	0.00
Vitamin E, kg/h	0.00	0.00	0.00	0.00	0.69	0.69	0.00	0.00	0.69	0.00	0.00	0.69	0.69	0.69	0.00	0.00	0.00	0.00	0.00
Amine, kg/h	0.00	0.00	0.00	0.00	0.12	0.12	0.00	0.00	0.12	0.00	0.00	0.12	0.12	0.12	0.00	0.00	0.00	0.00	0.00
Glycerol, kg/h	0.00	0.00	0.00	0.00	2.46	2.46	0.00	2.46	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Furfural, kg/h	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Levulinic acid, kg/h	0.00	0.00	0.00	0.00	0.14	0.14	0.00	0.14	0.00	0.00	0.00	0.00	0.00	0.00	0.32	0.32	0.00	0.00	0.32
Humins, kg/h	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.80	3.80	3.80	0.00	0.00
Amino acids, kg/h	0.00	0.00	0.00	0.00	18.24	18.24	0.00	18.24	0.00	0.00	0.00	0.00	0.00	0.00	7.91	7.91	0.00	0.00	7.91

Table A4. Material flow stream information for Case 3.

	ALGAE IN	SOLVENT IN	FEED IN	COLD IN	COLD OUT	HOT IN	HOT OUT	GAS	MIXTURE1	MIXTURE2	ALCOHOL	SOLVENT OUT	LIQUID	SOLID
Temperature, °C	25.00	25.00	24.98	29.51	68.63	250.00	220.88	25.00	29.00	29.00	29.00	25.00	25.00	25.00
Pressure, atm	1.00	1.00	1.00	50.00	50.00	50.00	50.00	1.00	1.00	0.20	0.20	1.00	1.00	1.00
Mass flow, kg/h	100.00	989.55	1089.55	1089.55	1089.55	1089.55	1089.55	7.32	1082.23	1043.67	38.56	38.56	1006.88	36.79
Protein, kg/h	40.82	0.00	40.82	40.82	18.43	18.43	40.82	0.00	18.43	18.43	0.00	0.00	18.43	0.00
Glucose, kg/h	29.03	0.00	29.03	29.03	4.03	4.03	29.03	0.00	4.03	4.03	0.00	0.00	4.03	0.00
Lipid, kg/h	20.70	0.00	20.70	20.70	0.00	0.00	20.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ash, kg/h	9.45	0.00	9.45	9.45	9.45	9.45	9.45	0.00	9.45	9.45	0.00	0.00	9.45	0.00
Water, kg/h	0.00	950.00	950.00	950.00	949.60	949.60	950.00	0.00	949.60	949.60	0.00	0.00	949.60	0.00
CO ₂ , kg/h	0.00	0.00	0.00	0.00	6.69	6.69	0.00	6.69	0.00	0.00	0.00	0.00	0.00	0.00

Table A4. Cont.

	ALGAE IN	SOLVENT IN	FEED IN	COLD IN	COLD OUT	HOT IN	HOT OUT	GAS	MIXTURE1	MIXTURE2	ALCOHOL	SOLVENT OUT	LIQUID	SOLID
H ₂ , kg/h	0.00	0.00	0.00	0.00	0.63	0.63	0.00	0.63	0.00	0.00	0.00	0.00	0.00	0.00
Fatty acids, kg/h	0.00	0.00	0.00	0.00	15.43	15.43	0.00	0.00	15.43	15.43	0.00	0.00	0.00	15.43
Fatty acid esters, kg/h	0.00	0.00	0.00	0.00	8.31	8.31	0.00	0.00	8.31	8.31	0.00	0.00	0.00	8.31
Fatty acid amides, kg/h	0.00	0.00	0.00	0.00	4.33	4.33	0.00	0.00	4.33	4.33	0.00	0.00	0.00	4.33
N-heterocyclic, kg/h	0.00	0.00	0.00	0.00	0.81	0.81	0.00	0.00	0.81	0.81	0.00	0.00	0.00	0.81
Cholesterol, kg/h	0.00	0.00	0.00	0.00	0.94	0.94	0.00	0.00	0.94	0.94	0.00	0.00	0.00	0.94
Oxygen compound, kg/h	0.00	0.00	0.00	0.00	0.95	0.95	0.00	0.00	0.95	0.95	0.00	0.00	0.00	0.95
Alkane, kg/h	0.00	0.00	0.00	0.00	0.95	0.95	0.00	0.00	0.95	0.95	0.00	0.00	0.00	0.95
Vitamin E, kg/h	0.00	0.00	0.00	0.00	0.35	0.35	0.00	0.00	0.35	0.35	0.00	0.00	0.00	0.35
Amine, kg/h	0.00	0.00	0.00	0.00	2.46	2.46	0.00	0.00	2.46	2.46	0.00	0.00	2.46	0.00
Glycerol, kg/h	0.00	0.00	0.00	0.00	0.52	0.52	0.00	0.00	0.52	0.52	0.00	0.00	0.52	0.00
Levulinic acid, kg/h	0.00	0.00	0.00	0.00	4.71	4.71	0.00	0.00	4.71	4.71	0.00	0.00	0.00	4.71
Humins, kg/h	0.00	0.00	0.00	0.00	22.39	22.39	0.00	0.00	22.39	22.39	0.00	0.00	22.39	0.00
Amino acids, kg/h	0.00	39.55	39.55	39.55	38.56	38.56	39.55	0.00	38.56	0.00	38.56	38.56	0.00	0.00
Methanol, kg/h	25.00	25.00	24.98	29.51	68.63	250.00	220.88	25.00	29.00	29.00	29.00	25.00	25.00	25.00

References

- Kumar, M.; Ansari, N.A.; Gautam, R. Algae Biodiesel as a Alternative Green Fuel: A Futuristic Scope. *Clean. Chem. Eng.* **2025**, *11*, 100178. [\[CrossRef\]](#)
- Wang, Z.; Zhao, Z.; Elendu, C.C.; Duan, P. Feedstock Loading and Pressure Synergy in High-Solid Microalgae HTL: Boosting Bio-Oil Yield While Reducing Nitrogen Content. *Biomass Bioenergy* **2026**, *204*, 108460. [\[CrossRef\]](#)
- Hognon, C.; Delrue, F.; Texier, J.; Grateau, M.; Thiery, S.; Miller, H.; Roubaud, A. Comparison of Pyrolysis and Hydrothermal Liquefaction of *Chlamydomonas Reinhardtii*. Growth Studies on the Recovered Hydrothermal Aqueous Phase. *Biomass Bioenergy* **2015**, *73*, 23–31. [\[CrossRef\]](#)
- Gollakota, A.R.K.; Kishore, N.; Gu, S. A Review on Hydrothermal Liquefaction of Biomass. *Renew. Sustain. Energy Rev.* **2018**, *81*, 1378–1392. [\[CrossRef\]](#)
- Toor, S.S.; Rosendahl, L.; Rudolf, A. Hydrothermal Liquefaction of Biomass: A Review of Subcritical Water Technologies. *Energy* **2011**, *36*, 2328–2342. [\[CrossRef\]](#)
- Yu, Q.; Zhuang, X.; Yuan, Z.; Qi, W.; Wang, W.; Wang, Q.; Tan, X. Pretreatment of Sugarcane Bagasse with Liquid Hot Water and Aqueous Ammonia. *Bioresour. Technol.* **2013**, *144*, 210–215. [\[CrossRef\]](#) [\[PubMed\]](#)
- Bondurant, L.C.; Obeid, W.; Hatcher, P.G. Two-Step Hydrothermal Liquefaction of *Scenedesmus/Desmodesmus* Algae for the Production of Hydrocarbon-Based Fuels. *Org. Geochem.* **2023**, *182*, 104637. [\[CrossRef\]](#)
- Wang, S.; Zhao, S.; Cheng, X.; Qian, L.; Barati, B.; Gong, X.; Cao, B.; Yuan, C. Study on Two-Step Hydrothermal Liquefaction of Macroalgae for Improving Bio-Oil. *Bioresour. Technol.* **2021**, *319*, 124176. [\[CrossRef\]](#) [\[PubMed\]](#)
- Piñkowska, H.; Oliveros, E. Application of the Doehrlert Matrix for the Determination of the Optimal Conditions of Hydrolysis of Soybean Protein in Subcritical Water. *Ind. Eng. Chem. Res.* **2014**, *53*, 1320–1326. [\[CrossRef\]](#)
- Shia, Y.-P.; Yu, B.-Y. Development of a Rigorous and Generalized Model on the Hydrothermal Liquefaction (HTL) Process for Bio-Oil Production. *Process Saf. Environ. Prot.* **2023**, *171*, 541–554. [\[CrossRef\]](#)
- Biller, P.; Ross, A.B. Production of Biofuels via Hydrothermal Conversion. In *Handbook of Biofuels Production*; Elsevier: Amsterdam, The Netherlands, 2016; pp. 509–547.
- Leng, L.; Zhang, W.; Peng, H.; Li, H.; Jiang, S.; Huang, H. Nitrogen in Bio-Oil Produced from Hydrothermal Liquefaction of Biomass: A Review. *Chem. Eng. J.* **2020**, *401*, 126030. [\[CrossRef\]](#)
- Dong, S.; Huang, X.; Yang, X. Optimizing on Flash Hydrothermal Liquefaction Environment for Improving the Quality of Bio-Crude. *Fuel* **2022**, *324*, 124641. [\[CrossRef\]](#)
- Chen, Y.; Wu, Y.; Zhang, P.; Hua, D.; Yang, M.; Li, C.; Chen, Z.; Liu, J. Direct Liquefaction of *Dunaliella Tertiolecta* for Bio-Oil in Sub-/Supercritical Ethanol–Water. *Bioresour. Technol.* **2012**, *124*, 190–198. [\[CrossRef\]](#) [\[PubMed\]](#)
- Hu, Y.; Qi, L.; Feng, S.; Bassi, A.; Xu, C. Comparative Studies on Liquefaction of Low-Lipid Microalgae into Bio-Crude Oil Using Varying Reaction Media. *Fuel* **2019**, *238*, 240–247. [\[CrossRef\]](#)
- Zhang, Q.; Xiao, J.; Hao, J.; Wu, Q.; Song, G. Energy and Exergy Analyses of Bio-Jet Fuel Production from Full Components in Lignocellulosic Biomass via Aqueous-Phase Conversion. *Appl. Therm. Eng.* **2022**, *201*, 117723. [\[CrossRef\]](#)
- Peralta, Y.; Sanchez, E.; Kafarov, V. Exergy Analysis for Third Generation Biofuel Production from Microalgae Biomass. *Chem. Eng. Trans.* **2010**, *21*, 1363–1368. [\[CrossRef\]](#)
- Talens Peiró, L.; Villalba Méndez, G.; Sciubba, E.; Gabarrell i Durany, X. Extended Exergy Accounting Applied to Biodiesel Production. *Energy* **2010**, *35*, 2861–2869. [\[CrossRef\]](#)
- Sorguven, E.; Özilgen, M. Thermodynamic Assessment of Algal Biodiesel Utilization. *Renew. Energy* **2010**, *35*, 1956–1966. [\[CrossRef\]](#)
- Milledge, J.J.; Heaven, S. A Review of the Harvesting of Micro-Algae for Biofuel Production. *Rev. Environ. Sci. Biotechnol.* **2013**, *12*, 165–178. [\[CrossRef\]](#)
- da Costa Magalhães, B.; Checa, R.; Lorentz, C.; Afanasiev, P.; Laurenti, D.; Geantet, C. Catalytic Hydroconversion of HTL Micro-Algal Bio-Oil into Biofuel over NiWS/Al₂O₃. *Algal Res.* **2023**, *71*, 103012. [\[CrossRef\]](#)
- Frątczak, J.; Sharkov, N.; De Paz Carmona, H.; Tišler, Z.; Hidalgo-Herrador, J.M. Cleaner Fuel Production via Co-Processing of Vacuum Gas Oil with Rapeseed Oil Using a Novel NiW/Acid-Modified Phonolite Catalyst. *Energies* **2021**, *14*, 8497. [\[CrossRef\]](#)
- Badoga, S.; Alvarez-Majmutov, A.; Xing, T.; Gieleciak, R.; Chen, J. Co-Processing of Hydrothermal Liquefaction Biocrude with Vacuum Gas Oil through Hydrotreating and Hydrocracking to Produce Low-Carbon Fuels. *Energy Fuels* **2020**, *34*, 7160–7169. [\[CrossRef\]](#)
- Wang, H.; Meyer, P.A.; Santosa, D.M.; Zhu, C.; Olarte, M.V.; Jones, S.B.; Zacher, A.H. Performance and Techno-Economic Evaluations of Co-Processing Residual Heavy Fraction in Bio-Oil Hydrotreating. *Catal. Today* **2021**, *365*, 357–364. [\[CrossRef\]](#)
- Kumar, A.; Watkins, J.D.; Cronin, D.; Schmidt, A.J.; Santosa, D.M.; Yang, Z.; Heyne, J.; Valdez, P.J. Hydrothermal Liquefaction of Wastewater-Grown Algae to Produce Synthetic Aviation Fuel: A Combined Experimental Study and Techno-Economic Assessment. *Energy Convers. Manag. X* **2025**, *27*, 101096. [\[CrossRef\]](#)

26. Dong, S.; Liu, Z.; Yang, X. Exploration of Hydrothermal Liquefaction of Multiple Algae to Improve Bio-Crude Quality and Carbohydrate Utilization. *Appl. Energy* **2024**, *361*, 122861. [[CrossRef](#)]
27. Men, Y.; Liu, X.; Zhang, T. A Review of Boiler Waste Heat Recovery Technologies in the Medium-Low Temperature Range. *Energy* **2021**, *237*, 121560. [[CrossRef](#)]
28. Tang, X.; Zhang, C.; Li, Z.; Yang, X. Element and Chemical Compounds Transfer in Bio-Crude from Hydrothermal Liquefaction of Microalgae. *Bioresour. Technol.* **2016**, *202*, 8–14. [[CrossRef](#)] [[PubMed](#)]
29. Li, H.; Xia, S.; Luo, H.; Ma, P. Experimental and Computational Study on the Compatibility of Biodiesel/Diesel/Methanol Blended Fuel. *Fuel* **2016**, *173*, 52–59. [[CrossRef](#)]
30. Kubiczek, A.; Kamiński, W.; Górak, A. Modeling of Single- and Multi-Stage Extraction in the System of Water, Acetone, Butanol, Ethanol and Ionic Liquid. *Fluid Phase Equilib.* **2016**, *425*, 365–373. [[CrossRef](#)]
31. Han, X.; Wang, Y.; Wang, Y.; Zhao, H.; Li, Q. Vapor–Liquid Equilibrium Experiment and Process Simulation for Methanol and Ethyl Formate at 101.3 KPa. *J. Chem. Eng. Data* **2021**, *66*, 1929–1938. [[CrossRef](#)]
32. Renon, H.; Prausnitz, J.M. Local Compositions in Thermodynamic Excess Functions for Liquid Mixtures. *AIChE J.* **1968**, *14*, 135–144. [[CrossRef](#)]
33. Gao, X.; Zhu, B.; Gu, Q.; Jiang, Y.; Yang, D. Process Simulation for Separation of Methyl Acetate-Methanol-Water by Double Solvent Synergistic Extractive Distillation. *Chin. J. Process Eng.* **2017**, *17*, 254–258. [[CrossRef](#)]
34. Ihadjadene, Y.; Kalliadan, S.; Laukens, K.; Roef, L.; Walther, T.; Streif, S.; Krujatz, F. Process Modeling and Optimization of *Nannochloropsis* sp. towards Commercial Scale Production. *Algal Res.* **2025**, *90*, 104196. [[CrossRef](#)]
35. Naaz, F.; Dhali, S.; Dey, S.; Bhattacharya, A.; Choudhary, P.; Pant, K.K.; Malik, A. Upgradation and Valorization of Hydrothermally Liquefied Wastewater Algae to Recover Multiple Products. *Algal Res.* **2024**, *82*, 103644. [[CrossRef](#)]

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