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Investigation in the Effect of Nitrogen Concentration in Wastewater and Light Conditions on the Yield of Biodiesel Produced by Microalgae

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Abstract. This paper simulates biofuel production from algae (Chlorella) in wastewater. It analyzes the effects of three factors—sunlight intensity, photosynthesis time, and nitrogen concentration in wastewater—on algal biomass and biodiesel yield. Additionally, the research establishes and applies mathematical models to the analysis of two different places, where the results show that in Shaanxi Province and Qinghai Province, the biodiesel yield per cubic meter of wastewater is 23.5 g/m³ and 8.9 g/m³ respectively. The biofuel yield of the system is 10% of the algal biomass. Furthermore, the paper concludes that the system's energy consumption mainly lies in the hydrogenation treatment section. The total energy consumption for producing 1 kg biodiesel is 937 MJ (blue H_2), 855 MJ (grey H_2) and 981 MJ (green H_2) respectively. The carbon emissions for producing 1kg biodiesel is -2.2 kg CO_2 (blue H_2), 25.9 kg CO_2 (grey H_2) and -17.8 kg CO_2 (green H_2) respectively.

Keywords: algae, biodiesel, system, case study, photo hours, wastewater

1. Introduction

With the continuous growth of global energy demand and the increasingly serious environmental problems, finding renewable energy has become an important research topic today. Algae, as an efficient raw material for biodiesel, can be used as a vegetable oil substitute for biodiesel due to their high oil content [1-3]. Moreover, algae grow rapidly and do not require arable land [2], and can survive and absorb nutrients in wastewater, which has attracted widespread attention. There are currently studies exploring the effects of different factors on algal growth. There are studies on the formation of bio-oil from algae through a series of treatment processes [4,5], as well as studies on the hydrogenation of bio-oil to produce biodiesel that can be directly used [6,7]. However, the research on these three processes is fragmented, and there is almost no exploration of the entire

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process from different cultivation conditions as independent variables to biodiesel as the dependent variable. Therefore, the aim is to explore the effects of light intensity, light duration, and nitrogen content in wastewater on biodiesel production from the cultivation of algae. This article also compares the effects of using green hydrogen and grey hydrogen as hydrogen production methods on energy consumption and carbon dioxide emissions throughout the entire process.

2. Overview of bio-oil produced by algae

2.1. Algae cultivation

2.1.1. The influence of light exposure time and intensity on cultivation

Under nitrogen concentration limitation, the article studied the lipid production of Scenedesmus ssp at three light intensities (levels of 50, 250, and 400μmol). When grown under conditions of light intensity of 250 and 400μmol, the ratio of carotenoids to chlorophyll in algal yield is higher than that under conditions of 50μmol, but the protein content of the former is lower than that of the latter. The condition for obtaining the highest biomass yield (3.88%), lipid content (41.1%), and neutral lipids (32.9%) is a light intensity of 400 μmol. The yield of lipids is slightly lower under 250μmol level conditions [8].

2.1.2. The effect of nitrogen concentration on cultivation

Explore the changes in lipid yield when N/P increases from 1:1 to 32:1 under the conditions of inorganic nitrogen (nitrate) and organic nitrogen (urea) as nitrogen sources. The highest growth rate is observed at N/P ratio of 16:1, and the highest lipid concentration is observed at 4:1. The yield of lipids in organic nitrogen medium is much higher than in other nitrogen phosphorus ratio media. This study suggests that a higher nitrogen phosphorus ratio is more favorable for cell growth, while a lower nitrogen phosphorus ratio is beneficial for lipid accumulation [9].

2.1.3. The influence of light and nitrogen concentration

This study selected the optimal light intensity and nitrogen concentration for four microalgae species (Ankistodesmus falcatus, Chlorella emersonii, Chaetoceros muelleri, and Isochrysis galbana) to improve their growth rate, biomass, and lipid content. The optimal conditions are a combination of 135 light intensity and a nitrogen concentration of 5g/l, resulting in a biomass of 0.31 to 0.56mg/l per day, a lipid content of 20.3% to 40.95% of dry weight, and a lipid productivity of 85.26 to 180.18mg/l per day [10].

2.2. The process of hydrotreating (HDT)

This article proposes a conceptual process design for producing algae biofuels from wastewater through hydrothermal liquefaction and hydrogenation treatment. The mass consumption and energy analysis of hydrocarbons throughout the entire process were calculated by simulating the steady-state process. Also illustrate how much bio-oil can be product after HTL process, also demonstrate how much hydrogen it needs in Hydrotreating and Hydrocracking process. Which gives an equivalent relation between bio-oil and hydrogen [11].

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3. Research implications

Since microalgae produce bio-oil and undergo a series of treatments to become biodiesel, it has become a reality. However, research on the final production of biodiesel from nitrogen concentration in wastewater, local light exposure time, and radiation as variables is very scarce. Therefore, it is very important to produce materials that can be directly used from start to finish as simulations. Due to the use of algae for oil production to achieve the goal of CCS, energy consumption and carbon emissions during the process are also factors that need to be considered. This study hopes that the total carbon emissions throughout the process will be negative and can absorb carbon dioxide. This study mainly explores the effects of light exposure time, light intensity, and sewage nitrogen concentration on the final biodiesel production of algae.

4. Outline of research

This study simulated algae cultivation using a MATLAB program. Using light exposure time, intensity, and wastewater nitrogen concentration as inputs, the try biomass generated is used as the output. After precipitation, centrifugation, and hydrothermal liquefaction treatment, blue hydrogen and grey hydrogen are introduced to treat the product with hydrogen, and finally biodiesel is produced. This article compares the energy consumption and carbon emissions of blue hydrogen and gray hydrogen used in hydrogen treatment. Qinghai and Shaanxi provinces are also used as case studies. Due to the significant difference in light exposure time between the two places, there is also a significant difference in the effectiveness of algae cultivation.

5. Methodology

This section highlights the steps we took to achieve the process of converting algal biomass into usable energy, including cultivation, processing, and conversion of microalgae into biofuel. Specifically, we aimed to improve biomass production and minimize energy consumption and carbon emissions. Then, we used both empirical data and computational simulations through MATLAB to compare the performance of these processes at two regions, which are Qinghai and Shaanxi. In the end, we tried to evaluate regional differences and the most suitable conditions that maximize biofuel yield.

5.1. Cultivation of microalgae

The first step of this research is the cultivation of microalgae, specifically Chlorella. We will place it under a controlled environment. We choose chlorella as the microalgal species due to its high adaptability, rapid growth rate, and established efficacy in biomass production. Also, Chlorella has high lipid content, which make it an ideal choice for hydrothermal liquefaction and subsequent conversion process.

During the cultivation process, we will use wastewater as the growth medium. Consequently, we can optimize nutrient absorption and enhance carbon capture. Also, we considered several factors as variables to maximize biomass yield, including the selection of algal strains with high adaptability and biomass productivity. In addition, we monitor the growth of algal species to evaluate the biomass yield to ensure optimal conditions.

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5.2. Flocculation

The next step is using a flocculating agent to induce the aggregation of microalgae cells. Consequently, larger clusters can be formed, which are easier to separate. We would carefully select the type of the flocculant based on the concentration of algae present. Then, we would adjust the pH to enhance the amount of cell aggregation. Consequently, we can recover the maximum number of microalgae for subsequent process using this approach. In the end, we would conduct an analysis of energy consumption and carbon emission for the two regions.

5.3. Centrifugation

The next step is to separate the algae biomass through centrifugation. By using high speed rotational forces, we can separate the biomass from the liquid. During centrifugation, we also carefully control several variables, including speed, duration, and temperature, to enhance separation efficiency while minimizing energy consumption. This process primarily uses electrical energy. Its efficiency directly influences both the energy input required and the carbon emissions generated. Comparative data analysis indicated that the centrifugation step in Shaanxi province exhibited higher energy consumption and carbon emissions compared to Qinghai. This is primarily due to the larger volume of biomass processed in Shaanxi. Despite these higher demands, centrifugation remains a preferred method for its ability to rapidly and effectively concentrate microalgae.

5.4. Hydrothermal liquefaction (HTL)

HTL was utilized to convert the wet biomass into biofuel through a thermochemical process. This method involved exposing the biomass to high temperatures and pressures with water, which facilitated the breakdown of macromolecules. It is true that this process would be very energy intensive. Nevertheless, HTL also contributed to negative carbon emissions due to the carbon sequestration capabilities of the biochar byproduct.

5.5. Hydrotreatment

The biofuel produced through HTL was subsequently subjected to hydrotreatment to enhance its quality by removing impurities, including sulfur and nitrogen. This process involved the different types of hydrogen, specifically grey and blue hydrogen. Even though it is commonly used, Grey hydrogen was less efficient due to its higher carbon emissions. In contrast, blue hydrogen demonstrated greater carbon neutrality and significantly reduced emissions.

5.6. Data analysis and simulation

Lastly, we employ a data analysis to optimize microalgae cultivation for biodiesel production, focusing on both upstream and downstream processes. The methodology combines MATLAB simulations and empirical data to investigate key factors influencing algal biomass production in Qinghai and Shanxi provinces. The upstream analysis was used to identify the optimal conditions for algal growth by examining key variables, including light intensity, photoperiod length, and nitrogen concentration. To achieve this, MATLAB simulations were conducted. We systematically adjust these conditions to evaluate their impact on algal biomass production. In fact, the simulations explored a wide range of scenarios, with light intensity levels varying from half to three times the reference value, photoperiods extending from 8 to 14 hours, and nitrogen concentrations ranging

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from 1 to 10 mol/m³. During this step, we use an ordinary differential equation model, which predict daily algal yield and dry mass concentration under a variety of environmental conditions. This model lead to a detailed analysis of how variations in each parameter influenced the rate of algal growth and the overall yield of biomass.

6. Upstream data analysis

Upstream processing in microalgae cultivation concentrates on the initial stages that significantly impact biomass production. According to this research, the cultivation pond design, nutrient availability, and light intensity are all factors that influence the ideal environment for algal growth. To establish regional differences in algal yield, mainly to evaluate the effect of ordinary photoperiod and acid rates, a comparative study of algal biomass production projections in Shaanxi and Qinghai Provinces has been conducted. We even examine how various factors, as well as other factors, change underground concentration and overall productivity over time.

For the downstream research to stay focused on energy consumption, carbon emissions, and the effectiveness of moving underground fuel into useful goods, it is necessary to understand these upstream processes.

6.1. Introduction to the MATLAB code for algal biomass production simulation

The effects of regular light intensity, photoperiod length, and nitrogen concentration on algal biomass production and product flow concentration are analyzed in this study employing MATLAB login. The words effectively examine a range of factors by imitating algal growth under a variety of conditions. Specifically, it assesses light intensity values from half to three times a reference level (172 MJ/m²/day), photoperiods ranging from 8 to 14 hours, and nitrogen concentrations from 1 to 10 mol/m³.

The speech employs an algal_pond_simu performance. Using an ordinary differential equation (ODE) model, daily algal yield and dry mass concentration are determined. Through a number of variations spread over a range of different factors, it provides a thorough examination of how each element affects biomass output. Many stories illustrate the connections between moist performance and design variables.

When determining the algal production data from Qinghai and Shaanxi Provinces, factors like initial algal concentration, nitrogen concentration, wastewater flow rate, feed nitrogen concentration, daily photoperiod hours, and monthly solar irradiation are all taken into account. These records were included in the MATLAB vocabulary to enable the development of algal growth under a range of circumstances [12].

6.2. Shaanxi and Qinghai Province case study

Comparing the algal production data from Qinghai and Shaanxi includes monthly solar irradiation, initial algal concentration, nitrogen concentration, wastewater flow rate, feed nitrogen concentration, video hours per day, and typical algae curiosity. These data were included in the MATLAB language to promote algal growth. For Qinghai, the initial algal concentration is 100 g/m³, nitrogen concentration is 0.014 mol/m³, wastewater flow rate is 24.3 m³/hour, feed nitrogen concentration is 5.51 mol/m³, daily image time is 11.67, and monthly solar irradiation is 153.3 k Wh/m²/month [13,14]. In contrast, Shaanxi has an initial algal concentration of 100 g/m³, nitrogen concentration of

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0.016 mol/m³, wastewater flow rate of 21.5 m³/hour, feed nitrogen concentration of 9.1 mol/m³, daily picture nights of 4.56, and monthly solar irradiation of 103.3 k Wh/m²/month.

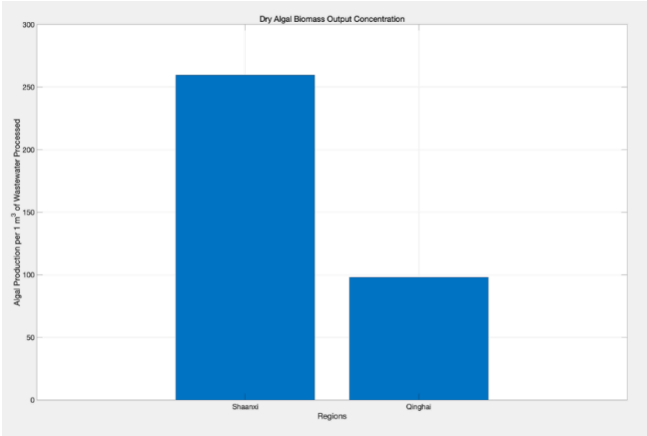

Figure 1. Dry algal biomass output

6.3. Investigation of algal production variables

The observed discrepancy in algal production between Qinghai and Shaanxi Provinces prompted further investigation into the variables. This exploration focused on general trends in algal production over time, specifically examining three key independent variables: light intensity, photoperiod length, and nitrogen concentration.

6.3.1. Effect of light intensity on algal yield

Simulations revealed a parabolic relationship between light intensity and algal yield as Figure 2 shows. At low light intensities, photosynthesis is constrained by limited light availability, resulting in lower growth rates. As light intensity increases, the rate of photosynthesis also rises, leading to enhanced algal growth rates until an optimal level is reached. However, beyond this optimal point, excessive light can damage the photosynthetic apparatus of the algae, causing a decline in growth rates. between light intensity and algal yield.

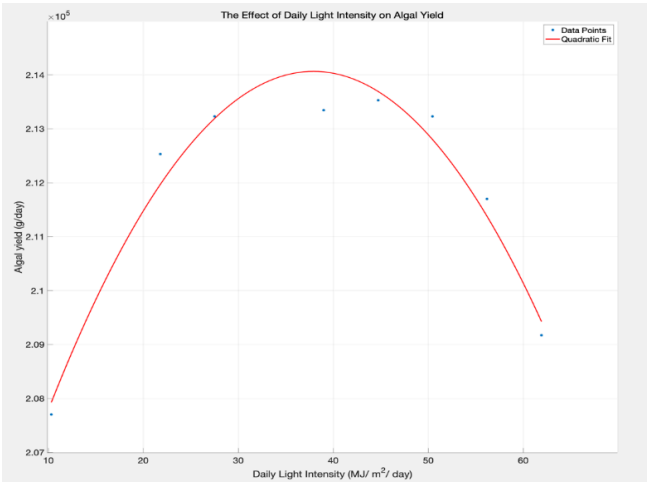

Figure 2. The effect of light intensity on algae yield

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6.3.2. Influence of photoperiod length on algal yield

The effect of photoperiod length on algal yield was also examined. The analysis indicated an overall linear pattern (Figure 3): longer photoperiods allow for extended periods of photosynthesis. This increased exposure enables algae to convert light energy into chemical energy more effectively, resulting in higher algal yields. Optimizing photoperiod length could significantly enhance biomass production.

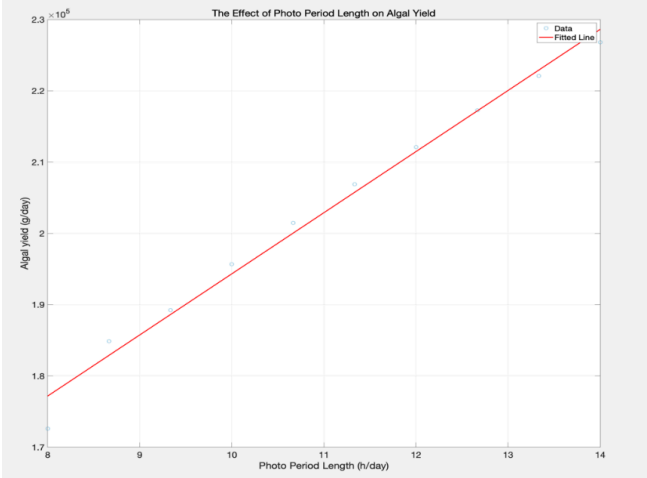

Figure 3. The effect of photo period length on algae yield

6.3.3. Impact of nitrogen concentration on algal production

Finally, the influence of nitrogen concentration on algal production was investigated. Similar to photoperiods, higher nitrogen concentrations correlate positively with increased algal biomass and growth rates. This relationship can be attributed to two main factors: first, increased nitrogen availability enhances protein synthesis, which is essential for cell growth and division; second, higher nitrogen levels promote chlorophyll production, thereby enhancing the algae's ability to perform photosynthesis effectively.

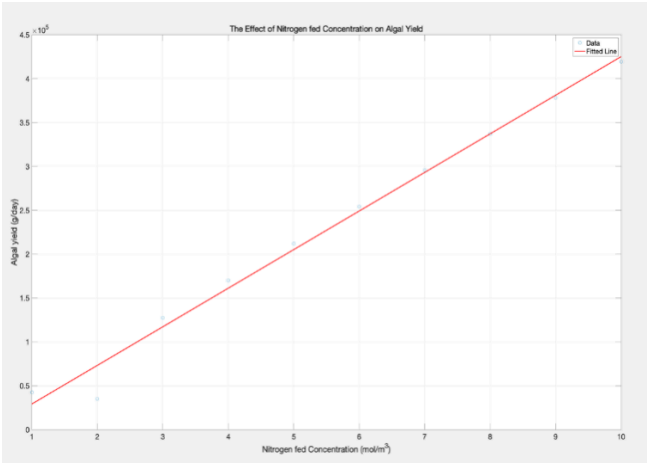

Figure 4. The effect of nitrogen fed concentration on algal yield

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7. Downstream data analysis

Downstream is concerned with the system's energy consumption, carbon emission, and ultimately the output. It mainly appears in the algae input， cultivation， flocculation， centrifugation, hydrothermal liquefaction and hydrotreatment. The system uses 1 cubic meter of wastewater as an example.

7.1. Algae input

This process adds algae directly to 1 cubic meter of wastewater, so there is little energy consumption. At the same time, the process absorbs carbon dioxide. The carbon emission is negative. According to Figure 5, Qinghai's carbon emission is -0.19kg, and Shaanxi's carbon emission is -0.52kg. According to the different concentrations of wastewater and the different contents of nitrogen and phosphorus in different areas of Qinghai and Shaanxi, it can be obtained that in 1 cubic meter wastewater, the algae production in Qinghai is 9.8×10^{-2}kg, and algae production in Shaanxi is 25.96×10^{-2}kg.

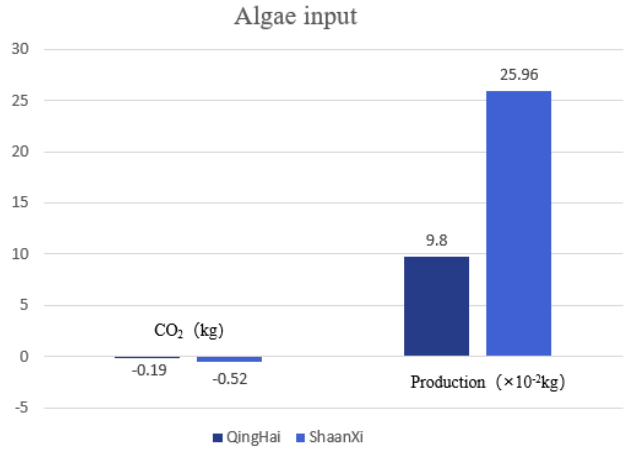

Figure 5. Carbon emission and production during the input of algae in Qinghai and Shaanxi Provinces

7.2. Cultivation

Cultivation is a complex process involving multiple stages and influencing factors. Appropriate environmental conditions are required, including light, temperature, pH, nutrient salts (such as nitrogen, phosphorus, potassium), and carbon dioxide supply. When the algae are cultured in 1 cubic meter of wastewater, the necessary photosynthesis will occur. Photosynthesis requires the absorption of carbon dioxide to help algae grow better. Combined with the different conditions of light, temperature, nutrient salts (such as nitrogen and phosphorus concentrations) in the two places, the carbon dioxide released in the process, the energy required, and the final biomass production can be calculated, as shown in the Fig2 below.

As can be seen from Figure 6, the energy consumption in the culture process is 2.4×10^{-4}GJ in Qinghai Province and 6.4×10^{-4}GJ in Shaanxi Province. The carbon emission in Qinghai and Shaanxi were -0.1658kg and -0.4393kg respectively. The final biomass yield was 9.80×10^{-2}kg in Qinghai province and 25.96×10^{-2}kg in Shaanxi Province.

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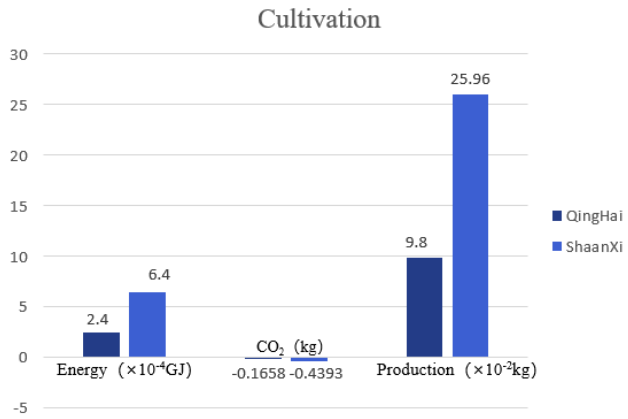

Figure 6. Energy consumption, carbon emission and production during cultivation in Qinghai and Shaanxi Provinces

7.3. Flocculation

The biomass of the obtained algae is extracted through flocculation for subsequent processing. The flocculant is first added to the solvent containing the microalgae material, so that the microalgae cells can condense together to form a larger flocculant, which is easier to separate.

According to the data obtained in the previous step, it can be acquired that the energy consumption of Qinghai province is 0.17×10^{-4}GJ, the carbon emission is 2.10×10^{-3}Kg, and the production is 9.80×10^{-2}Kg. The energy consumption of Shaanxi Province is 0.44×10^{-4}GJ, the carbon emission is 5.55×10^{-3}Kg, and the production is 25.96×10^{-2}kg (Figure 7).

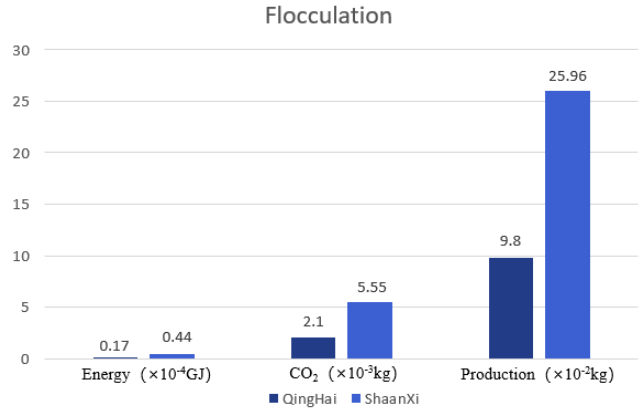

Figure 7. Energy consumption, carbon emission and production during flocculation in Qinghai and Shaanxi Provinces

7.4. Centrifugation

The flocculates obtained after flocculation need to be separated by centrifugation. Centrifugation is a separation technique that utilizes the different sedimentation rates of different substances under centrifugal force to achieve rapid sample separation and purification. The centrifugal process mainly consumes electrical energy and directly or indirectly produces carbon dioxide. According to the data in Figure 8, the energy consumption of Qinghai Province in this step is 0.67×10^{-4}GJ, the carbon emission is 8.39×10^{-3}kg, and the output is 9.39×10^{-2}kg. The energy consumption of Shaanxi

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Province in this step is 1.77×10^{-4}GJ, the carbon emission is 22.2×10^{-3}Kg, and the output is 24.87×10^{-2}kg.

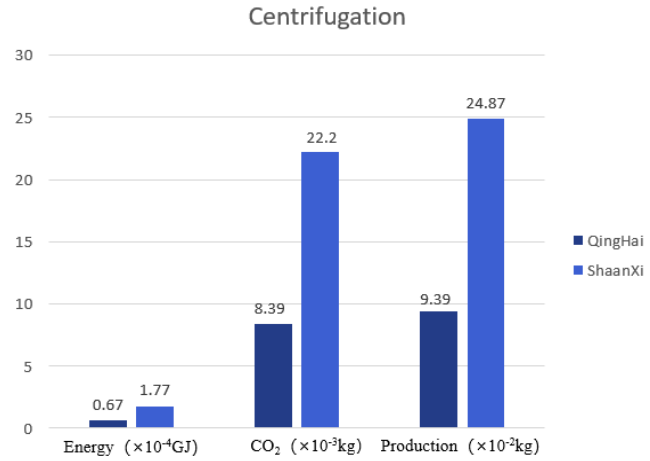

Figure 8. Energy consumption, carbon emission and production during centrifugation in Qinghai and Shaanxi Provinces

7.5. Hydrothermal liquefaction

Hydrothermal liquefaction is a technology that converts macromolecules in biomass into products such as bio-oil through a series of chemical reactions. The whole process uses water as a solvent, through high temperature and high pressure, water molecules decompose biomass in a non-liquid and non-gaseous supercritical state, to obtain bio-oil and other products. This process is relatively simple, no harmful solvents are used, and the produced biochar is returned to the soil using soil carbon sequestration technology to achieve negative carbon emissions. The data of hydrothermal liquefaction are shown in Figure 9, the energy consumption of Qinghai Province and Shaanxi province in this step is 2.61×10^{-4}GJ and 6.91×10^{-4}GJ respectively. Carbon dioxide emissions were -2.97×10^{-3}kg and -7.88×10^{-3}kg, respectively. The final yields were 1.01×10^{-2}kg and 2.69×10^{-2}kg respectively.

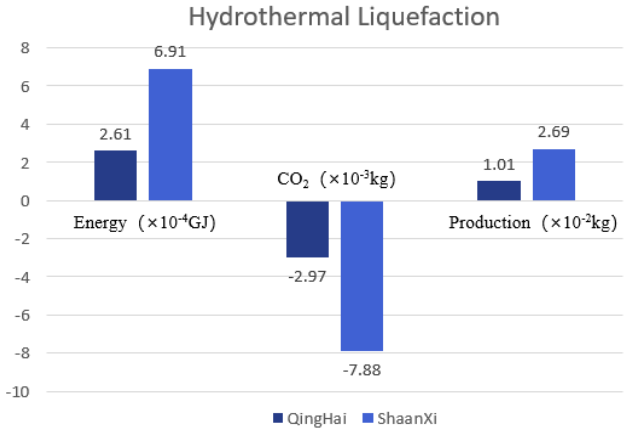

Figure 9. Energy consumption, carbon emission and production during hydrothermal liquefaction in Qinghai and Shaanxi Provinces

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7.6. Hydrotreating

The bio-oil extracted through the above steps still has many impurities (such as sulfur, nitrogen, etc.), and cannot meet most uses in life. It needs to be hydrotreated. The purpose of hydrotreating is to improve the quality of raw oil and remove impurities in bio-oil. The type of hydrogen selected is also one of the factors that affect the energy consumption, output and carbon emissions of the system. In this study, traditional grey hydrogen and blue hydrogen were selected for simulation calculation.

Figure 10 lists the energy consumption and carbon emission required to produce 1kg of grey and blue hydrogen respectively [6].By comparison, blue hydrogen has more advantages than gray hydrogen. When getting the same amount of product, the energy consumption of blue hydrogen and gray hydrogen is not different, but the carbon dioxide emissions of blue hydrogen are far less than that of gray hydrogen. Therefore, blue hydrogen is selected as a raw material to be added to the system.

The data obtained during the whole process are shown in Figure 11. The energy consumption of Qinghai province is 0.77×10^{-2}GJ, the carbon dioxide emission is 0.14kg, and the final yield is 0.89×10^{-2}kg. Shaanxi's energy consumption is 2.05×10^{-2}GJ, carbon dioxide emissions are 0.37kg, and the final output is 2.35×10^{-2}kg.

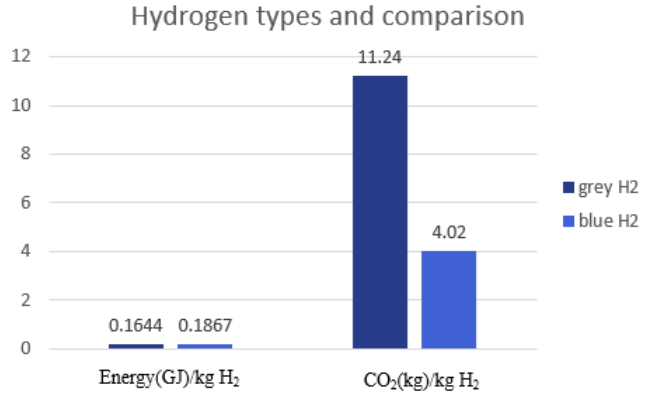

Figure 10. Energy consumption and carbon emission to produce 1 kg blue hydrogen and grey hydrogen

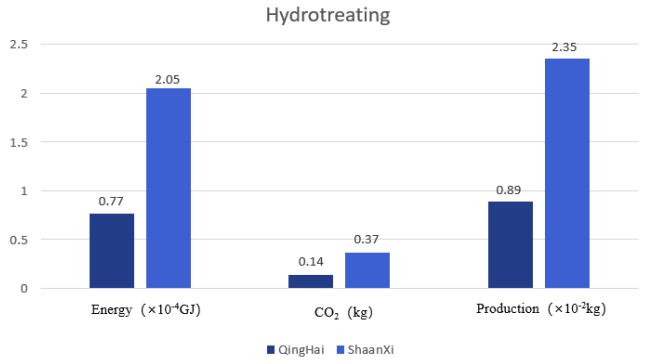

Figure 11. Energy consumption, carbon emission and production during hydrotreatment in Qinghai and Shaanxi Provinces

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In general, in the process of extracting biomass from algae and finally producing biodiesel, the energy consumption of hydrotreating accounts for the largest proportion, followed by hydrothermal liquefaction, while the energy consumption of flocculation and centrifugation is small. And in this process, algae culture and hydrothermal liquefaction not only don‘t produce carbon dioxide but will consume a certain amount of carbon dioxide and carbon storage, to achieve negative carbon emissions. In 1 cubic meter of wastewater, the amount of diesel oil that can be obtained in Qinghai and Shaanxi is 0.88×10^{-2}kg and 2.35×10^{-2}kg respectively.

8. Conclusion

Carbon emissions have been a pressing problem in the process of producing fuels around the globe in the past decades, and the overuse of non-renewable resources in fuel production affects energy sustainability. In this context, the paper explores the simulation of the system that produces biodiesel based on the hydrothermal liquefaction of microalgae (chlorella) in wastewater, and the system consists of four main units, including algae cultivation, pre-treatment of algal mixtures, hydrothermal liquefaction, and hydrotreating. The study focuses on three aspects by taking Shaanxi and Qinghai as the analysis objects. Firstly, the study investigates the effect of nitrogen concentration in wastewater and light conditions on the yield of biodiesel. Secondly, the study discusses the energy consumption in the life circle of the system and carbon capture when producing 1 kg of biodiesel. Thirdly, the paper makes a comparison of three techniques of producing hydrogen that are utilized in HDT.

The biodiesel yield correlates with algal biomass yield (algal growth rate). For every 1 kg of algae in 1 m^3 of wastewater, it produces 0.09 kg of biodiesel in the final step of the system, which is showed in Figure 12. Light intensity, photoperiod, and nitrogen concentration will affect the yield of biodiesel indirectly by influencing the yield of algal biomass. As light intensity is between 10 ~ 38 $MJ/m^2/day$, the rate of photosynthesis increases, leading to higher algal growth rates but slowing down when it approaches 38 $MJ/m^2/day$. 38 $MJ/m^2/day$ is the optimal light intensity at which photosynthesis occurs most efficiently. When light intensity exceeds 38 $MJ/m^2/day$, the algal growth rate declines due to the occurrence of photoinhibition, where the excess light intensity damages the photosynthetic apparatus. Longer photoperiods correlate with increased algal biomass and growth rates, since longer photoperiods provide more time for photosynthesis, allowing algae to convert light energy into chemical energy more effectively. When nitrogen concentrations are between 1～10 mol/m^3, higher nitrogen concentrations correlate with increased algal biomass and growth rates. Here are the two reasons for this. First, increased nitrogen availability enhances protein synthesis, which is essential for cell growth and division. Second, higher nitrogen concentrations lead to increased chlorophyll production, enhancing the algae's ability to perform photosynthesis effectively.

A comparison of two places with significant differences in light intensity, photoperiod, and sewage nitrogen content roughly shows the extent to which three independent factors influence the biodiesel yield. The daily light intensity of Qinghai and Shaanxi is respectively 18.4 $MJ/m^2/day$ and 12.4 $MJ/m^2/day$; the photoperiod length of Qinghai and Shaanxi is respectively 11.67 hours and 4.56 hours; the nitrogen concentration of Qinghai and Shaanxi is respectively 5.51 mol/m^3 and 9.1 mol/m^3; and the final biodiesel production of Qinghai and Shaanxi is respectively 8.9 g/m^3 and 23.5 g/m^3. Although the light intensity of Shaanxi is about 33% less than that of Shaanxi and the photoperiod of Shaanxi is half of Qinghai’s, the final biodiesel yield of Shaanxi becomes three times as much as Qinghai’s when the nitrogen in waste water of Shaanxi doubles. Thus, it’s indicated that nitrogen concentration in waste water is the more decisive factor in biodiesel yield. For further

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study, a regression model can be established to determine the impact of each independent variable on the dependent variable.

HDT contributes more than 90% of energy consumption to the system that utilizes algal biomass to produce biodiesel. When different techniques of hydrogen production are considered, they result in the different total energy consumption of the system, which are shown in Figure 13. For energy embodied in the system, when producing 1 kg of biodiesel, gray H2 requires the lowest energy. The energy consumption of producing blue H2 is higher than producing gray H2 since blue H2 involves carbon capture storage that needs energy input. Energy consumption of green H2 is the highest since there is a greater loss of energy compared with steam methane reforming in the process of electrolyzing water to produce hydrogen.

Moreover, when different techniques of hydrogen production are considered, they also lead to different carbon emission levels in the system, which are shown in Figure 14. Using gray H2 in HDT generates 26 kg of carbon emissions for producing 1 kg of biodiesel. Both the utilization of blue H2 and green H2 will make it possible for carbon neutrality and carbon capture, but green H2 outperforms blue H2 because there is no carbon emission in the process of electrolyzing water.

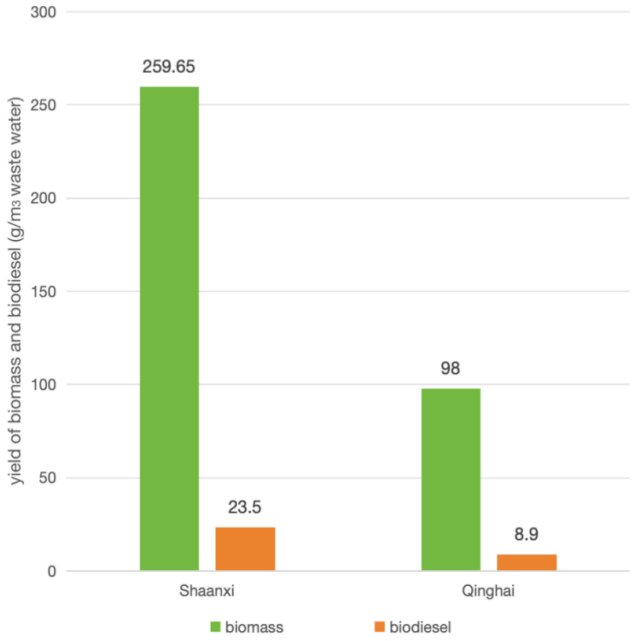

Figure 12. Yield of biomass (upstream) and yield of biodiesel (downstream) for 1 m³ waste water

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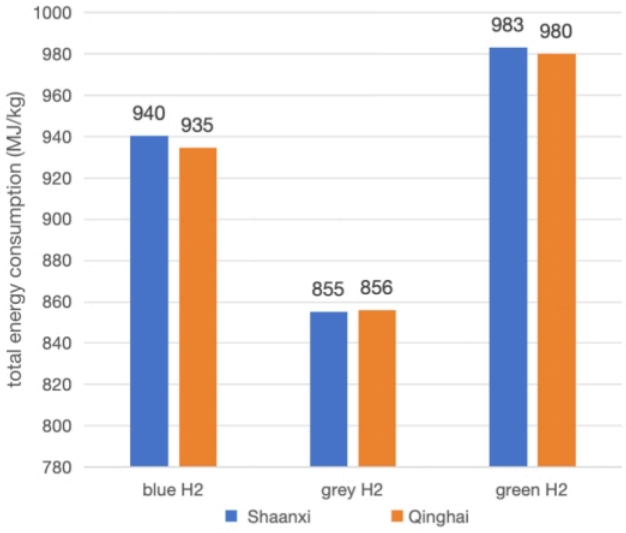

Figure 13. Total energy consumption of the process from algal cultivation to HDT (transportation energy consumption is not considered)

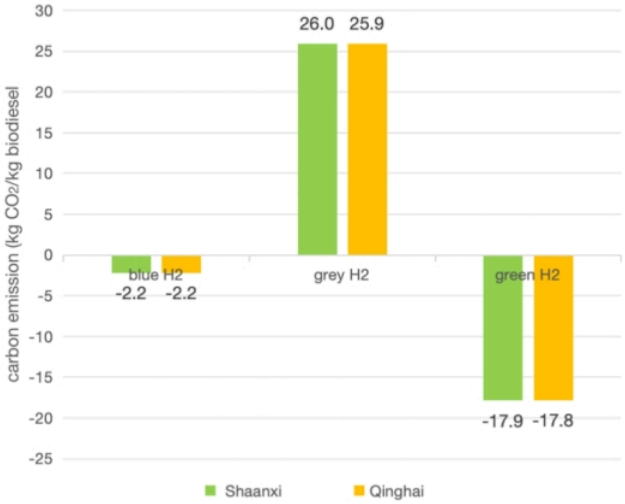

Figure 14. Total carbon emission of the process from algal cultivation to HDT (using different hydrogen producing techniques)

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ZHANG Wandong and DU Pengyu contributed equally to this work and should be considered co-second authors.

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