Life cycle assessment of biofuel production from microalgae cultivated in anaerobic digested wastewater

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Abstract: The whole process of biofuel production from Desmodesmus sp. EJ 8-10 cultivated in anaerobic digested wastewater (ADW) under the optimal temperature was evaluated by using the method of Life Cycle Assessment (LCA). The energy efficiency and environment emissions were under considerable for the corresponding parametric study. The functional unit was 1 kg microalgae. It was concluded that the harvest stage was responsible for the main energy consumption during the microalgal whole pyrolysis process. The energy conversion efficiency of the whole process was larger than 1, which indicated that the process was profitable. The environmental impact of the whole process was 1.16567 MtPE T2000, among which the primary impact on the environment was eutrophication that accounts for 57.36%, followed by photochemical ozone synthesis (22.56%), acidification (17.36%); and global warming (2.73%), respectively.

Keywords: microalgae, fast pyrolysis, life cycle assessment (LCA), anaerobic digested wastewater (ADW), biofuel production

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1 Introduction

Microalgae, known as new sources of biofuel production, have features such as extensive distribution, wide adaptability, rapid growth and high lipid content[1-2]. Microalgae can grow in different kinds of wastewater, which reduces the cost of microalgae cultivation and mitigates pollution[3,4]. Anaerobic digested wastewater (ADW) comprises quantities of nitrogen, phosphorus, potassium, amino acids, vitamins, protein, carbohydrates, and other substances that can promote the growth and development of microalgae[5-7]. Conducing ADW to cultivate microalgae not only benefits wastewater disposal but also effectively lowers the cost of algae production.

During the process of biomass gasification, liquefaction and combustion, biomass pyrolysis technology is indispensable for converting biomass to liquid fuel or other valuable chemical products[8-10]. Recently, many studies have focused on the potential of biofuel production from microalgae cultivated in wastewater[11-14]. This approach is recognized as a cost-effective way for better waste remediation, lowering the environmental influence of biofuel production[15]. However, the energy needed, the conversion efficiency, and the degree of environmental impact during the entire process are still unknown and need to be evaluated.

As a well-established scientific framework and methodology, a life cycle assessment (LCA) aims to both evaluate the energy consumption and environmental influence of a product over its whole life cycle and identify the main sources of pollution[16,17]. As shown in Figure 1, the analytical procedures of an LCA mainly consist of the objective and scope definition, inventory analysis, results interpretation and assessment improvement[18,19]. Indeed, LCA could be accomplished by compiling a comprehensive inventory of inputs, such as raw materials, water and electricity, and quantifying the outputs, such as products, emissions and by-products, with the potential environmental impact associated with the whole process[20,21].
In this study, LCA was employed to evaluate the energy conversion efficiency and potential environmental impacts associated with the process of microalgae fast pyrolysis for biofuel production based on ADW cultivation. The specific energy input was comprised of the main energy consumption, the energy output and conversion efficiency, the categories of environmental impact and the primary contribution substances.

2 Research objective and life cycle system boundary

2.1 Research objective

The research objective of this study was the pyrolysis process of Desmodesmus sp. EJ 8-10. According to previous research results, the optimum pyrolysis temperature of EJ 8-10 was about 600°C. This study used 1 kg Desmodesmus sp. EJ 8-10 as the functional unit, and the pyrolysis process of microalgae at the optimum temperature was comprehensively evaluated, including the energy efficiency analysis and environmental impact potential.

2.2 Life cycle system boundary

The life cycle system boundary of Desmodesmus sp. EJ 8-10 pyrolysis process was mainly defined by three stages: the cultivation stage, harvest stage and pyrolysis stage. The following assumptions and simplifications were made in the study of Desmodesmus sp. EJ 8-10 pyrolysis process using the LCA technology:

1. This study focused on analyzing the cultivation, harvest and pyrolysis of microalgae, ignoring the depreciation and loss of centrifuge, pyrolysis and other equipment during the process;
2. The environmental impact generated by the growth process of microalgae was excluded;
3. The pollutants generated by each link of the system were directly discharged into the environment without post-treatment or reuse;
4. The energy consumption of the temperature control equipment was ignored because the environmental temperature was relatively consistent with the growth temperature of microalgae.

3 Environmental impact assessment

According to the basic principles and framework of life cycle analysis proposed by ISO 14040, the entire research process consisted of four parts: research objective and scope definition, inventory analysis, impact assessment and results interpretation.

3.1 Inventory analysis

3.1.1 Cultivation stage

In this study, the laboratory cultivation of Desmodesmus sp. EJ 8-10 mainly included three processes: the sterilization of the ADW (121°C for 20 min), the inoculation in the clean bench and the 14-day cultivation on the culture shelf. The characteristics of ADW before and after sterilization were shown in Table 1. The main energy consumption includes the electricity consumption of the autoclave, the clean bench and the plant light source on the culture shelf.

Table 1 Characteristics of the ADW

| Items  | ADW before sterilization/mg L⁻¹ | ADW after sterilization/mg L⁻¹ |
|--------|--------------------------------|-----------------------------|
| NH₄⁺⁻N | 1490.47                        | 1056.27                     |
| PO₄³⁻  | 33.39                          | 37.16                       |
| COD    | 2820                           | 2950                        |

In this experiment, a 5 L Erlenmeyer flask with 3 L medium was used, and the biomass obtained after 14 days of cultivation was 0.646 g/L. Due to the limited capacity of the autoclave, only an 8 L culture medium could be processed once, and 194 sterilization times were needed to obtain 1 kg EJ 8-10, which consumed 200.5 kWh during the process. The inoculation time was 10 min, and since only 10 5-L triangular bottles could be inoculated each time, 52 inoculation times were needed to obtain 1 kg EJ 8-10, for a total of 3.5 kWh. With a day/night ratio of 14 h/10 h during the 14 days cultivation, 28.2 kWh was needed to provide the light source.

The energy that required to produce electricity per kWh is considered as 8.02 MJ, and the main pollutants produced are CO₂, 725.90 g; CO, 0.23 g; CH₄, 1.80 g; NOₓ, 1.12 g; particulate matter (PM₁₀), 0.07 g; SO₂, 1.14 g; and volatile organic compounds (VOC), 0.04 g. Table 2 shows the energy consumption and various emissions during the cultivation of 1 kg Desmodesmus sp. EJ 8-10.

Table 2 Inventory analysis of Desmodesmus sp. cultivation, harvest and pyrolysis process

| Energy consumption | Cultivation kWh | Harvest kWh | Pyrolysis kWh |
|--------------------|----------------|-------------|--------------|
| Electricity/kWh    | 232.2³          | 1226.4⁴     | 722.2⁴       |
| Energy needed/MJ   | 1862.2⁶         | 9835.7⁷     | 5792²        |
| CO₂/g              | 168 554         | 890 243.8   | 524 245      |
| CO/g               | 53.4            | 282.1       | 166.1        |
| CH₄/g              | 418             | 2207.5      | 1300         |
| Air pollutants     |                |             |              |
| NOₓ/g              | 260.1           | 1373.6      | 808.9        |
| SO₂/g              | 264.7           | 1398.1      | 823.3        |
| PM₁₀/g             | 16.3            | 85.9        | 50.6         |
| VOC/g              | 9.3             | 49.1        | 28.9         |

Note: ³ The sum of the electrical energy consumed during Desmodesmus sp. cultivation including the sterilization of the medium, the inoculation in clean bench and the cultivation on the culture shelf for 14 d; ⁴ Converting the sum of electrical energy consumed during Desmodesmus sp. cultivation to the energy required to produce electricity per kWh; ⁵ The sum of electrical energy consumed during the harvest of Desmodesmus sp. including the energy consumed by centrifugation and freeze drying; ⁶ Converting the sum of electricity consumed during the harvest of Desmodesmus sp. to the energy required to produce electricity per kWh; ⁷ The sum of electricity consumed in the pyrolysis process of Desmodesmus sp.; ² Converting the sum of the electricity consumed during the pyrolysis process of Desmodesmus sp. to the energy required to produce electricity per kWh.

3.1.2 Harvest stage

After the cultivation of 14 d, the samples were placed in 5 L triangular flasks and then stood for more than 24 h for the sedimentation of microalgal cells. A large amount of supernatant samples could be centrifuged each time (6000 r/min, 10 min). Due to the limited volume of the centrifuge, only 1.5 L of samples could be centrifuged each time (6000 r/min, 10 min). Totally, the collection of 1 kg EJ 8-10 required 1032 centrifugations, which consumed about 1135.2 kWh. The centrifuged EJ8-10 suspension was freeze-dried for 48 h and collected as the raw material for subsequent pyrolysis, the energy consumption to obtain 1 kg Desmodesmus sp. EJ 8-10 was 722.2 kWh during the freeze-drying process. Table 2 shows the energy consumed during the harvest stage of Desmodesmus sp. EJ 8-10 was 1226.4 kWh, and the main atmospheric emissions were CO₂, CH₄, NOₓ and SO₂.

3.1.3 Pyrolysis stage

The pyrolysis stage of Desmodesmus sp. EJ 8-10 included pyrolysis and pyrolysis analysis of pyrolysis...
products. According to previous research conclusions, the optimum pyrolysis temperature of *Desmodesmus* sp. EJ 8-10 was approximately 600°C\(^\text{13}\). The pyrolysis products were monitored and analyzed in real time by Curie-point pyrolyzer–gas chromatography/mass spectrometry (Py-GC/MS). By comparing the NIST 2011 spectra library data (Version 2.0, National Institute of Science and Technology, USA), the composition and relative content of the pyrolysis products were obtained. According to the characteristics of Py-GC/MS instrument, the following assumptions were made:

1. Since *Desmodesmus* sp. EJ 8-10 was instantaneously pyrolyzed in the pyrolyzer, the instantaneous energy consumption was neglected.
2. The energy transfer inside the pyrolyzer was neglected.
3. Since the proportion of the pyrolysis time in the life of the pyrolysis device was very small, the maintenance of the device was neglected.
4. The on-line analysis of pyrolysis products only considered the energy consumed in the whole process after the pyrolysis products enter the GC/MS instrument, which was separated by the programmed temperature and detected by mass spectrometry in real time.

Other energy consumption factors were neglected. According to the previous research results, it took 50 min for temperature-programmed heating, and the pyrolysis product analysis consumed around 2.2 kW·h.

During the pyrolysis stage of *Desmodesmus* sp. EJ 8-10 at 600°C, it took 10.8 min for the chamber temperature inside the pyrolyzer to increase from room temperature (25.6°C) to the optimal temperature (600°C). The pyrolysis of 1 kg *Desmodesmus* sp. EJ 8-10 consumed 720 kW·h of electricity. The energy consumption during the pyrolysis stage of *Desmodesmus* sp. EJ 8-10 was 722.2 kW·h, and the main gas emission was CO\(_2\) (Table 2).

### 4 Impact assessment

#### 4.1 Energy efficiency analysis

As shown in Table 3, the energy consumption of *Desmodesmus* sp. EJ 8-10 throughout the life cycle was 17489.9 MJ. In the entire life cycle of these three stages, the energy consumption in the harvest stage was the highest, up to 56.24%, followed by the pyrolysis stage, and the lowest was the cultivation stage.

| Stage       | Energy consumption/MJ | Percentage% |
|-------------|------------------------|-------------|
| Cultivation | 1862.2                 | 10.65       |
| Harvest     | 9835.7                 | 56.24       |
| Prolysis    | 5792.0                 | 33.12       |
| Sum         | 17489.9                | 100.01      |

In this study, the High Heating Value (HHV) Equation was used to calculate the energy of the pyrolysis products\(^\text{24}\). To facilitate the research and data calculations, the following assumptions were made:

1. The pyrolysis products with larger peak areas and stable detection results were summarized and compared, and the pyrolysis products with matching degrees greater than 80% were studied.
2. In the process of calculating HHV of pyrolysis products, the relative content of the pyrolysis products was determined by using the area normalization method, the chemical formula (a) was determined according to the chemical abstracts service number (CAS No.) of each pyrolysis product, and a new chemical formula (b) was obtained by multiplying the atomic number of the elements in the chemical formula of each pyrolysis product by the relative content of each component, according to the principle of the addition of the atomic number of the same element. All pyrolysis products were combined to fit into a new empirical chemical formula (c), namely, C\(_x\)H\(_y\)O\(_z\)N\(_m\)S

According to previous research, the pyrolysis products of *Desmodesmus* sp. EJ 8-10 at 600°C (the matching degree was more than 80%) are shown in Table 4. According to the above steps, a new chemical formula for fitting the pyrolysis products of EJ 8-10 with 600°C was C\(_{672.31}\)H\(_{1150.67}\)O\(_{18.72}\)N\(_{5.79}\)S, and the HHV was considered to be 38512.67 MJ/kg.

The energy conversion efficiency \(\eta\) was calculated as Equation (1):

\[
\eta = \frac{q_{\text{pyrolysis products}}}{LCA_{\text{energy}}} (1)
\]

where, \(\eta\) is the energy conversion efficiency; \(q_{\text{pyrolysis products}}\) is the HHV of the pyrolysis products; \(LCA_{\text{energy}}\) is the energy consumption in the life cycle.

The \(\eta\) of *Desmodesmus* sp. EJ 8-10 was 2.2, greater than 1, which indicated that the pyrolysis process of *Desmodesmus* sp. EJ 8-10 was beneficial.

| Compounds                              | Relative content% |
|----------------------------------------|-------------------|
| Cyclopropane, octyl-                   | 0.81              |
| cis-1-Butyl-2-methyl cyclopropane       | 0.71              |
| cis-1-Hexyl-2-propyl cyclopropane       | 1.07              |
| Cyclooctadecane                        | 0.75              |
| (7R,8S)-cis-anti-cis-7,8-Epoxytriacyclo[7.3.0(2,6)] dodecane | 0.42 |
| Pentadecane                            | 0.28              |
| Cyclopentadecane                       | 2.50              |
| Cyclohexadecane, 1,2-diethyl-           | 1.08              |
| Heptadecane                            | 1.29              |
| E,Z-4-Ethylidene cyclohexene           | 0.11              |
| 1,4-Cyclohexadienopropionate           | 0.23              |
| 1-Heptene                              | 0.71              |
| 1,4-Cyclooctadiene                     | 0.49              |
| Bicyclo[4.2.0]octa-1,3,5-triene         | 0.24              |
| 1-Nonene                               | 0.43              |
| 1-Decene                               | 0.64              |
| 1-Tridecene                            | 0.55              |
| 1-Tetradecene                          | 0.80              |
| 1-Pentadecane                          | 1.15              |
| 2-Hexadecene, 2,6,10,14-tetramethyl-   | 0.74              |
| 2-Hexadecene, 3,7,11,15-tetramethyl-   | 1.60              |
| 1-Heptadecene                          | 0.36              |
| 3-Heptadecene, (Z)-                    | 0.29              |
| 1-Octadecene                           | 0.24              |
| 1-Nonadecene                           | 4.82              |
| n-Hexadecanoic acid                    | 3.23              |
| 9-Hexadecenoic acid                    | 0.69              |
| Oleic acid                             | 1.71              |
### 4.2 Environmental impact load

#### 4.2.1 Calculation of the environmental impact potential

The environmental impact potential of the products refers to the sum of all environmental emission impacts (including resource consumption) in the whole product system, which can be expressed by the following formula:

\[
EP(j) = \sum EP(j) = \sum (Q(j) \times EP(j))
\]

where, \(EP(j)\) is the contribution of the research system to the \(j\)th potential environmental influence; \(EP(j)\) is the contribution of the \(i\)th emission substance to the \(j\)th potential environmental potential; \(Q(i)\) is the discharge amount of the \(i\)th substance; \(EP(j)\) is the equivalent factor of the \(i\)th emission substance to the potential environmental influence\[25-27].

There were four types of environmental impacts analyzed in this study, followed by global warming, acidification, photochemical ozone synthesis and eutrophication\[28-30\]. Table 5 shows the environmental impact potential analysis of the *Desmodesmus* sp. EJ 8-10 pyrolysis life cycle. First, the global warming potential of the *Desmodesmus* sp. EJ 8-10 pyrolysis life cycle was 2423.799 kg CO\(_2\)eq, where CO\(_2\) was the main influencing factor, up to 65.31%; NO\(_x\) emission (31.25%) was the second, followed by CH\(_4\) and CO. The acidification potential of *Desmodesmus* sp. EJ 8-10 was 4.196 kg SO\(_2\)eq; the main emission substance to the potential environmental influence potentials or resource consumption\[28\]. In this system, all depreciations and losses were neglected. Therefore, in this study, global warming was the biggest share (65.34%), and the contribution of VOC was slightly higher than that of CH\(_4\). In the eutrophication potential analysis of *Desmodesmus* sp. EJ 8-10, eutrophication was caused entirely by NO\(_x\) emissions (0.3176 kg PO\(_4\)eq).

#### Table 5 Analysis on potential environmental impact of *Desmodesmus* sp. EJ 8-10

| Impact category | Desmodesmus sp. EJ 8-10 |
|-----------------|-------------------------|
| Substance       | CO\(_2\) | CH\(_4\) | NO\(_x\) | CO |
| Effect equivalent factor | 1 | 21 | 310 | 2 |
| Quantity/kg     | 1583.04 | 3.925 | 2.443 | 0.502 |
| Sum/kg CO\(_2\)eq | 1583.04 | 82.425 | 757.33 | 1.004 |
| Proportion/%    | 65.31 | 3.40 | 31.25 | 0.041 |

- **Global warming**
  - Substance: CO\(_2\), CH\(_4\), NO\(_x\), CO
  - Effect equivalent factor: 1, 21, 310, 2
  - Quantity/kg: 1583.04, 3.925, 2.443, 0.502
  - Sum/kg CO\(_2\)eq: 1583.04, 82.425, 757.33, 1.004
  - Proportion/%: 65.31, 3.40, 31.25, 0.041

- **Acidification**
  - Substance: SO\(_2\), NO\(_x\)
  - Effect equivalent factor: 1, 0.7
  - Quantity/kg: 2.443, 2.443
  - Sum/kg SO\(_2\)eq: 2.443, 1.71
  - Proportion/%: 59.25, 40.75

- **Photochemical ozone formation**
  - Substance: VOC, CO, CH\(_4\)
  - Effect equivalent factor: 0.6, 0.3, 0.007
  - Quantity/kg: 0.0873, 0.502, 3.925
  - Sum/kg CO\(_2\)eq: 0.05238, 0.1506, 0.02748
  - Proportion/%: 22.73, 65.34, 11.92

- **Eutrophication**
  - Substance: NO\(_x\)
  - Effect equivalent factor: 0.13
  - Quantity/kg: 2.443
  - Sum/kg PO\(_4\)eq: 0.3176
  - Proportion/%: 100

#### 4.2.2 Standardization of the environmental impact potential

Although the types of environmental impacts and the equivalent factors have been determined, the environmental impact potential needs to be standardized for evaluating. The standardization process is primarily to establish a standardized benchmark, then provide a comparable standard for the relative size of the various types of impact. The formula for data standardization in inventory analysis is shown as followed:

\[
NP(j) = P(j) \times \frac{1}{T \cdot R(j)}
\]

where, \(T\) is the product service period; \(R(j)\) is the standard benchmark for the \(j\)th year; \(P(j)\) is the various environmental influence potentials or resource consumption\[28\]. In this system, all depreciations and losses were neglected. Therefore, in this study, global warming was the biggest share (65.34%), and the contribution of VOC was slightly higher than that of CH\(_4\). In the eutrophication potential analysis of *Desmodesmus* sp. EJ 8-10, eutrophication was caused entirely by NO\(_x\) emissions (0.3176 kg PO\(_4\)eq).

In this study, the year 2000 was selected as the reference year. According to Equation (4), the environmental impact potential of the standardized *Desmodesmus* sp. EJ 8-10 pyrolysis was calculated and listed in Table 6\[31\]. The standardized environmental impact potential unit was the standard person equivalent (PE), which was the average environmental impact potential per person per year\[32\].

Among the four environmental impact types evaluated (Table 6), the *Desmodesmus* sp. EJ 8-10 pyrolysis process had the greatest impact on global warming, reaching 58.14%. Then, the eutrophication and acidification processes accounted for 27.54% and 13.23%, respectively. The least influential factor was photochemical ozone synthesis, which accounted for only 1.09% of the total. The analysis of the proportion of impact types after standardization was in the following sequence: global warming > eutrophication > acidification > photochemical ozone synthesis.
The energy conversion efficiency of the entire pyrolysis process was beneficial. The whole life cycle environmental impact of EJ 8-10 was 1165.67 mPET2000. Among them, the main environmental impact was eutrophication, accounting for 57.36%, followed by photochemical ozone synthesis and acidification, accounting for 22.56% and 17.36%, respectively; the global warming impact only accounted for 2.73%.

5 Conclusions

The energy consumption of the Desmodesmus sp. EJ 8-10 throughout its life cycle was 17489.9 MJ. The analysis of the energy consumption resulted in the following sequence: the microalgae harvest stage > pyrolysis stage > cultivation stage. The energy conversion efficiency η of the entire pyrolysis process of Desmodesmus sp. EJ 8-10 was 2.2 (greater than 1), which indicated that the entire pyrolysis process was beneficial. The whole life cycle environmental impact of EJ 8-10 was 1165.67 mPET2000. Among the environmental factors, eutrophication (57.36%), photochemical ozone synthesis (22.56%), acidification (17.36%) and global warming (2.73%) exhibited the major impact. Therefore, the biofuel production from microalgae combined with wastewater treatment could be recommended as a promising way.

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