

# Simulation of the Biomass and Lipid Production Process from *Parachlorella Sp.*

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Microalgae are a renewable source of biomass for the production of third-generation biofuels that have aroused great interest worldwide because of their rapid growth and ability to fix atmospheric CO<sub>2</sub>. Additionally, they are capable of accumulating oil in proportions that can exceed 60% of the dry weight, which makes them attractive for biodiesel production. This project aims to evaluate the simulation of the biomass and oil production process using the alga *Parachlorella sp.* via ASPEN software. The simulation is based on the fixation of CO<sub>2</sub> by algae, which, via their cellular metabolism, transforms it into oil, which is then extracted and transesterified into biodiesel. The simulation demonstrated significant biomass growth, since a mass flow of 1000 kg/h of *Parachlorella sp.* was entered and 336.435 kg/h of biomass was produced, taking into account the necessary nutrients such as water, CO<sub>2</sub>, oxygen, hydrogen, and carbon sources and a nitrogen source. In addition, a stoichiometric reaction for the conversion of CO<sub>2</sub> into tripalmitic oil was generated, resulting in 224.809 kg/h CO<sub>2</sub>. Through this simulation, a new perspective of decarbonization, biomass generation and, in some cases, biofuels can be developed.

## Introduction

Human actions, primarily the burning of fossil fuels such as coal, oil and gas, have driven climate change since the 19th century, generating 75% of greenhouse gas (GHG) emissions and approximately 90% of carbon dioxide (CO<sub>2</sub>) emissions (Huang et al., 2012). This has raised the average global temperature by 1.1°C compared with the 1850–1900 period (IPCC, 2023), releasing large amounts of CO<sub>2</sub> into the atmosphere. In 2019, atmospheric concentrations of CO<sub>2</sub> reached 410 parts per billion, an increase of 47% since 1750 (IPCC, 2023). Thus, to avoid the negative impacts of climate change, emissions must be reduced by approximately 50% by 2030, and net zero must be achieved by 2050.

For this reason, renewable energy applications have generated interest in sustainable development, energy security, depletion of fossil fuels and nonrenewable resources (Amjith & Bavanish, 2022), with biofuels and biomass being the only renewable energy sources capable of directly replacing them (Mahmood et al., 2022). For some years, biofuels whose raw material is of biological origin have been produced, and the first generation of biofuels is the most common form of production, which uses vegetable oils derived from edible biomass as raw material. The second generation of biofuels is obtained from nonedible oils, industrial waste, and agricultural and forestry waste (Escobedo & Calderón, 2021). Finally, third-generation biofuels from microalgae are considered a technically viable alternative energy resource (Abdelsalam et al., 2019).

The third generation of biofuels from microalgae has emerged as a sustainable alternative to traditional biodiesel feedstocks (Abdelsalam et al., 2019; Escobedo & Calderón, 2021). Microalgae are unicellular microorganisms that are easy to cultivate and have the ability to fix atmospheric CO<sub>2</sub> while reproducing rapidly, so they are promising prospects for effectively sequestering carbon and mitigating GHG emissions (Pekko et al., 2024). In addition, they contain more than 80% organic matter, allowing carbon to be stored in the form of lipids, carbohydrates, proteins, vitamins and fatty acids to produce biodiesel and bioethanol (Escobedo & Calderón, 2021; Mousavi et al., 2022; Wang et al., 2020; Zebian et al., 2024). Because they are in aqueous media, they

can absorb large amounts of CO<sub>2</sub> and nutrients, and through photosynthesis, they convert solar energy into microalgal biomass (Escobedo & Calderón, 2021).

For their growth, they need three main components, which are sources of light, water and carbon (Rizwan et al., 2018); however, factors such as temperature, nutrients (mainly nitrogen and phosphorus), pH and salinity must also be considered (Debnath et al., 2021; Escobedo & Calderón, 2021; Johnson, 2012; Mahmood et al., 2022). Owing to their remarkable adaptability in their habitat, they can grow in wastewater, including sanitary, industrial and agro-industrial wastewater (Debnath et al., 2021; Wu et al., 2014). The oil content of microalgae (20% - 50%) (Escobedo & Calderón, 2021; Johnson, 2012) is higher than that of other oil sources, producing between 15 and 300 times more oil for biodiesel production than traditional crops per surface area (Saifullah et al., 2014; Johnson, 2012).

The simulation of the production process is highly complex due to the various reactions occurring within the cells, and since ASPEN was developed for chemical reactions, simulating biochemical reactions is particularly challenging. In this work, the simulation of the biomass and lipid production process from *Parachlorella sp.* will be carried out, thus establishing the stages required for the process, the operating conditions of each of these stages and, finally, determining the material and energy balances.

## Materials and methods

### 2.1. Biomass characteristics

To simulate the behavior of *Parachlorella sp.* in the ASPEN simulator, it was necessary to model the biomass as a nonconventional component. For this purpose, proximate and ultimate analyses of *C. vulgaris* were used, as shown in Table 1, including its percentages of ash, volatile matter (VM), fixed carbon (FC), and moisture (M):

Table 1. Proximal and ultimate (C, H, O, N, S) analysis of *Chlorella vulgaris*

| Characteristic  | (Magalhães et al., 2022) |
|-----------------|--------------------------|
| Moisture        | 6.18                     |
| Volatile matter | 66.56                    |
| Ash             | 15.64                    |
| Fixed carbon    | 11.62                    |
| C               | 43                       |
| H               | 6.77                     |
| O               | 27.95                    |
| N               | 6.64                     |
| S               | 0                        |

### 2.2. Aspen Plus Modeling

The biomass production process from *Parachlorella sp.* consists of 5 main stages: 1) cultivation, 2) harvesting, 3) drying, 4) oil extraction and 5) obtaining residual biomass (Escobedo & Calderón, 2021; Maldonado Barraza, 2011). Figure 1 shows a diagram of the process with 5 stages. This process shows that the production of oil by *Parachlorella sp.* is complex because it includes different biochemical reactions (Table 3). CO<sub>2</sub> must be dissolved in water for incorporation into the cell, and the solubility of CO<sub>2</sub> is approximately 1.45 g CO<sub>2</sub>/L at 30°C (temperature of the culture). Once the CO<sub>2</sub> is dissolved in the water, an equilibrium is reached such that the CO<sub>2</sub> is transformed into carbonic acid (H<sub>2</sub>CO<sub>3</sub>), carbonate (CO<sub>3</sub><sup>2-</sup>) or bicarbonate (HCO<sub>3</sub><sup>1-</sup>), depending on the pH of the solution. At a pH of 7.0, most carbonic acid is converted into bicarbonate and CO<sub>2</sub>, and as shown in Table 3, the presence of both substances was considered. CO<sub>2</sub> is transformed into biomass and oil following the Calvin cycle, the glycolysis pathway, the Krebs cycle, the tricarboxylic acid pathway, the acetyl-CoA carboxylase and fatty acid synthase pathway and triglyceride synthase (Table 2). The global reaction was considered for the simulation in the reactor in two stages: biomass and oil formation using a stoichiometric reactor.

The simulation was developed for a flow of 1000 kg/h of CO<sub>2</sub> entering the biomass reactor and for 625 kg/h of CO<sub>2</sub> entering the oil reactor (Figure 1). From this quantity of CO<sub>2</sub>, the other substances involved in the reactions were calculated according to the reactions (Table 2). The stoichiometric reaction given by (Yu & Lu, 2019) was used, where an autotrophic microalga is used in a steady state, and this was adjusted for the generation of

biomass on a large scale, thus obtaining Eq (1). The thermodynamic model used in Aspen Plus was a Peng-Robinson model. A centrifuge was used to separate the liquids from the solids. At the end of the process, an extraction column with hexane was used to extract the oil from the biomass. Finally, the evaporated hexane is recovered and recirculated so that it enters the extraction column again (Gurreri et al., 2024).

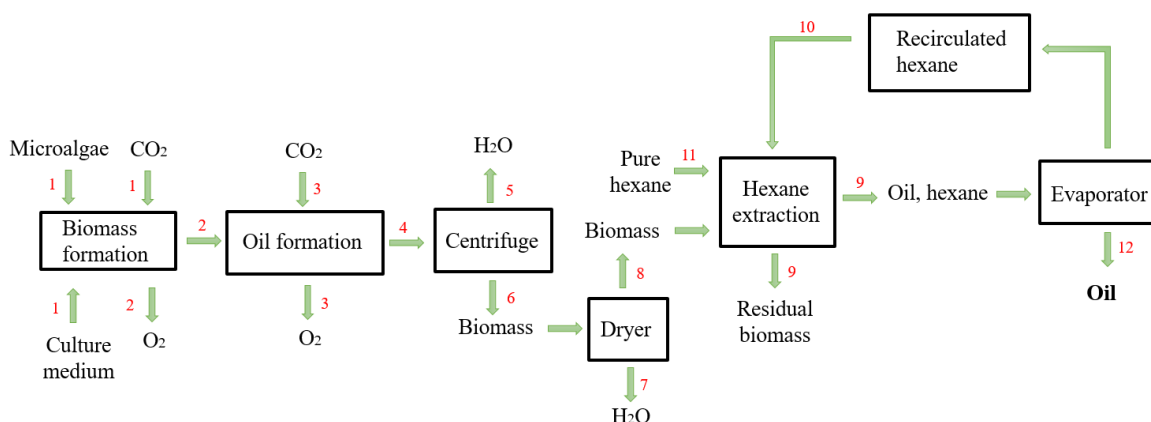


Figure 1. Diagram of the process of producing biomass and oil from *Parachlorella* sp.

Table 2. Stoichiometric reactions

| Reaction  | Equipment | Stoichiometric reactions  |
|---|-----------|---|
| Biomass cultivation from <i>Parachlorella</i> sp.                             | Reactor 1 | $56.4\text{CO}_2 + 1000\text{H}_2 + 424\text{O}_2 + 17.82\text{NaHCO}_3 + 17.821\text{NH}_4\text{Cl} \rightarrow 74.22\text{CH}_{1.68}\text{O}_{0.46}\text{N}_{0.24} + 982\text{H}_2\text{O} + 17.82\text{NaCl}$ (1)  |
| Formation of $\text{HCO}_3^-$ from $\text{CO}_2$                              |           | $72\text{CO}_2 + 72\text{H}_2\text{O} \rightarrow 72\text{HCO}_3^- + 72\text{H}^+$ (2)  |
| Carbon fixation (Calvin Cycle)  |           | $72\text{HCO}_3^- + 72\text{NADPH} + 108\text{ATP} + 72\text{H}_2\text{O} \rightarrow 12\text{C}_6\text{H}_{12}\text{O}_6 + 72\text{H}_2\text{O} + 72\text{ADP} + 72\text{Pi} + 72\text{NADP}^+ + 72\text{O}_2$ (3)   |
| Glycolysis and pyruvate pathway   |           | $12\text{C}_6\text{H}_{12}\text{O}_6 + 24\text{H}_2\text{O} \rightarrow 24\text{C}_3\text{H}_4\text{O}_3 + 12\text{ATP} + 96\text{NADH} + 12\text{O}_2$ (4)   |
| Tricarboxylic acid cycle (Krebs cycle)  |           | $24\text{C}_3\text{H}_4\text{O}_3 + 24\text{CoA} + 2\text{NAD}^+ \rightarrow 24\text{C}_2\text{H}_3\text{O-S-CoA} + 24\text{CO}_2 + 24\text{NADH}$ (5)  |
| Fatty acid synthesis (Acetyl-CoA carboxylase and fatty acid synthase pathway) |           | $24\text{C}_2\text{H}_3\text{O-S-CoA} + 42\text{NADPH} + 21\text{ATP} \rightarrow 3\text{C}_{16}\text{H}_{32}\text{O}_2 + 24\text{CoA} + 42\text{NADP}^+ + 21\text{ADP} + 21\text{Pi} + 9\text{H}_2\text{O} + 4.5\text{O}_2$ (6)                                  |
| Formation of $\text{C}_3\text{H}_8\text{O}_3$                                 |           | $0.5\text{C}_6\text{H}_{12}\text{O}_6 + \text{ATP} + 2\text{NADH} \rightarrow \text{C}_3\text{H}_8\text{O}_3 + \text{ADP} + \text{Pi} + 2\text{NAD}^+$ (7)  |
| Palmitate esterification (triglyceride synthesis)                             |           | $3\text{C}_{16}\text{H}_{32}\text{O}_2 + \text{C}_3\text{H}_8\text{O}_3 \rightarrow \text{C}_{51}\text{H}_{98}\text{O}_6 + 3\text{H}_2\text{O}$ (8)   |
| Global reaction: Formation of tripalmitin oil from $\text{CO}_2$              | Reactor 2 | $51\text{CO}_2 + 117\text{NADPH} + 122.5\text{ATP} + \text{C}_3\text{H}_8\text{O}_3 \rightarrow 78\text{H}^+ + \text{C}_{54}\text{H}_{103}\text{O}_9 + 117\text{NADP}^+ + 97\text{ADP} + 97\text{Pi} + 9\text{H}_2\text{O} + 91.5\text{O}_2 + 118\text{NADH}$ (9) |

## Results

*Parachlorella* sp. is a species of algae that belongs to the *Chlorella* family and is characterized by its high production of lipids, starch, proteins and carbohydrates in short periods of time (Singh & Sharma, 2012). They are photosynthetic and photoautotrophic microorganisms that use light as an energy source and inorganic carbon ( $\text{CO}_2$ ) as a carbon source (Mahmood et al., 2022), demonstrating a high potential to produce biofuels with higher performance and lower resource consumption (Abdelsalam et al., 2019; Escobedo & Calderón, 2021).

The reactions presented in Table 2 were considered but in their overall form in the biomass reactor and oil reactor (Figure 1). Similarly, the modeling of oil formation was treated as an independent reaction in a separate reactor, this phenomenon is related to the stress required to increase the oil concentration. It has been reported

that nitrogen, oxygen, and phosphorus depletion can increase oil production in *Parachorella* sp. (Mahmood et al., 2022)

Table 4 shows the global mass balance for each stage in the production process. The primary energy consumption in this process is associated with the formation of biomass and oil. This is a key aspect, as the energy source is solar energy, making the process both cost-effective and low in CO<sub>2</sub> emissions. The centrifugation stage is the second most energy-consuming phase of the process (540.061 kW). This high energy requirement is due to the low density of the biomass (approximately 1.1 g/mL), which is near the water density. In industrial processes, it is common to add adsorbent substances to increase the density of the biomass and reduce the power required for its recovery. In the simulation, we assumed that no adsorbent was added. Therefore, the energy consumption could be lower than the reported value.

Similarly, extraction with hexane is not highly energy-consuming because of the low pressure used in the system (0.4 atm). Low pressure is very common in extraction for avoiding reactions at high temperatures, which could decrease the quality of the oil. The low temperature (70°C) and high pressure are sufficient for evaporating the hexane. The hexane loss rate was low (5.84 kg/h), so the extraction was very efficient.

**Table 3. Energy required by stages**

| Stage               | Energy (kW) | Mass balance<br>Inlet flow (kg/hr) | Mass balance<br>Outlet flow (kg/hr) |
|---------------------|-------------|------------------------------------|-------------------------------------|
| Biomass formation   | 27070.100   | 19636                              | 19635                               |
| Oil formation       | 3434.920    | 1250                               | 1250                                |
| Centrifuge          | 540.061     | 9808.59                            | 9808.58                             |
| Dryer               | 7.376       | 561.80                             | 561.79                              |
| Hexane extraction   | 0.001       | 604.90                             | 604.90                              |
| Recirculated hexane | 24.319      | 374.24                             | 374.24                              |
| Evaporator 2        | 7.534       | 243.83                             | 243.83                              |

**Table 4. Mass flows**

| Components         | Stream flows (kg/hr) |        |     |        |        |       |       |       |       |       |     |       |
|--------------------|----------------------|--------|-----|--------|--------|-------|-------|-------|-------|-------|-----|-------|
|                    | 1                    | 2      | 3   | 4      | 5      | 6     | 7     | 8     | 9     | 10    | 11  | 12    |
| Biomass            | 10                   | 345.4  | 0   | 345.4  | 0      | 345.4 | 0     | 345.4 | 354.4 | 0     | 0   | 0     |
| Water              | 1000                 | 8127.2 | 0   | 7578.4 | 7575.1 | 3.3   | 194.3 | 0.1   | 0     | 0     | 0   | 0     |
| Carbon dioxide     | 1000                 | 0      | 625 | 0      | 0      | 0     | 0     | 0     | 0     | 0     | 0   | 0     |
| Oxygen             | 13185                | 7718.9 | 813 | 0      | 0      | 0     | 0     | 0     | 0     | 0     | 0   | 0     |
| Hydrogen           | 2000                 | 1187.8 | 21  | 0      | 0      | 0     | 0     | 0     | 0     | 0     | 0   | 0     |
| Sodium bicarbonate | 605                  | 1.9    | 0   | 0      | 0      | 0     | 0     | 0     | 0     | 0     | 0   | 0     |
| Ammonium chloride  | 385                  | 0.9    | 0   | 0.9    | 0.7    | 0     | 0     | 0     | 0     | 0     | 0   | 0     |
| Sodium chloride    | 0                    | 419.6  | 0   | 419.5  | 419.4  | 0.1   | 0     | 0     | 0     | 0     | 0   | 0     |
| Hexane             | 0                    | 0      | 0   | 0      | 0      | 0     | 0     | 0     | 754.1 | 748.3 | 5.8 | 5.8   |
| Tripalmitin oil    | 0                    | 0      | 0   | 224.8  | 0      | 224.8 | 0     | 224.8 | 224.8 | 0     | 0   | 224.8 |

On the other hand, the process absorbs CO<sub>2</sub>, contributing to atmospheric decarbonization. The production of biomass and oil from algae provides an important source of raw materials for third-generation biofuel production. The biomass yield from CO<sub>2</sub> is 0.336 kg of biomass per kg of CO<sub>2</sub>, which is lower than some values reported in the literature (0.546–2 kg biomass per kg of CO<sub>2</sub>) (Li et al., 2011). The oil yield is 0.346 kg of oil per kg of CO<sub>2</sub>, and the oil content in the biomass is 66.82%, which is similar to that of some algal species (greater than 50%) (Jaiswal et al., 2022). Another important aspect of biomass formation is the production of oxygen (8531.93 kg/h), which positively impacts air quality.

This highlights the potential of algae as an excellent means of decarbonization, as they can capture up to five times more CO<sub>2</sub> per hectare than terrestrial crops, such as palm oil (Chanana et al., 2023). The use of algae-

derived oil in biodiesel production results in a lower carbon footprint. Additionally, residual biomass can be converted into other biofuels through processes such as pyrolysis or gasification.

## Conclusions

It is important to recognize that results may differ from reality due to multiple factors, such as environmental conditions, light intensity, temperature, nutrients (mainly nitrogen and phosphorus), pH, and salinity, which can vary in real-life environments and affect cell growth and lipid accumulation. Furthermore, differences between the mathematical models used in the simulation and the actual physiology of microalgae can introduce discrepancies. Operational factors, such as the efficiency of the cultivation systems and the presence of contaminants or biological competitors, can also influence the final results. Therefore, it is essential to validate the models with experimental data and consider these aspects when interpreting the simulation results. However, no proprietary experimental results were used in this simulation; all data used were obtained from the scientific literature. Previous studies that report relevant parameters for microalgae growth and lipid accumulation under different conditions were selected. This allowed us to build a model based on previously validated data, although it involves certain limitations, since the specific conditions of each study may differ from a controlled experimental environment or industrial applications.

In this work, the production of *Parachorella sp.* in a bioreactor was simulated. The flow of matter and energy was established. The process stages with the highest energy consumption are biomass and oil formation, both of which are powered by solar energy. In this way, a total of 1600 kg of CO<sub>2</sub> is consumed every 224.80 kg of oil produced. As a result, decarbonization of the atmosphere can be achieved while producing oil for third-generation biofuel production. The recirculation of hexane shows that nearly 5.84 kg/h is lost during the process. The integration of alternative energy sources into the process could help achieve a negative CO<sub>2</sub> balance, contributing to the decarbonization of the planet.

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## References

- Abdelsalam, I. M., Elshobary, M., Eladawy, M. M., & Nagalr, M. (2019). Utilization of multitasking nonedible plants for phytoremediation and bioenergy source—a review. In *Phyton* (Vol. 88, Issue 2, pp. 69–90). Fundacion Romulo Raggio. <https://doi.org/10.32604/phyton.2019.06831>
- Amjith, L. R., & Bavanish, B. (2022). A review on biomass and wind as renewable energy for sustainable environment. *Chemosphere*, 293, 1–3. <https://doi.org/10.1016/J.CHEMOSPHERE.2022.133579>
- Chanana, I., Kaur, P., Kumar, L., Kumar, P., & Kulshreshtha, S. (2023). Advancements in Microalgal Biorefinery Technologies and Their Economic Analysis and Positioning in Energy Resource Market. *Fermentation*, 9(3), 202.
- Debnath, C., Bandyopadhyay, T. K., Bhunia, B., Mishra, U., Narayanasamy, S., & Muthuraj, M. (2021). Microalgae: Sustainable resource of carbohydrates in third-generation biofuel production. *Renewable and Sustainable Energy Reviews*, 150, 111464. <https://doi.org/10.1016/J.RSER.2021.111464>
- Escobedo, M. J., & Calderón, A. C. (2021). Microalgal biomass with high potential for the biofuels production. In *Scientia Agropecuaria* (Vol. 12, Issue 2, pp. 265–282). Universidad Nacional de Trujillo. <https://doi.org/10.17268/SCI.AGROPECU.2021.030>
- Gurreri, L., Rindina, M. C., Luciano, A., Falqui, L., & Mancini, G. (2024). Life Cycle Assessment Based on Primary Data of an Industrial Plant for Microalgae Cultivation. *Chemical Engineering Transactions*, 109, 493–498. <https://doi.org/10.3303/CET24109083>
- Huang, J.B., Wang, S. W., Luo, Y., Zhao, Z. C. & Wen, X. Y. (2012). Debates on the Causes of Global Warming. *Advances in Climate Change Research*, 3 (1), 38–44.
- IPCC. (2023). *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. IPCC, Geneva, Switzerland, 184 pp.
- Jaiswal, K.K., et al. (2022). Bioflocculation of oleaginous microalgae integrated with municipal wastewater treatment and its hydrothermal liquefaction for biofuel production. *Environ Technol Innov*, 26, 102340.
- Johnson, M. C. (2012). *Hydrothermal Processing of High-Lipid Biomass to Fuels*. Massachusetts Institute of Technology.
- Li, Z. S., Yuan, H. H., Yang, J. S., & Li, B. Z. (2011). Optimization of the biomass production of oil algae *Chlorella minutissima* UTEX2341. *Bioresour Technol*, 102 (19), 9128–9134.

- Magalhães, I. B., Pereira, A. S. A. de P., Silva, T. A., & Renato, N. dos S. (2022). Predicting the higher heating value of microalgae biomass based on proximate and ultimate analysis. *Algal Research*, 64. <https://doi.org/10.1016/j.algal.2022.102677>
- Mahmood, T., Hussain, N., Shahbaz, A., Mulla, S., Iqbal, H., & Bilal, M. (2022). Sustainable production of biofuels from the algae-derived biomass. 46, 1077–1097. <https://doi.org/10.1007/00449-022-02796-8>
- Mousavi, M., Setoodeh, P., & Farsi, M. (2022). Theoretical study of flue gas CO<sub>2</sub> conversion to microalgae *Chlorella vulgaris* biomass in a bubble column photobioreactor: Tanks-in-series approach, kinetic modeling, and dynamic optimization. *Journal of Environmental Chemical Engineering*, 10(3), 1–11. <https://doi.org/10.1016/j.jece.2022.107868>
- Pekkoh, J., Ruangrit, K., Aurepatipan, N., Duangjana, K., Sensupa, S., Pumas, C., Chaichana, C., Pathomaree, W., Kato, Y., & Srinuanpan, S. (2024). CO<sub>2</sub> to green fuel converter: Photoautotrophic-cultivation of microalgae and its lipids conversion to biodiesel. *Renewable Energy*, 222, 119919. <https://doi.org/10.1016/J.RENENE.2023.119919>
- Rizwan, M., Mujtaba, G., Memon, S. A., Lee, K., & Rashid, N. (2018). Exploring the potential of microalgae for new biotechnology applications and beyond: A review. *Renewable and Sustainable Energy Reviews*, 92, 394–404. <https://doi.org/10.1016/j.rser.2018.04.034>
- Saifullah, A. Z., Karim, A., & Ahmad-Yazid, A. (2014). Microalgae: An Alternative Source of Renewable Energy. *American Journal of Engineering Research*.
- Singh, R. N., & Sharma, S. (2012). Development of suitable photobioreactor for algae production - A review. In *Renewable and Sustainable Energy Reviews* (Vol. 16, Issue 4, pp. 2347–2353). <https://doi.org/10.1016/j.rser.2012.01.026>
- Wang, Y., Liu, X., Liu, Y., Wang, D., Xu, Q., Li, X., Yang, Q., Wang, Q., Ni, B. J., & Chen, H. (2020). Enhancement of short-chain fatty acids production from microalgae by potassium ferrate addition: Feasibility, mechanisms and implications. *Bioresource Technology*, 318. <https://doi.org/10.1016/j.biortech.2020.124266>
- Wu, Y. H., Hu, H. Y., Yu, Y., Zhang, T. Y., Zhu, S. F., Zhuang, L. L., Zhang, X., & Lu, Y. (2014). Microalgal species for sustainable biomass/lipid production using wastewater as resource: A review. In *Renewable and Sustainable Energy Reviews* (Vol. 33, pp. 675–688). Elsevier Ltd. <https://doi.org/10.1016/j.rser.2014.02.026>
- Yu, J., & Lu, Y. (2019). Carbon dioxide fixation by a hydrogen-oxidizing bacterium: Biomass yield, reversal respiratory quotient, stoichiometric equations and bioenergetics. *Biochemical Engineering Journal*, 152. <https://doi.org/10.1016/j.bej.2019.107369>
- Zebian, B., Bouallou, C., Greses, S., Rajaonison, A., & Pérez-López, P. (2024). Modeling of Biomethane Production from Microalgae. *Chemical Engineering Transactions*, 114, 619–624. <https://doi.org/10.3303/CET24114104>