A Review on Using Photobioreactors for The Cultivation of Microalgae for Biodiesel Production

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Due to excessive energy consumption and rising global warming levels, scientists are looking for other renewable energy sources. Microalgae offers good potential as an alternative energy source for biodiesel production. The purpose of this review is to explore the current advantages and disadvantages of using enclosed photobioreactors (PBRs) to produce biodiesel from algae in order to assess the economic viability. The current advantages of using PBRs are the high oil yield, the ability to clean the enviroment, and its positive environmental impacts. On the contrary, the current disadvantages of using PBRs are high matinees like light consumption, pH, and sterility. Though those are a few of the disadvantages, the largest is the PBR's economic viability. The current average gas price in the U.S. is doubled when using algae biodiesel created by PBRs. As of present the current disadvantages of using enclosed PBRs to evaluate the economic viability exceed the advantages of using PBRs to produce biodiesel from algae.

Introduction

Globally, energy consumption is ever-increasing, amounting to 97.33 quadrillion thermal units a year in 2021[1]. Of those nearly 100 quadrillion thermal units, renewable energies made up 12% of global energy consumption in 2021.[1] The remaining energy consumption comes from non-sustainable energy sources such as fossil fuels. During their combustion, fossil fuels create harmful greenhouse gases such as carbon dioxide, methane, nitrogen oxide, chlorofluorocarbons, and carbon monoxide, which have damaging effects on the environment[2]. These harmful gases cause an increase in the earth's temperature, known as global warming, which results in heat waves, droughts, floods, strong storms, and wildfires[3].

To reduce these harmful effects, alternative renewable energy sources are emerging. Currently, biomass makes up 40% of renewable energy sources in the U.S.[1]. Other than biomass, possible renewable energy sources include solar, geothermal, and wind energy. A particular interest exists in biomass due to its wide availability and carbon neutrality[4]. Corn, rapeseed, sugar cane, palm oil, soybeans, switchgrass, and algae are all possible biomasses for biofuel. The disadvantage of using plant-based biomass for biofuel is that it takes away from potential food resources. Algae are one of the only biofuels that do not compete for land in the food market. This protist proliferates, utilizing waste and salt water. Being biodegradable and nontoxic, algae can reduce carbon emissions depending on where it is planted. Algae also have the ability to grow in various climates and are very efficient due to their high growth rate and ability to produce large quantities of lipids[5]. Furthermore, algae's biomass generates a higher biofuel yield and can produce higher volumes of oil than other biomasses[6].

The two most current systems used to produce algae biofuel are open ponds and closed photobioreactors (PBRs). Open-pond systems are built with a raceway-like structure with a wheel constantly pumping water and nutrients to the algae. PBRs are closed vertical tube-like structures suspended in a way that allows diluted sunlight to hit every tube[6]. Nutrients and water constantly flow through these structures much like the open pond system. These closed structures are sterile, and clean, and conserve resources like water, energy, and chemicals. To compare the two systems, open pond systems often lead to a higher chance of infected algae and wasting resources while PBRs more often double the growth of algae[6,7]. This research will explore the current advantages and disadvantages when using enclosed PBRs for the production of biodiesel from algae to assess the economic viability. Research in this paper will elucidate how algae are cultivated in PBR and how this can be used for biofuel production, and thereafter discuss the advantages and disadvantages of PBR and its economic viability for the production of biofuel.

Cultivation of Algae in PBR

The type of algae used in PBRs are microalgae and aerobic photo-autotrophic eukaryotic cells. Being photo-autotrophic means these microalgae use light to convert food for themselves. Microalgae are also called phytoplankton and are found in damp and aerobic environments, ranging in size between 1-50mm in diameter[8]. A substantial part of algae cultivation is photosynthesis which can be represented by this equation $CO_2 + 6H_2O \rightarrow C_6H_1 2O_6 + 6O_2$, as can be seen in Figure 1. Photosynthesis is the plant's ability to convert sunlight for energy consumption[9].

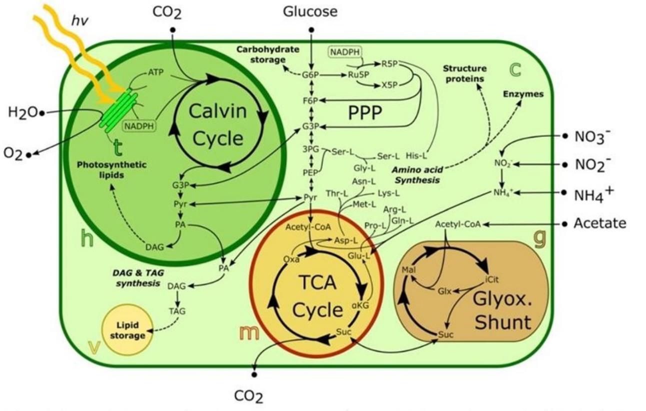

Fig. 1 An overview of the metabolism of microalgae. The image was obtained from Tibocha-Bonilla et al. (2018)

Many algae species contain a pigment called chlorophyll[10]. Chlorophyll absorbs photons from the sun, to generate Adenosine Triphosphate (ATP) and Nicotinamide Adenine Dinucleotide Phosphate Hydrogen (NADPH) for the Calvin Cycle. Pyruvate (Pyr) is then produced from the Calvin Cycle which concludes the cycle by forming diacylglycerol (DAG) and triacylglycerol (TAG) which are lipids. However, DAG and TAG are not merely created through the Calvin Cycle, the mitochondria also play a role in lipid formation. As can be observed in Figure 1, glycolysis takes place in the cytosol where the oxidation of glucose to Pyr occurs. Subsequent to glycolysis, Pyr can enter the tricarboxylic acid cycle (TCA) cycle, to further generate precursors for amino acids for the synthesis of proteins and enzymes[8].

Production of biofuel from algae using Photobioreactors (PBR)

Photobioreactor design

When producing algae, various types of bioreactors can be used such as tubular PBR, flatplanted PBR, inclined triangular tubular PBR, rectangular tanked PBR, continuously stirred tank reactors (CSTR), helical coils, and hybrid systems. Open ponds as seen in Figure 2, are the oldest and simplest method, dating back to the 1950s. Open ponds use paddle wheels to circulate algae cells and nutrients to harvest the algae behind the wheel, once the protist has concluded one cycle. Referring to Figure 3, tubular PBRs are made of glass or flexible plastic[11]. They can be organized at any angle to maximize the illumination surface-to-volume ratio, which directly affects the number of photons absorbed from the light and, thus the rate of photosynthesis and cell growth[12].

Flare-planted PBRs are transparent with a large surface area, which allows for high photosynthesis efficiency, low oxygen concentration build-up, and immobilization of algae. This system is inexpensive, easy to construct, and maintainable[11]. Inclined triangular tubular PBR is built next to power plants, utilizing fuel as feed gas. In these systems, 15-30% of algae are harvested daily. The rectangular tanked PBR does not require a stirring device as drain pumps and gas spargers are located at the bottom of the tank. CSTRs are spacious, empty, cylindrical pipes, which are capable of running on fluorescent and sunlight. Enclosed PBRs are made of a group of helical coils, which are plastic tubes laid across Columb-like structures. Helical coils run independently on fluorescent or sunlight. Lastly, hybrid systems combining open ponds and closed bioreactor systems are known to be more cost effective and are easily contaminated[11].

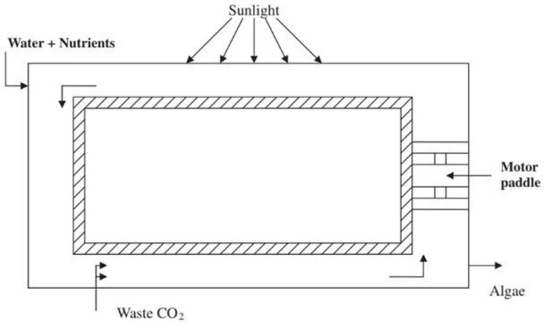

Fig. 2 Open pond system absorbing light to convert into biofuel[11].

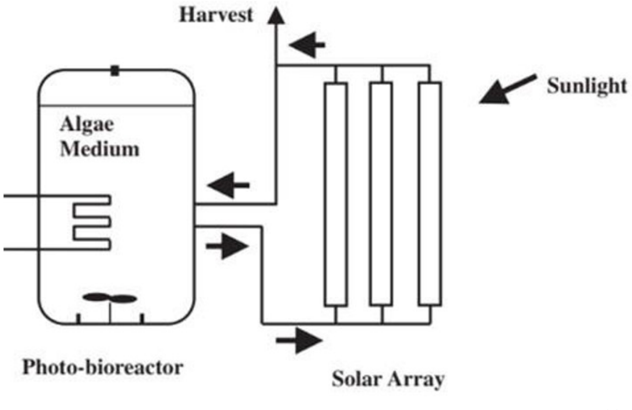

Fig. 3 Tubular PBR absorbing light to convert into algae biofuel[11].

Photobioreactor cultivation

During cultivation, algae go through several growth stages. These stages are the lag phase, exponential, declining relative growth, stationary, and death/lysis. While it is common for algae cultivation to double every twenty-four hours, some algae, during their peak of growth, double every 3.5 hours. The flourishing algae contain high oil/lipid contents, which are extracted. High oil contents range from 20-50% (dry) and even some strands reach 80% (dry). Cultivators must monitor pH, nutrients, temperature, mixing, predators, and light intensity[10].

Nutrients are a vital part of successfully growing algae. Carbon, nitrogen, and phosphorus are the primary nutrients algae consume to grow successfully[13].

Conditions such as temperature, pH, and light affect algae growth rate and need to be tightly regulated. Algae are particularly sensitive to temperature, thus the temperature in these algae growth systems needs to be closely monitored. Algae can survive at temperatures up to 62°C, but due to chlorophyll's instability, algae cannot grow beyond 75°C. Growing beyond 75°C affects carbon fixation by disrupting the energy balance in cells. Particularly in outdoor systems, high temperatures can reduce cell growth and biomass growth[14].

The pH at which these systems are held regulates the uptake of ions, enzymatic activity, phosphorus availability, inorganic carbon availability, and ammonia toxicity. Algae in marine water can live between 7.9 and 8.3 pH, and algae are typically cultivated with a pH range between 6.0 and 8.0 pH[15]. However, in closed systems, pH can be held up to a pH of 10 because they are in a much more contained environment rather than being left to the elements. Algae are pH-sensitive and are controlled with flushing CO2 or other acids.

Photosynthesis can start to decline due to too much sunlight called photoinhibition, which damages proteins in the algae[15].

Finally, the biochemical process to produce biodiesel from algae is a process called Esterification. Esterification is the first process used in creating biodiesel where the reduction of free fatty acids from the lipids occurs. Then, a process called transesterification (TF) occurs. TF is a chemical process used to produce biodiesel from vegetable oils or animal fat. By combining biomass, a catalyst, and alcohol, biodiesel is produced[16,17].

Advantages and disadvantages of Photobioreactors

PBRs are the preeminent options for algae biodiesel production but they have their disadvantages, such as the need for tight regulation of temperature and sunlight, high-cost cultivation methods, and the limited range of algae species that can be cultivated in PBR[6,18]. Furthermore, a challenge often encountered when cultivating algae in PBRs is oxygen accumulation. The oxygen produced during photosynthesis collects in high concentrations leading to a decrease in the growth of microalgae. However, this challenge can be overcome by increasing the sodium bicarbonate levels, allowing oxygen to reaccumulate without compromising the productivity of the plant[19].

While oxygen accumulation is a concern with PBRs, there are other concerns regarding their maintenance. The temperature of these systems must constantly be regulated to increase growth because any temperature below or beyond the optimal temperature will decrease the algae's growth rate[20]. Then, when algae absorb too much sunlight, the photosynthetic machinery becomes overwhelmed, causing the extra energy (photons) to destroy the algae[21]. Moreover, out of the three-hundred thousand to one million strands of algae, there are only three stands viable to use in PBR which are Coelastrella sp., Verrucodesmus verrucosus, and Neochloris oleoabundans[22,23].

While there are some disadvantages to PBRs, there are also advantages. An advantage of PBRs in terms of sustainability is that PBRs can reduce the CO2 and sulfur levels in the atmosphere. In addition, algae are a nonedible food source, thus algae are not in the competition for consumers' food sources[5]. Though algae are useful to our environment, algae also contribute to our labor force. For example, during the production of algae biodiesel, large companies need employees to assist in production. Therefore, creating more jobs in our society[24].

Economical viability

Though algae may sound promising, economic viability is still a necessary concern to address accordingly. For example, in Table 1, the total cost for producing algae biomass in PBRs is between $55-62.80 million, while open pond systems cost between $37-42.7 million. PBRs have an estimated cost of $1.40/L of biodiesel whilst the price needs to be less than $0.48/L to compete with its on-the-market competitors[20]. To break down the costs between system: PBRs has a total of $5.32-8.68/L, open ponds are $4.16/L, and hybrid systems are $5.32-8.68/L. Therefore, PBRs are still the most expensive in algae biofuel production systems[25].

When comparing different biofuel sources, in Table 2, oats are rated at $26/tonne, rice is $28/tonne, and switchgrass is $55-74/tonne. Then, in different conversions and resources, sugarcane is $.20/L, soybean oil is $.50-1/L, and microalgae is $.25-3+/L[25]. The costliest stage of producing algae biodiesel is the dehydration stage. The dehydration stage costs a total of $45,251 per capital cost[26].

Table 1 The economic advantages and disadvantages of using photobioreactors, open ponds, and hybrid systems as cultivation systems for algae from 2011.

System	Total Cost in Dollars[20]	Dollars per liter[25]
PBR	55.00-62.80	5.32-8.68
Open Pond	37.00-42.70	4.16
Hybrid	N.A.	5.32-8.68

Currently, PBRs are being researched using models that are

Table 2 The economic advantages and disadvantages of using other forms of biomass[25].

Sources	Dollars per liter	Sources	Dollars per liter of gasoline equivalent
Oats	0.02	Sugar Cane	0.20
Rice	0.033	Soybean Oil	0.50-1
Switchgrass	0.031	Microalgae	0.25-3

the most cost-effective option for biofuel companies. The process efficiency depends mainly on the light absorption efficiency, which is based on the pigment content of the microalgae strains. This varying factor of pigment results in each microalga stain need to be modeled differently[27]. These models not only include finding more cost-efficient production methods but also minimizing the occurrence of shaded zones, a complex and crucial aspect of PBR research.

The summary of the cost of PBRs falls into two categories: capital costs and manufacturing costs. The capital cost is a substantial $84,900,000. Of that, the largest percentage comes from the PBR structure, which makes up a significant 79% of the capital costs or $67,700,000. The manufacturing costs are around $45.8mm/yr. Nutrients like Ammonia and DAP take up $3.51mm/yr, PBR replacement is around $7.14mm/yr, and fixed costs are estimated to be $6.13mm/yr, which are the costliest elements of the manufacturing costs. PBRs total an electricity usage of 2,851KW/yr, around $1.53mm/yr. PBR gross operating costs amount to $22.7mm/yr. PBR bag replacement comprises 31.4% of the operating costs, and the algae cultivation area, which ranges from 500 to 3000 acres, comprises the most significant operating costs. However, the costs for replacement bags or the land are not specified[28].

In all, PBRs only increase in cost as the economy grows yearly. Companies are dispersing because of the extreme costs and lack of funding for biofuel research. Moreover, there is not enough viable research studying PBRs yet to acquire funding solutions for the costly machines, which makes finding solutions impeccably difficult.

As of current, open ponds reign as the most efficient method for companies economically. Though they do produce a lower oil yield, the cost of the PBRs trumps the cost of open ponds, making them the default choice for companies in the biofuel business.

When looking at the viability of using algae as biofuel, it is not certain whether or not algae is potentially a better resource than others. While biofuels produced from the production of algae approach carbon neutrality by likely reducing CO2 emissions by 90% in contrast to petrol/diesel, algae's economic viability raises an alarm when capitalizing the oil. Costs are too high, for the time being, to dispense to consumers[29].

Conclusion

PBR are valuable replacements for an alternative energy source. PBR, open ponds, tubular PBR, flat-planted PBR, inclined triangular tubular PBR, rectangular tanked PBR, CSTR, helical coils, and hybrid systems are used to create algae biofuel. PBR is a viable alternative due to its high success rates with algae cultivation and sterility. Temperature, pH, and light must be closely regulated for the algae to successfully grow. While they reduce pollution, are non-edible, abundant, adaptive, and create jobs for our growing workforce, they require careful attention to temperature control and specific sunlight, have a high cost, and work with limited algae species. Most importantly, the cost of using PBR to create biodiesel from algae is the dominant factor of why this biofuel is not on the market yet. As of now, in 2023, the of using PBR to produce algae biofuel is far too great to be on the market for consumers.

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References

1 U.S. Energy Information Administration (EIA), 2000.

2 G. Yadav, T. Mathimani, M. Sekar, R. Sindhu and A. Pugazhendhi, *Science of The Total Environment [Internet]*, 2021, **796**, 149049.

3 F. Barbir, T. Veziroglu and H. Plass Jr, *International Journal of Hydrogen Energy*, 1990, **15**, 739–749.

4 E. Johnson, *Environmental Impact Assessment Review*, 2009, **29**, 165–168.

5 X. B. Tan, M. K. Lam, Y. Uemura, J. W. Lim, C. Y. Wong and K. T. Lee, *Chinese Journal of Chemical Engineering [Internet]*, 2018, **26**, 17–30.

6 P. M. Schenk, S. R. Thomas-Hall, E. Stephens, U. C. Marx, J. H. Mussgnug, C. Posten *et al.*, *BioEnergy Research*, 2008, **1**, 20–43.

7 J. N. Rogers, J. N. Rosenberg, B. J. Guzman, V. H. Oh, L. E. Mimbela, A. Ghassemi *et al.*, *Algal Research [Internet]*, 2014, **4**, 76–88.

8 J. D. Tibocha-Bonilla, C. Zuñiga, R. D. Godoy-Silva and K. Zengler, *Biotechnology for Biofuels*, 2018, **11**, year.

9 D. C. Youvan and B. L. Marrs, *Scientific American [Internet]*, 1987, **256**, 42–49.

10 A. Yousuf, *Microalgae Cultivation for Biofuels Production [Internet]*, Academic Press, 2019.

11 M. F. Demirbas, *Applied Energy [Internet]*, 2011, **88**, 3473–3480.

12 K. K. Vasumathi, M. Premalatha and P. Subramanian, *Renewable and Sustainable Energy Reviews*, 2012, **16**, 5443–5450.

13 T. Cai, S. Y. Park and Y. Li, *Renewable and Sustainable Energy Reviews [Internet]*, 2013, **19**, 360–369.

14 M. V. Zuccaro, J. Xu, C. Mitchell, D. Marin, R. Zimmerman, B. Rana *et al.*, *Cell*, 2020, **183**, year.

15 M. Y. Menetrez, *Environmental Science & Technology*, 2012, **46**, 7073–7085.

16 A. Talebian-Kiakalaieh and S. N. Aishah, *Chemical Catalysts for Biomass Upgrading*, Springer, 2019, pp. 439–468.

17 R. P. B. Costa-Felix and J. R. L. Ferreira, *Physics Procedia*, 2015, **70**, 1066–1069.

18 A. Demirbas and M. Fatih Demirbas, *Energy Conversion and Management*, 2011, **52**, 163–170.

19 C. Sousa, 2013.

20 S. P. Singh and P. Singh, *Renewable and Sustainable Energy Reviews [Internet]*, 2015, **50**, 431–444.

21 T. E. Murphy and H. Berberoglu, *Journal of Quantitative Spectroscopy and Radiative Transfer*, 2011, **112**, 2826–2834.

22 M. C. Rodríguez-Palacio, R. B. E. Cabrera-Cruz, J. C. Rolón-Aguilar, R. Tobías-Jaramillo, M. Martínez-Hernández and C. Lozano-Ramírez, *Energy, Sustainability and Society*, 2022, **12**, year.

23 M. D. Guiry, *Journal of Phycology [Internet]*, 2012, **48**, 1057–1063.

24 M. H. Kamani, I. Eş, J. M. Lorenzo, F. Remize, E. Roselló-Soto, F. J. Barba *et al.*, *Green Chemistry [Internet]*, 2019, **21**, 3213–3231.

25 M. A. Carriquiry, X. Du and G. R. Timilsina, *Energy Policy*, 2011, **39**, 4222–4234.

26 N. Rafa, S. F. Ahmed, I. A. Badruddin, M. Mofijur and S. Kamangar, *Frontiers in Energy Research*, 2021, **9**, year.

27 S. N. Chanquia, G. Vernet and S. Kara, *Engineering in Life Sciences*, 2021, **22**, 712–724.

28 Y. Zhu, S. B. Jones and D. B. Anderson, *Algae Farm Cost Model: Considerations for Photobioreactors [Internet]*, 2018, `https://www.osti.gov/servlets/purl/1485133`, Available from: https://www.osti.gov/servlets/purl/1485133.

29 F. Alam, A. Date, R. Rasjidin, S. Mobin, H. Moria and A. Baqui, *Procedia Engineering [Internet]*, 2012, **49**, 221–227.