DESIGN IMPROVEMENT OF PHOTOBIOREACTOR

BY:

LEE MING WEI

(MATRIC NUMBER: 129360)

Supervisor:

ASSOCIATE PROFESSOR DR. MOHD SALMAN ABU MANSOR

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Declaration

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Abbreviations	Descriptions
CO_2	Carbon Dioxide
PVC	Poly Vinyl Chloride
LDPE	Low-density Polyethylene
CAD	Computer Aided Design
3D	3 Dimensional
FMEA	Failure Mode and Effect Analysis

Abstrak

Projek ini bertujuan untuk merekabentuk photobioreactor baru yang lebih baik berbanding dengan photobioreactor yang sedia ada. Untuk merekabentuk photobioreactor baru yang lebih baik, maka kajian perlu dilakukan pada parameter yang penting dan parameter yang akan mempengaruhi proses pembiakan microalgae. Projek ini juga menggunakan beberapa teknik dan pengetahuan tentang reka bentuk produk semasa proses rekabentuk untuk photobioreactor. Ini sangat penting kerana photobioreactor juga dianggap sebagai produk untuk kegunaan industri, oleh itu teknik untuk reka bentuk produk mesti digunakan dalam proses merekabentuk photobioreactor yang baru. Teknik yang digunakan adalah seperti pengumpulan data keperluan pelanggan, penjanaan konsep, pemeriksaan konsep, pemilihan konsep, analisis mod kegagalan dan kesan serta pengetahuan lain juga telah digunakan. Analisis mod kegagalan dan kesan adalah penting untuk mengesan kegagalan yang berlaku dalam reka bentuk dan menyediakan penyelesaian bagi setiap kegagalan yang mungkin. Akhir sekali, photobioreactor baru yang direka dan difabrikasi adalah berupaya untuk mengawal dan menyesuaikan intensiti cahaya, kadar aliran udara dan juga dilengkapi dengan sistem penapisan di mana reka bentuknya lebih baik berbanding dengan photobioreactor yang sedia ada yang sistem penapisan (penapisan sentrifugasi) berfungsi sebagai sistem yang berasingan.

Abstract

This project aimed to design a new photobioreactor that improve from the current existing photobioreactor. In order to design a new photobioreactor with the improvements, thus studies are required on the parameters that important and affect the cultivation process of the microalgae. This project also applied several techniques and knowledge of product design during the designing process for the photobioreactor. This is very important because the photobioreactor is also considered as a product for the industrial use, therefore the techniques for product design must be applied. The techniques uses are such as data collection of customer needs, concept generation, concept screening, concept selection, failure mode and effect analysis and other knowledges also have been used. The failure mode and effect analysis is important to detect the possible failure occurs in the design and provide the solution for each possible failure. Finally, the new photobioreactor designed and fabricated is able to control and adjust the light intensity, air flow rate and also equipped with filtration system where the design are improved compared to the existing photobioreactor which the filtration system (centrifugation filtration) worked as separate system.

Chapter 1 Introduction

1.1 Overview

Global warming has been raised as one of the most concerned issues around the world for the past century. The global surface temperatures have been augmented by 0.8˚C over the 20th century, and the global mean temperature was expected and predicted to be increase by 1.4-5.8˚C during the twenty-first century. There are many factors that contributed to the occurring of global warming but the most significant contribution is the rising level of atmospheric carbon dioxide, CO_2 and the carbon dioxide, CO_2 is expected to account for about 60% of the warming over the next century. The emission of carbon dioxide, CO_2 is mainly comes from the combustion or use of the energy in human daily lives. In other words, the activities that happen all around the world which related to production, consumption and use of energy will contribute and responsible for the global warming issue [1]. Although according to law of the conservation of energy, energy is not able to neither create nor destroy, but energy is transform to other forms such as from heat energy to electrical energy. Therefore, the most energy in this world is transformed from the combustion of fossil fuels into electrical energy which is the non-renewable energy. The non-renewable energy not only cause the global warming issue, but it is also limited and will not be able to support the increasing demand for the energy due to the rapid growth in the world population. Therefore, there is urgency in demand for finding and exploitation of the renewable energy to support the demand of energy for human population in future [2]. There are many types of renewable energy that available in this world such as solar energy, wind energy, and one of them is biofuels. Biofuels are any organic material that can be utilized for energy [3]. One of the organic materials that can be utilized for energy is algae or microalgae.

Microalgae are the longest living autotrophic taxon in this world and they are tissue-less organisms, simple multicellular organisms that can reproduce sexually or asexually [4]. Algae can be consider as one of the most robust organisms on earth because they are able to grow in a wide range of conditions such as damp areas or bodies of water and thus they are common to be appear in terrestrial as well as the aquatic environment [5]. Microalgae can be used to produce the biofuels because they synthesize three main biochemical compounds which are carbohydrates, proteins and lipids in large amount. Those biochemical compounds are the main compounds for the production of biofuels. Algae is more suitable than other plants in cultivating to produce biofuels because they produce large amount of those three compounds and it is possible for them to produce 10 to 100 times of more oil compared to those oil plants [4]. Since algae are so important for the production of biofuels, then they should be cultivated by human so that they can be used to fulfill the demand for the energy of rapid growth in human population in future. Algae can be cultivated in two types of systems which is open system such as pond or lake and the closed system which is called or known as photobioreactor [2, 4, 5, 6].

Photobioreactor can be described as an enclosed, illuminated culture vessel designed for controlled biomass production [4]. The photobioreactor are usually made of glass, poly vinyl chloride (PVC), low-density polyethylene (LDPE) or other materials that are transparent [2]. Photobioreactor are usually used for the cultivation of microalgae because it is a closed system, so the environment or condition inside the photobioreactor can be easily controlled by the scientists. Besides, photobioreactor also prevent the system from contaminants which will destroy or damage the growth of microalgae in the system. Other than that, the photobioreactor also provides the advantages over the open system where photobioreactor can achieve higher productivity per unit area, allow to save water and chemical agents, and also photobioreactor is suitable for outdoor or indoor installation [4]. However, there are many parameters that will affect the performance of the photobioreactor such as light, mixing, temperature, and mass transfer. Besides, the photobioreactor that available now is not suitable for the mass production of algae due to many factors such as cost, design and especially the productivity that affected by the design of the photobioreactor and also due to lack of deep understanding in the parameters mentioned before and also understanding of efficient reactor design [20].

Therefore, this project is to design the photobioreactor to improve the productivity of algae in mass production.

1.2 Research background

Sustainability is a very important principle in every natural resources management. Human have been exploited the use of non-renewable energy which is mainly the fossil fuels for the past centuries. However, the non-renewable energy will not be able to support the high demand of energy in future anymore due to the rapid growth of human population. Therefore, people need to start focus on the renewable energy such as solar energy, wind energy and biofuels in order to develop the renewable energy that will be able to support the high demand of energy by human population use in the future. Vigorous and a lot of research have been done by many scientists to discover and develop the renewable energy such as the use of solar energy, wind energy, hydropower, geopower and biopower which obtained from biofuels. However, the most promising energy is the biofuels because it can be produced by microalgae in large amount within a short period of time, so the biofuels energy produced can be support and fulfill the high demand for energy in human daily lives. Besides, biofuels also the most promising energy because it is produce from the cultivation of microalgae and microalgae have a rapid growth rate and it also can be growth under a very wide range of environment [5].

Microalgae can be cultivated in two types of systems which are open system and closed systems. However, the result from the open system is not promising because it may have contaminated during the growth of algae. So, many scientists and engineers have been focus on the development of photobioreactor which is the close system from many aspects such as the design, cost, and productivity. However, the photobioreactor that available is still not suitable for the mass production of growth of microalgae due to many factors such as cost, practicality, and others. Therefore, this project is to study, investigate, design and improve the functionality of photobioreactor from many aspects such as the cost, productivity, design, and the controllable of cultivation parameters such as water flow rate, light intensity and others.

1.3 Problem Statement

Photobioreactor is the main device or equipment used for the cultivation of microalgae in a closed system. Since, the cultivation of microalgae are used for the production of biofuels which is the most promising renewable energy for the future, then the photobioreactor plays an important role for the future of human being. This is because the photobioreactor will affect the growth of the microalgae due to the control of cultivation parameters depends on the photobioreactor. However, the photobioreactor that available now is still not suitable or ineffective for the cultivation of microalgae in the industry scale due to many factors such as the inappropriate design that cause the slow or low growth rate of the microalgae, small quantity of microalgae cultivated and high investment capital or cost where the vertical tubular required approximately 57 USD/m^2 [27]. Thus, this project is to study on the design of photobioreactor from several aspects and improve the growth of cultivation of microalgae in the photobioreactor in order to allow the use of photobioreactor in the industry scale and promise the future of human beings.

1.4 Objectives

1. To investigate problem exist on current photobioreactor design.
2. To redesign the photobioreactor with higher efficiency rate.
3. To fabricate the photobioreactor with lower costs so that suitable for large scale industrial implementation.
4. To validate the photobioreactor to the design in CAD modelling.

1.5 Scope of research

This research is to design a photobioreactor that have improved from different aspects as the efficiency, cost reduction and controllable of cultivation parameters such as water flow rate and light intensity. The design, 3D modelling and simulation of the photobioreactor have been done by using the CAD software which is the SolidWorks software. Then, a laboratory scale prototype of the photobioreactor also has fabricated at the end of this project. In addition, some simple experiment is performed on the photobioreactor to determine and validate the design of the photobioreactor.

Chapter 2 Literature Review

A photobioreactor is a device or container used for the controlled biomass production. Therefore, a photobioreactor will usually have an enclosed and illuminated culture vessel for the production. Besides, photobioreactor also can refer as close system because it makes sure that the environment inside is not exposed to the outside environment. Due to photobioreactor has an enclosed system which makes it has several main advantages compared to open system such as it will minimize contamination, better control over conditions such as temperature, light intensity, gases concentration, prevention on water loss due to evaporation and also permit higher cell concentrations. Therefore, the cultivation of microalgae is recommended to be done by using the photobioreactor which has the enclosed system. There are many types of photobioreactors have been designed and developed for the production of microalgae throughout the previous years. The 5 main types of the photobioreactors are listed as below [5]:

i. Vertical tubular photobioreactor

   It is made up of transparent vertical tubing allow for the penetration of light. Sparger is used to converts the sparger gas into tiny bubbles and it is attached at the bottom of the reactor. The sparging with gas mixture will provides overall mixing, mass transfer of CO_2 and removes O_2 produced during the photosynthesis undergo by the microalgae.

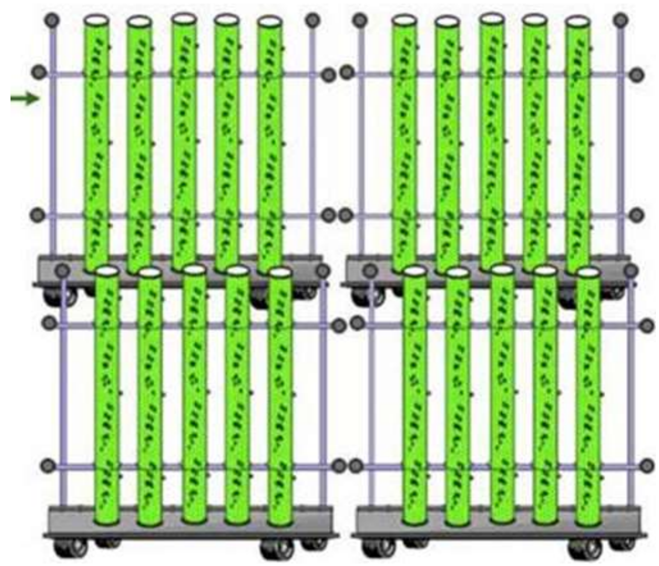

Figure 2-1: Example of vertical tubular photobioreactor [5].

ii. Flat panel photobioreactor

The flat panel photobioreactor also made from transparent materials like glass, plexiglass, polycarbonate and it has cuboidal shape with minimal light path. The flat panel photobioreactor is characterized by high surface area to volume ratio and open gas disengagement system. The agitation is provided either by bubbling air form its one side through perforated tube or by rotating it mechanically through motor.

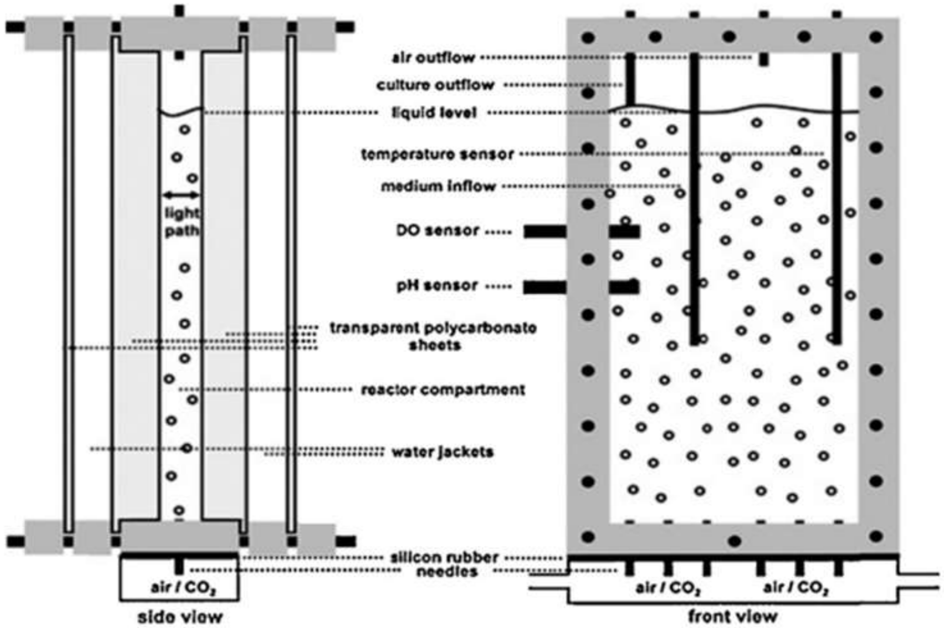

Figure 2-2: Example of flat panel photobioreactor [5].

iii. Horizontal tubular photobioreactor

This photobioreactors are placed horizontally giving the design of parallel set of tubes, loop shape, inclined tubular shape or horizontal. The shape gives it the advantage in outdoor culture for their orientation towards sunlight resulting in high light conversion efficiency. The gases mixture is introduced into the tube connection via a dedicated gas exchange system. However, the oxygen build up during photosynthesis causes photo bleaching and reduces the photosynthetic efficiency. Methods adapted for cooling of the system has been spraying water on the surface of the tubes, overlapping of tubes and others.

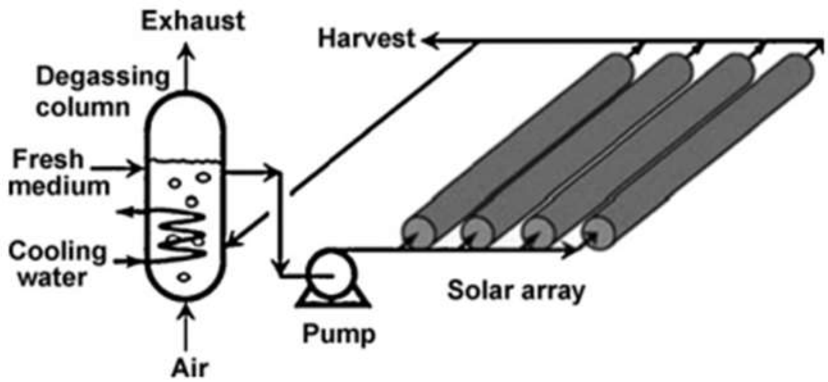

Figure 2-3: Example of horizontal tubular photobioreactor [5].

iv. Helical type photobioreactor

Helical type photobioreactor consists of coiled transparent and flexible tube of small diameter with separate or attached degassing unit. A centrifugal pump is used to drive the culture through long tube to the degassing unit.

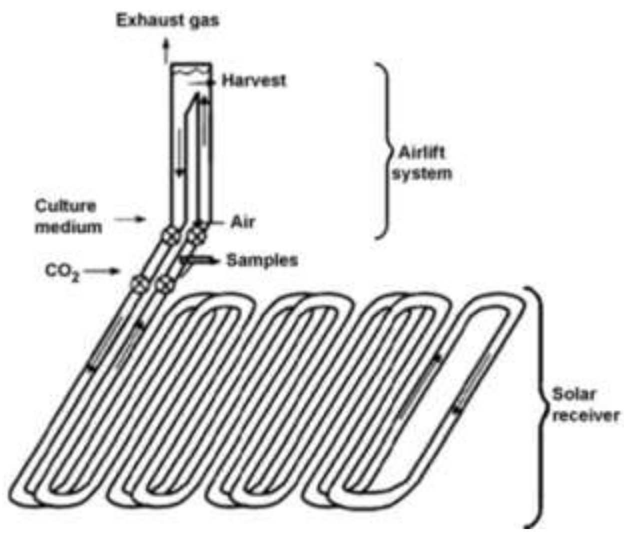

Figure 2-4: Example of helical type photobioreactor [5].

v. Stirred tank photobioreactor

This type of bioreactor is the most conventional where the agitation is provided mechanically by using the impeller of different sizes and shapes. The CO_2 enriched air is bubbled at the bottom to provide carbon source for the growth of algae and this type of bioreactor has been turned into the photobioreactor by illuminating it externally by fluorescent lamps or optical fibers.

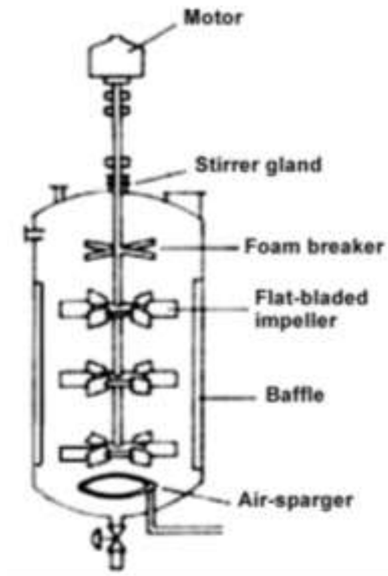

Figure 2-5: Example of stirred tank photobioreactor [5].

The production of biofuels from the microalgae requires an energy-efficient, economically profitable cultivation systems and this highlighted the importance of photobioreactor design and operation as major factors influencing the production costs. There are several major factors that determine the practical applications of photobioreactor such as the energy-efficient transfer of carbon dioxide and oxygen, dewatering of the harvested, dilute microalgae cultures and the high energy input for aeration. Therefore, an innovative idea was popped up where the foam-bed photobioreactor with high gas holdup was developed as the photobioreactor will increased the mass transfer and biomass concentration due to the thin liquid layers between the foam bubbles reducing the microalgae self-shading. In a foam-bed reactor, small gas bubbles are passed through a thin liquid layer resulting in foam generation. The liquid can be self-foaming or contains a foam stabilizing agent. Thus, the culture is composed of a thin liquid layer at the bottom of the reactor with a large volume of foam exposed to light. Due to the continuous gas supply, the generated foam bubbles rise. Simultaneously, the liquid film separating adjacent gas bubbles is continuously draining downwards due to gravity. The foam-bed photobioreactor can be a good alternative to conventional microalgae cultivation system because a foam-bed photobioreactor was successfully developed for the cultivation of microalgae and the ability to support the growth of microalgae has been confirmed [7].

A high efficient photobioreactor that have high biomass and lipid production can also be produced or developed through the assessment of the hydrodynamic properties. A 20L scale up X-shape photobioreactor has been developed due to its highest hydrodynamic properties. There is several photobioreactor characterization parameters used such as the gas holdup, mixing time, gas liquid mass transfer coefficient, and shear stress effect. The results obtained from the photobioreactor are analyzed mainly based on two aspects which are cell growth and lipid analysis; and biodiesel quality assessment. The X-shape photobioreactor also is a good alternative for the cultivation of microalgae because it has many advantages for algae cultivation in terms of homogenous flow pattern, high mixing, high mass transfer coefficient and low operating cost. Besides, the lipid produced from the X-shape photobioreactor also suitable for the high quality of biodiesel, suggesting that it can be practically utilized production of algae biofuel [8].

One of most important disadvantage of photobioreactor is the huge amount of water loss during the cultivation of microalgae in the photobioreactor. This problems causes the limited development and usage of photobioreactor as it related to the sustainability because clean water on earth are limited the reprocessing dirty water process can be very costly. Thus, an algae biofilm photobioreactor has also been developed in the past that offers a significant reduction of the energy and water requirements of the cultivation of microalgae. The green alga *Botryococcus braunii* was cultivated as a biofilm in the algae biofilm photobioreactor. The photobioreactor was able to reduce the volume of water required to cultivate a kilogram of algae biomass by 45% and reduce the dewatering energy requirement by 99.7% and this also made the algae biofilm photobioreactor as a good alternative for cultivation of microalgae [9].

Other than the conventional design of photobioreactor, there is a design, single-use bioreactors (SUBs) which have found increasing applications in recent years. Single-use bioreactors usually made from multi-layer films and operate on a slowly rocked platform. The slowly rocked platform will induce wave motion in single-use bioreactors to promote the mixing and gas mass transfer. Single-use bioreactors have been increase in applications because it is a useful tool for early stage of microalgae cultivation. This is because it can increase the experimental throughput and reducing operating costs because it does not the bioreactor cleaning and sterilization process. According to the research that has been done, the single-use bioreactors was able to produce 6.6 gL^{-1} of biomass concentration at 180 $\mu molm^2s^{-1}$ light intensity; 90 rpm of shaking frequency; and range of 15-40s for mixing time. The research shows that single-use bioreactors are suitable for early stage development of microalgae cultivation because the rapid mixing can be obtained from the orbital shaking and produced ideal results. However, further studies also required for the scale translation and ability to predict algae growth kinetics [14].

Meanwhile, there is a design of photobioreactor which is miniature photobioreactor where it also uses quite similar working principle as the single-use bioreactors. The miniature photobioreactor also placed on an orbitally shaken platform to provide rapid mixing, effective gas-liquid mass transfer and constant light intensity throughout each wall. The results from the research shows that the miniature photobioreactor on shaker platform was able to enable higher throughput evaluation compare to normal shake flask systems. However, the miniature photobioreactor is suitable for early stage and parallel evaluation of algae cultivation conditions [21].

Other than the single-use bioreactors, there is also new design of photobioreactor created in the past few years which is the twisted tubular photobioreactor. The twisted tubular photobioreactor was able to provide good exposure of microalgae to light/dark cycle because it induces the swirl mixing. From the research, the results show that the twisted tubular photobioreactor with moderate swirl motion demands less energy for pumping and it would reduce 38% of energy consumption from the conventional tubular photobioreactor [17].

Although there are many designs of photobioreator have been innovated, but most designs are just improvised from the conventional design of photobioreactor. Even though every improvised designs have been improved from the aspects of efficiency, but a research and experiment has been conducted to determine the most promising design that have highest efficiency. The research is very important because it allows the engineers and researchers to redesign a new design from the most promising conventional design and make sure the new design will also have most promising results. According to the research, the most promising conventional design of photobioreactor is horizontal photobioreactor where it was able to produce maximum biomass concentration which is around $7.11gL^{-1}$. Horizontal photobioreactor is the most promising conventional design because it possess the best configuration which the the best bioenergetics and thermodynamic parameters [19].

Microalgae can grow under many types of conditions such as autotrophic, heterotrophic, mixotrophic, or photoheterotrophic condition. However, all microalgae are photoautotrophs and can use light as their only energy source for the synthesis of biomass and metabolites in photoautotrophic conditions. Therefore, light is one of the most critical parameters for the cultivation of microalgae. Since the photobioreactor is used for the cultivation of microalgae, thus the design of photobioreactor needs to consider the light intensity for the optimal condition. There are two types of light source can be used which is the sunlight or artificial light source. Artificial light source is a better choice because it is stable and controllable and it also can be easily integrated with the photobioreactor design. During the photosynthesis in the microalgae, only certain wavelengths of light, ranging from 400 to 700nm are effective because the absorption bands of each pigment are different. In addition, different species respond differently to light wavelengths due to variations in their pigments. The effects of different wavelength to the growth rate of different species of microalgae are shown in Table 2-1 below.

Table 2-1: Effects of light wavelength on the growth of different microalgae species [10].

Species	Cell growth rate
Mixed culture of *Chlorella sp.* and *Saccharomyces cerevisiae* BCRC21 812	Red > blue > green
Spirulina platensis	Green > white > red > blue
S. platensis	Red > white > yellow > green > blue
Chlorella vulgaris	Red > white > yellow > blue
C. vulgaris and *Microcystis aeruginosa*	Red, blue, white > green, yellow
Chlorella sp.	Red > white > yellow > blue
C. vulgaris	Red > white > yellow > purple > blue > green
Nannochloropsis sp.	Blue > white > green > red
Botryococcus braunii	Red > blue > green

Since the growth rate of the different species of microalgae will be affected by the wavelengths of lights, then the growth rate of different species will affected by different light intensity. There is a research have been done shows that microalgae was able to perform photosynthesis at a higher efficiency under the low light conditions. The reason microalgae were not able to achieve high photosynthetic efficiency under high light intensity because microalgae need to dissipate part of the absorbed light energy as heat instead of biochemical energy [18]. Although the research shows that low light intensity is better for the cultivation of microalgae, but actually the optimal light intensity for microalgae is varies significantly among different algal species. The optimal light intensity for different species for microalgae is shown in Table 2-2 below [10].

Table 2-2: The optimal light intensity for different species for microalgae [10].

Species	**Purpose**	**Optimal Light Intensity**
Chlorella vulgaris	Biomass and lipid production	200 μmol$m^{-2}s^{-1}$
C. vulgaris	Biomass production	105.41 – 175.68 μmol$m^{-2}s^{-1}$
C. vulgaris	Wastewater treatment	2500 μmol$m^{-2}s^{-1}$
C. vulgaris	Biomass production Saturated fatty acids accumulation Monounsaturated fatty acids and polyunsaturated fatty acids accumulation	62.5 μmol$m^{-2}s^{-1}$ 100 μmol$m^{-2}s^{-1}$ 37.5 μmol$m^{-2}s^{-1}$
Chlorella sp.	Biogas upgrading	2000 μmol$m^{-2}s^{-1}$
Chlorella sp.	Biogas upgrade and biogas effluent nutrient reduction	350 μmol$m^{-2}s^{-1}$
Nannochloropsis sp.	Biomass production	100 μmol$m^{-2}s^{-1}$
Nannochloropsis salina	Biomass production	250 μmol$m^{-2}s^{-1}$
Botryococcus spp.	Lipid accumulation	82.5 μmol$m^{-2}s^{-1}$
Botryococcus braunii KMITL 2	Lipid accumulation	87.5 μE$m^{-2}s^{-1}$
B. braunii BOT-22	Biomass production	100 μmol$m^{-2}s^{-1}$
Spirulina platensis	Biomass production	1200 lux
S. platensis	Biomass production	166 μmol$m^{-2}s^{-1}$
Arthrospira platensis	Glycogen production	700 μE$m^{-2}s^{-1}$
Scenedesmus obliquus CNW-N	Biomass, lipid, and carbohydrate production	420 μmol$m^{-2}s^{-1}$
Scenedesmus sp. 11-1	Biomass and lipid production	400 μmol$m^{-2}s^{-1}$
Desmodesmus sp.	Biomass and lutein production	600 μmol$m^{-2}s^{-1}$
Mixed culture of Chlorella sp. and Saccharomyces cerevisiae	Oil production	1000 lux