DESIGN OF PHOTOBIOREACTOR

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DECLARATION

I hereby declare that the dissertation is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at Universiti Sains Malaysia or other institutions.

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LIST OF ABBREVIATION

Symbols	Descriptions
CO_2	Carbon dioxide
LEDs	Light emitting diodes
S/V	Surface to volume
3D	Three dimensional
CAD	Computer Aided Design
etc.	et cetera means and other things
SOP	Standard Operating Procedures
QFD	Quality Function Deployment
D	Diameter
L	Length
W	Width
MIG	Metal Inert Gases
USM	Universiti Sains Malaysia

REKA BENTUK FOTOBIOREAKTOR

ABSTRAK

Penanaman mikroalga dalam keadaan persekitaran yang terkawal membenarkan hasil pengeluaran biojisim yang mempunyai kadar pencemaran yang rendah serta sesuai untuk kegunaan dalam produk farmaseutikal bernilai tinggi. Persekitaran yang terkawal untuk penanaman mikroalga boleh disempurnakan dengan penggunaan fotobioreaktor sebagai medium untuk memperkenal keperluan asas yang diperlukan oleh mikroalga bagi melakukan proses fotosintesis dan dapat hidup dan membiak secara efektif. Namun, disebabkan oleh beberapa masalah seperti pengeluaran kos yang tinggi, kadar pencahayaan yang kurang dan sistem penuaian yang merumitkan dalam fotobioreaktor yang sedia ada telah menyumbang kepada kekurangan penggunaan fotobioreaktor dalam penghasilan biojisim. Kajian ini menjurus kepada mereka bentuk sebuah fotobioreaktor berskala makmal yang baru untuk mengatasi beberapa masalah yang wujud dalam fotobioreaktor sedia ada. Semasa proses pembinaan fotobioreaktor, keperluan pengguna telah dikenal pasti dan konsep yang paling sesuai dengan keperluan pengguna telah dijana. Konsep tersebut difabrikasi kepada prototaip dan prestasinya dipantau dalam jangka masa lima hari dengan menanam kultur mikroalga yang diambil dari sebuah kolam terbiar yang terletak di kawasan Penang, Malaysia. Kultur mikroalga tersebut berubah warnanya daripada hijau muda kepada hijau yang lebih gelap selepas lima hari ditanam. Proses penuaian kemudiannya dilakukan dan berjaya memerangkap banyak biojisim mikroalga atas siratan yang digunakan. Prestasi positif dalam proses penanaman dan penuaian ditunjukkan dengan penggunaan sebuah fotobioreaktor berskala makmal yang mempunyai isipadu operasi 13.5 litres, menggunakan cahaya buatan daripada diod pemancar cahaya berwarna merah, menggunakan buih udara untuk proses pencampuran dan melaksanakan proses penapisan yang mempunyai siratan dengan liang bersaiz antara 38.7 μm to 423 μm. Kajian ini menunjukkan bahawa menjana konsep baru dengan mengambil kira keperluan pengguna dan masalah dalam fotobioreaktor sedia ada adalah penting dalam menghasilkan sebuah fotobioreaktor berskala makmal yang beroperasi dalam keadaan baik dan optimum.

ABSTRACT

The cultivation of microalgae within a controlled condition allows the production of biomass with lower contamination and suitable for high value pharmaceutical products. The controlled environment for microalgae growing can be accomplished by utilizing photobioreactor as a medium for introducing the basic needs needed by microalgae to do photosynthesis and to grow efficiently. However, due to some problems of high cost, low illumination and complicated harvesting systems which regarding available photobioreactors had contribute to low usage of photobioreactor in biomass production. This study deals with designing a new lab scale photobioreactor for overcoming the problems contributed by the available photobioreactors. During the developing process of the photobioreactor, customer needs are identified and the most suitable concept based on the customer needs is generated. The concept is then fabricated to prototype and its performances are monitored for five days by cultivating microalgae culture that collected from an abandon pond located in Penang, Malaysia. The microalgae culture changed colour from light green to darker green after have been cultivated for five days. The harvesting process then followed which resulted in trapping of most microalgae biomass on meshes used. These positive performances for growing and harvesting process of microalgae have been shown from the used of the lab scale of photobioreactor prototype which having high operating volume of 13.5 litres, utilizing the artificial lights from red light emitting diodes (LEDs), utilizing air bubbles for mixing process and implementing filtration process that having meshes with pore sizes range from 38.7 μm to 423 μm. The study shows that generating new concept which considering about customer needs and problems in available photobioreactor is important for producing good and optimum lab scale of photobioreactor.

CHAPTER 1

INTRODUCTION

1.1. Project Background

Algae is a type of phototropic microorganisms which utilizes light as a source of energy having a huge potential in biotechnological for production of valuable substances such as animal feed, biomass fuels, food and supplements, cosmetics, pharmaceuticals and others. Biofuels which can be produced from algae also serving a great potential to meet the future challenges of energy resources shortage. These biofuels also renewable and environmental friendly and have been attracting the attention of researches during the past few years. Algae can be specifies into two types which are microalgae and macro-algae. According to Pulz [1], both macro-algae and microalgae playing an important role for current world economy with approximation turnover about USD 5 billion (RM 21.405 billion) per year. However, much attention are given to production of microalgae since microalgae are promising with a high variety of applications and commercialized value. According to Suganya et al. [2], microalgae are having three fundamentals attributes of very diverse, usually phototrophic and virtually unexplored which providing significant advantages in technical and commercial value. Thus, the efficient system in cultivation of microalgae is really crucial and important in order to cope the higher demand of microalgae in industries. The design of the efficient system should consider both technical and technological basis so that the production target for microalgae can be successfully achieved by industries.

Due to high potential and numerous commercial applications of microalgae, further research about production of microalgae is more diversified and economically competitive. Microalgae can be grown in the two type of systems which are either open systems, such as raceway ponds or closed systems, such as photobioreactors [3]. Nowadays, only a few microalgae growing are maintained in traditional open systems due to contamination in environment. Open systems can be from natural waters like ponds and lakes, from artificial ponds or containers. Even the open systems are simpler than closed systems, but the open systems are not suitable for future applications which are high quality and high value of algae are required. There are various commercial

applications for microalgae nowadays which are enhancing the nutritional value of animal feed and human food, helping in aquaculture and improving cosmetics production [4]. Moreover, in open system, the growing microalgae are having potential for highly exposed to contamination. These conditions occurred because the environment for microalgae growing cannot be controlled as in closed systems. Even open systems are less preferable due to low quality of microalgae produced, however, open systems are preferable for the ability of producing the microalgae in larger scale with low cost.

Low photosynthetic efficiency of open systems like open pond due to long light path and other environmental factors such as microbial contaminants and fluctuations in temperature have led to the design and development of closed systems of photobioreactors. Low photosynthetic effect in open systems usually due to poor utilization of light, high temperature, high CO_2 desorption caused by wind, inefficient mixing and higher prospect of contamination. Due to better control of the cultivation conditions than open systems, photobioreactors have attracted much interest. A closed equipment which utilizing closed system is called as photobioreactor and useful for providing a controlled environment which able for enabling the high productivity of microalgae [5]. Recently, many industries which involves in biotechnology like Astaxa (German company), Soleno Group and Heliae prefer to use the photobioreactors as a medium to grow microalgae. Closed systems of photobioreactors seem more benefits for future applications as the environment and condition of the algae growing can be controlled and the produced algae will be more clean and safe because the microalgae not easily exposed to harmful or toxic materials.

Photobioreactor is a closed equipment which provides a controlled environment to cultivate phototropic microorganisms by utilizing light source. The example of phototropic microorganisms is microalgae. As photobioreactor is a closed system, all the basic needs such as light, CO_2 and water have to be supplied to the photobioreactor in order to allow the process of photosynthesis by algae occur efficiently. The phototrophic cultivation like microalgae cultivation occurs when the microalgae use light such as sunlight, as the source of energy and inorganic carbon such as carbon dioxide as the source of carbon to form chemical energy through photosynthesis [6]. In addition, another additional condition that need to be controlled besides basic needs for helping microalgae growing are temperature, pH level, nutrients and etc. After certain

period of time, the growing microalgae can be harvested and the photobioreactor can be used again. The harvesting system used is also important when cultivating microalgae as microalgae need to harvest first before consume. An ideal harvesting system are usually effective for the majority of microalgae strains and allowing the achievement of high concentrations of biomass while requiring moderate costs of energy, operation and also maintenance [7]. According to Barros et al. [7], at this time, there is no harvesting method for which both having economically efficient and viable. Thus, developing a photobioreactor which having low harvesting cost seems beneficial to be further explored.

Even photobioreactor tends to be more expensive than open systems due to the use of expensive and complex equipment but it contributes to several advantages. The use of photobioreactor can reduce or prevent contamination, allow only one species of algae to grow and offer better control over cultural conditions (light, CO_2, water, temperature, nutrients, pH level and etc.). Moreover, photobioreactor prevent the losses of carbon dioxide to environment due to the process of gasses exchanging.

The efficient design in photobioreactor is important to allow high productivity of algae so that the potential in photobioreactor will not be limited and can be fully utilised. Several advances have been seen in the design of photobioreactors recently. However, only few of them can effectively utilised light energy for high production of microalgae. Therefore, the shortcomings or limitations in available photobioreactor must be eliminated or minimised by further research. For facilitating the researchers to do their research, it is important for them to work with lab scale sized of photobioreactors. The needs of optimal system in lab scale photobioreactors has led for this research project.

1.2. Problem Statement

Photobioreactor used to cultivate algae by utilizing light and carbon dioxide for photosynthesis process. There are quite a number of lab scale photobioreactors that have been in the market but most of the available photobioreactors are having a high cost, low illumination surface area and complicated algae harvesting systems. According to Raphael and Ausilio [8], photobioreactor systems allow for better control of the algae culture environment but the systems tend to be more expensive than the raceway ponds. Chun-Yen et al. [6], argue that although many efforts have been made to develop an efficient and cost-effective of photobioreactor, however, the high cost of installing and

operating artificial light sources in conventional photobioreactors with artificial illumination systems remains a major problem. According to Chun-Yen et al. [6], mass production of microalgae oil faces a number of technical problems that render the current development of the algae industry economically unfit. In addition, it is also necessary but very difficult, to develop cost-effective technologies that would permit efficient biomass harvesting and oil extraction [6]. Thus, these limitations in available photobioreactors must be diminished or eliminated to exploit the potential in algae industries.

1.3. Objectives

- To develop a lab scale photobioreactor for microalgae growing.
- To fabricate a prototype based on the developed lab scale photobioreactor.
- To study the performance of the photobioreactor.

1.4. Project Scopes

The project consists of designing a lab scale photobioreactor that is simple and reliable to overcome the limitations of high cost, low illumination surface area and complicated algae harvesting systems in available photobioreactors. The new photobioreactor should have minimum parts as to reduce the cost. Moreover, the photobioreactor should allow high penetration of light to cultivation medium as to increase the illumination and complicated harvesting systems can be diminished by designing a photobioreactor with simple harvesting systems. In order to allow the high productivity of algae by using the photobioreactor, sufficient amount of CO_2 and light supplied should also be considered in designing the new photobioreactor. A lab-scale prototype of photobioreactor will be developed and testing will be carried out to test the effectiveness of the new design of photobioreactor. By June 2017, this project is expected to be finished.

CHAPTER 2

LITERATURE REVIEW

2.1. Types of algae and Their Applications

Microalgae and macro-algae are two types of algae which different to each other. Macro-algae are commonly bigger than microalgae in size and are multicellular that consist of branches, leaves and roots [9]. The range size of microalgae usually from nanometre (nm) to millimetre (mm). The size of microalgae can be as small as 2-30 μm [10]. Moreover, microalgae are unicellular that having no stems, leaves and roots and are autotrophic organisms. Autotrophic organisms utilize sunlight, water and carbon dioxide for growth [9]. Microalgae also having wide potential to be used in commercialize applications. According to Pulz [1], there are large biotechnological potential for microalgae for producing valuable substances to be used in food, feed, cosmetics and pharmacy industries as well as in processes of biotechnology. Lately, there are many commercial applications involved microalgae. For example, microalgae are used for enhancing the value of nutrition in food and also animal feed due to their chemical composition, incorporated into the products of cosmetics and also playing an important role in aquaculture [4]. In short, the objectives for culturing microalgae and obtaining their biomass are usually for aquaculture, value-added products, carbon dioxide mitigation, or biofuel production [4].

There are various research need to be done for development of coal, natural gas and petroleum based refinery for exploiting the less expensive price of fossil feedstock. Fossil feedstock currently not regarded as sustainable resources and usually questionable from ecology, environmental and economic point of views [2]. Fossil resources are questionable because the fossil fuels burning is one of the big contributor for increasing the level of CO_2 in atmosphere. This phenomena directly leads to global warming observed recently [2]. Therefore, microalgae biomass becoming a source of production renewable and sustainable energy. The interest in cultivation of microalgae is currently high because oil from microalgae, among other uses, could be an alternative to complement and eventually replace the use of fossil fuels in the years to come [3]. Biofuels are the most interest among the various potential sources of energy that is renewable and are expected for becoming the crucial role in the future infrastructure of

global energy [6]. Microalgae are believed as a potential feedstock for biofuel production due to their chemical composition. Depends on the cultivation conditions and species, microalgae can produce useful quantities of polysaccharides (sugars) and triacylglycerides (fats) [8]. The types of sugars and fats are important as raw materials for producing biofuels such as biodiesel and bioethanol which useful as transportation fuels. According to Suganya et al. [2], biomass energy becoming the largest source of renewable energy, representing 10.4% of the world's total supply of primary energy or 77.4% of global renewable energy supply. Recently, several countries are already using biofuels such as biodiesel and bioethanol to replace the fossil fuels. These countries include Germany, United States, Brazil, Australia, Austria and Italy.

Microalgae are microscopic algae which require the aid of microscope in order to be seen clearly. They typically found in freshwater and also marine systems [2, 11]. The example of freshwater microalgae are *Chlorella sp.* and they are green algae species [12, 13]. According to Gim et al. [12], *Chlorella sp.* are better being cultivated under the conditions of 100 µmol/m^2s of light intensity and 11 days incubation. Moreover, the operating temperature for *Chlorella sp.* is usually 30^{o}C which suitable to be grown in Malaysia climate. Temperature in Malaysia usually influenced by its seasons. The Malaysia's meteorological conditions from 2007 to 2011 are shown in Table 2.1 as reported by Kamarul Zaman et al. [14].

Table 2.1: The meteorological conditions in Malaysia shows the range of values of temperature from 2007 to 2011.

Parameter	Dry Season (June-Sept)	Wet season (Nov-March)	April-May	October
Temperature (^{o}C)	28.21-30.86	25.61-29.90	28.10-31.15	26.97-30.98
Relative Humidity (%)	65.94-79.35	54.12-86.03	67.41-83.41	64.62-79.41
Wind Speed (m/s)	4.40-8.84	4.59-9.18	1.46-7.51	3.17-7.16

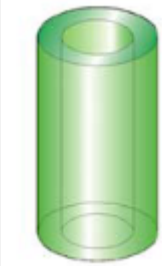
2.2. Systems for microalgae growing

Microalgae can be grown by using open systems and closed systems. Open systems are providing benefits in terms of low operating costs and suitable for mass production of algae. However, the existence of benefits in open systems cannot prevent from choosing the closed systems as systems for growing algae. Closed systems are more preferable compared to open systems due to the higher overall productivity, good

management of contaminant and better photosynthesis process. According to Sforza et al. [3], even open systems are not expensive, but they contribute to some drawbacks which are lower the long term of productivity due to difficult carbon management, large probability to occur contamination and low exposition of light. Photobioreactors are the example of closed systems. Most of these closed systems are using transparent materials and consist of tubular photobioreactors with tubes of various shapes, sizes, and length [1].

Recently, various types of photobioreactors have been designed and developed for production of algae. Photobioreactors can be placed indoor or outdoor. Indoor photobioreactors usually having lab scale size which is smaller than outdoor photobioreactors and suitable to be used by researches. Outdoor photobioreactors are suitable for large scale production of microalgae and mostly used by industries. There are few standard designs of photobioeactors that can be used as a foundation for further improvisations which are categorized as flat plate reactors, annular reactors and tubular reactors [5, 15]. The shapes of these reactors are shown in Table 2.2. Annular reactor usually acts as bubble column which the inner cylinder is empty to increase the surface to volume ratio, surface to volume (S/V) ratio and to avoid any dark parts [15]. Among these reactors, tubular reactors which having transparent tubes are more preferable and commonly used in photobioreactors design. According to Schenk et al. [15], there are big numbers of closed photobioreactors designed are made by using tubular reactor.

Table 2.2: Different designs of closed photobioreactor which commonly used for production of microalgae.

Reactors	Flat plate reactors	Tubular Reactors	Annular Reactors
Shapes			

In designing the tubular reactors, the choice of the tube diameter are becoming an important decision for getting the optimal design of the photobioreactors. The choice

of tube diameter affects the surface to S/V ratio which resulting the light uptake of the culture [16].

2.3. Growth Requirements of Microalgae

Microalgae are plants which require to perform photosynthesis process in order to grow. Since the photobioreactors are closed systems, all the growth requirements need for microalgae growing must be introduced into the systems and controlled accordingly. The close culture of cultivation systems for microalgae are carried out in photobioteactors, in which it is possible for controlling the process conditions (amount of nutrients, temperature, light intensity, pH and etc.) [17]. Photobioreactors are having better control for culture environment such as the supply of CO_2 gas, supply of water, optimal temperature, efficient exposition of light, the density of culture, pH levels, the rate of gas supply, culture density, mixing regime and etc. [5]. However, there are only few growth requirements which considered as basic requirements for allowing photosynthesis process to occur which are CO_2 supply, water supply and light exposure.

For indoor and outdoor cultivation systems of microalgae, light intensity and also light source are becoming the factors which critical that can affect the growth performance of the microalgae [6]. The source of light for photobioreactors can be sunlight or artificial light. Both sunlight and artificial light are able for driving microalgae to perform photosynthesis process [18]. The use of sunlight as a light source in photobioreactors usually will be more economical since the use of artificial light consuming a lot of cost or money. However, the use of direct sunlight sometimes not providing an optimal illumination for microalgae growing since the light intensities are varies. The intensities of the light can be too low or too high. Another major problem of using solar light energy (sunlight) is the day-night cycles in which by depending on the season and location, the period of when the intensity of light is optimal enough to support the photosynthesis process by microalgae can be too short [19]. Shriwastav et al. [20] stated that the growth of algae are limited by the availability of light in low intensities of light whilst photo inhibition will occur and contribute to algae growth problems in high intensities of light. To overcome the problems contributed from the usage of sunlight, artificial light can be used. There are various types of artificial light exist in market such as fluorescence light and LEDs. However, LEDs light are more promising for microalgae growing. The LEDs can mounted on a rod and installed in the reactors. This will create internal illumination for the photobioreactors. The use of

LEDs as internal illumination for photobioreactors promising a method to enable scalability [21]. When scalability is enabled, the cultivation systems performance are able to be maintained or increased.

There are various colour for LEDs' light available such as red, blue, green and etc. LEDs which having longer wavelengths released more photons compared to shorter wavelengths. Red LEDs emitting longer wavelength compared to blue and green. Red LEDs are able to emit double number of photons compared to blue LEDs emit, whereas LEDs of green are able to emit three times fewer photons compared to red LEDs [18]. These facts suggest that LEDs which having the wavelength of 660 nm can sustain the growth of microalgae biomass with highest efficiency in energy usage. Among various light colour of LEDs, red to far-red light of LEDs with the wavelength, λ of 630 nm to 750 nm are able to induce the high growth rates and also smaller cells by helping to accelerate the cell cycle [18]. According to Shulze et al. [18], photons with 660 nm to 680 nm of wavelength yield about the highest quantum efficiencies in most plants and microalgae which containing chlorophyll. Based on research conducted by Zhao et al. [22], optimal wavelength of light for microalgae growth such as *Chlorella sp.* culture is the red light with moderate light intensities of 800, 1200, 1600 and 2000 μmol/m^2s.

High illumination of surface to S/V ratio and efficient mixing system must be designed for photobioreactors to make the cultured cells be illuminated as uniform as possible, allow efficient gas exchange and also allow temperature to be controlled [23]. According to Jones et al. [24], optimal operation in photobioreactors require the sufficient mixing and sufficient liquid mass transfer. Mixing system also important for operation in photobioreactors. The utilisation of mechanical agitations are able to enhance the mixing performance [25]. Recently, most photobioreactors are using gas sparging in order to facilitate mixing and to provide CO_2 [24]. Thus, more components and energy can be reduced when gas sparging is used.

2.4. Harvesting System for Photobioreactors

After some period of time, the grown microalgae have to be harvested. Efficient harvesting methods for recovering the biomass of microalgae from the culture medium are needed. However, the universal method that can be used for harvesting all the microalgae strains with same efficiencies still not discover yet [7]. The selection of harvesting methods for microalgae are dependent on their characteristics and properties

such as value of the target products, density and size [26]. The methods that usually applied in harvesting the grown microalgae include filtration and screening, centrifugation, gravity sedimentation, flotation, flocculation and electrophoresis techniques [6].

Filtration and screening is a conventional method which is economic costs. This method involves introducing a suspension through a screen which having certain pore size. The use of microstrainers also have some advantages. Microstainers contribute to low investment cost, easy to operate, simplicity in construction and function and environmentally safe. However, the high concentration of microalgae may result in screen blocking, whereas, the low concentration of microalgae may contribute to inefficient capture [6]. Centrifugation is one of the expensive method compared to other methods. By using this method, pure and uncontaminated products are able to be delivered and therefore made this method preferable to be used in health food industry. The process for centrifugation is energy intensive and rapid. However, the disadvantages of this process are higher energy costs and higher maintenance requirements because of the existence of freely moving parts [26]. Gravity sedimentation is becoming familiar for harvesting microalgae biomass in waste water treatment due to large volumes treated and low value of generated biomass [26]. The disadvantages of this method is the method only suitable for harvesting large microalgae such as *Spirulina sp.* which having the size of more than 70 µm [26]. Moreover, according to Uduman et al. [27], gravity sedimentation is one of the process that is slow to operate. Another harvesting method is flotation. Flotation process requires no addition of chemical. This method involves of trapping microalgae cells by using micro-air bubbles without addition of any chemical substances [26]. Flotation benefits from gravity separation process. The process makes solid particles attached to gas or air bubbles and go to the liquid surface [6]. Flotation also suitable to capture particles which having less than 500 µm diameter [6]. Even flotation is becoming potential harvesting method, but there is limited existed evidence about its viability in technical and economic value [26]. Moreover, flocculation is a dewatering technique that consume less energy when operated under optimum conditions [27]. Flocculation requires flocculant [27]. Flocculant is a substance that promotes the clumping of particles in cultivation medium. The microalgae biomass will forming flocs and rises to the top of the water surface or sink to the bottom of water depending on their density. However,

flocculation requires the addition of chemicals which may result in expensive operating cost, water pollution and requiring treatment for water. Another technique is electrophoresis. This method requires no addition of chemicals substances. Electrophoresis method uses water electrolysis method. In water electrolysis, hydrogen is generated and adhered to the flocs of microalgae and then carried to the water surface [6]. All the harvesting methods that have been discussed are having their own advantages and disadvantages. The optimal harvesting method used for microalgae should use minimum amount of chemicals and energy, independent to species and if possible should also release the materials of intracellular for collection [6].

2.5. Economic Issues According Development of Photobioreactors

Photobioreactors frequently used compared to open pond because of their advantages of better control in culture environment conditions and avoid contamination [3, 8]. Nevertheless, there is some drawbacks related to development of photobioreactors which are higher costs for operating and maintenance compared to open system [9]. Illumination in photobioreactors can be from natural sunlight or artificial lighting. Some investment of money must be invested in order to utilize artificial lighting in operation of photobioreactors. Artificial lighting can be fluorescents light or LEDs light. LEDs light are giving better option for cultivation of microalgae compared to fluorescents light especially in energy efficiency and lifetimes. However, LEDs lighting systems are more expensive than fluorescents light [18]. The harvesting techniques used for photobioreactors also cost a lot of money investment. Some of the techniques require to use chemical substances which need for water treatment. Uduman et al. [27] stated that flocculation has energy process, but it consumes high cost if flocculants use are expensive and require high dosage. Centrifugation process also consume high cost due to requirement of high energy input and expensive initial capital cost [27].

CHAPTER 3

RESEARCH METHODOLOGY

3.1. Introduction

In this chapter, the methods used for completing the research are briefly discussed. A lab scale of photobioreactor which suitable to be used for microalgae is developed based on demands from customers. The demands from customers then being translated to the desired specifications for the lab scale photobioreactor. From the specifications, several concepts are generated and the best concept is chosen to develop as a final product. Moreover, the prototype of developed photobioreactor consisted of several parts, some parts are fabricated and some parts are standard. Once the prototype is completed, the performance for the photobioreactor is studied. This chapter has been divided into three stages which are designing stage, fabrication stage and lastly performance monitoring stage. The flowchart for this project is shown in Figure 3.1.

3.2. Designing stage

3.2.1 Defining product mission and vision statement

The project for designing a new lab scale of photobioreactor is begun by defining mission statement and vision statement after the problem statements have been determined. The mission statement and vision statement are created as shown in Table 3.1. At this point, the earlier opportunity statements could be shown and these statements were crucial as the statements provide general direction to be followed in order to complete the project. Both mission and vision statements provide the goals of this project. However, both of these served different purposes for the project. Mission statement dealt with things need to be achieve now while vision statement dealt with things need to be achieve in the future. The vision statements for this project consisted of product description, benefit proposition, key business goals, primary market, secondary market, assumptions and constraints and stakeholders. All the information in the vision statements are very general and they are created by:

- Product description: The description is identified by the basic function of the photobioreactor. However, it was not implied the specific product concept.
- Benefit proposition: The benefit proposition is created by determining the critical few reasons which making the customers would buy the product, photobioreactor.
- Key business goals: Key business goals are identified by including the goals for time, cost and quality.

- Primary and secondary markets: Primary market and secondary market are determined based on available target markets of such product.
- Assumptions and constraints: Assumptions and constraints are created based on possible advantages and ability that the new photobioreactor could serve.
- Stakeholders: The end users and external customers who would benefit from the photobioreactor were determined.

Table 3.1: Mission and vision Statements for developed lab scale phaotobioreactors.

Mission Statement: Laboratory Scale Photobioreactor Project	
Product Description	• Provide place for growing algae • Harvesting system • Cleaning system after harvesting
Benefit Proposition	• Less time consuming for cleaning • Provide good productivity of algae • Attractive design • Easy to use
Key Business Goals	• Environmentally friendly • Low time for cultivating algae
Primary Market	• People who involved in algae products industries
Secondary Markets	• Researchers
Assumptions and Constraints	• Incremental improvements to existing products • Simple and less complex materials or parts • Has aesthetic value • Affordable price • Not rusting • Can be used for several times • Convenience and easy to use • Allow high algae productivity
Stakeholders	• Purchasers and consumers • Manufacturing operations • Service operations • Distributors and resellers

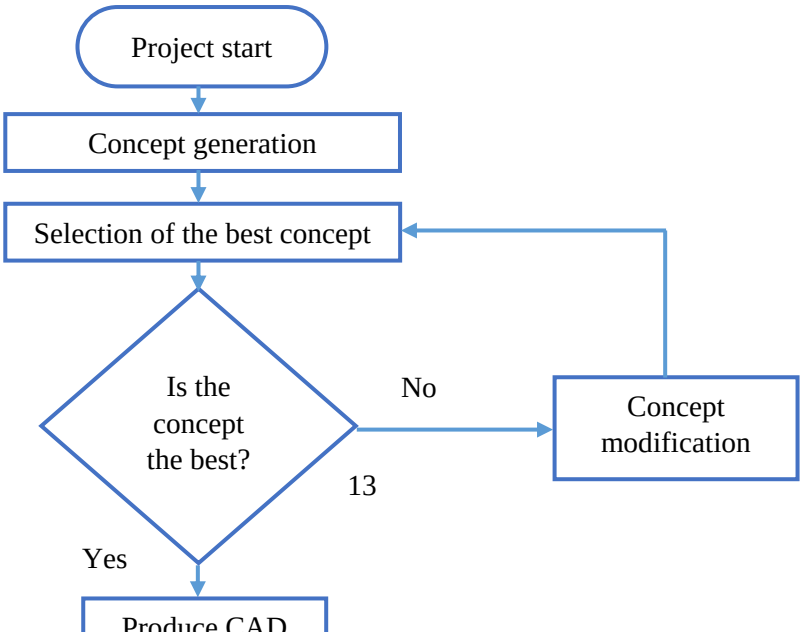


Figure 3.1: Flowchart for this project. A series of modification and improvement are done for getting the most suitable design for the lab scale photobioreactor.

3.2.2 Identifying the customers need

Customers need identification are crucial in order to design a new product. As stated before, the product for this project is lab scale photobioreactor. It is really important and necessary to make sure that the designed photobioreactor satisfied the customers need. One of the condition for the product success is that the product provided benefits to the customers. The methods that have been used for gathering raw data from customers are shown below:

- Interviews:

In this method, the needs from customer are gathered from discussion session with a single customer. The customer is one of the lecturer from School of Industrial Technology, Universiti Sains Malaysia (USM), Dr. Aziah and has been involved and familiar with photobioreactor. The discussion session lasted about one hour.

- Information gathered from journal reading:

This method is done by reviewing some of the journal related to the photobioreactor and algae growing which commonly written by a group of researchers or someone who are familiar with photobioreactor. Since researchers also one of the target market for this product, it was really important to gather their needs through their written journals.

- Observing the product in used:

The method is done by watching customers used an existing product or perform a task for which an improvement is needed to the existing product. This information could reveal an important details about the needs of the customers. This observation method is completely passive which involved no direct interaction with the customers.

The raw data gathered from customers are in customer statements not in needs statements. The customer statements which gathered directly and indirectly from customers are then be interpreted to need statements. The interpretation of customer statements into need statements are shown in Table 3.2. All the needs are then be organized into hierarchy which are primary and secondary. The primary needs are the most general needs while the secondary needs expressed needs in more details.

Table 3.2: Need statement translated from customer statements.

Customer statement	Need statement	Source
"Outdoor tubular photobioreactors and open ponds have the advantages of require large spaces and difficulty for maintaining the conditions of sterile"	The photobioreactor uses small spaces for high productivity.	[19]
"Even photobioreactor systems have good control for algae culture environment, but the systems are expensive than raceway ponds" "Cultivating algae in a tank is really expensive. The estimation is about 10 dollars (RM 42.66) up to 50 dollars (RM 213.32) or 60 dollars (RM 255.99) per gallon (3.8 Liter)"	The photobioreactor consume low cost as raceway ponds.	[8, 28]
"There is major problem about high cost for installing and operating the artificial light sources in photobioreactors even many efforts have been done for creating efficient and cost effective photobioreactors"	Artificial light in photobioreactor consumes low cost of implementation.	[6]
"It is really difficult even necessary to develop technologies which effective in cost to allow efficient biomass harvesting"	Efficient harvesting system in photobioreactor consumes low cost.	[6]
"Only 95% of the grown algae are harvested from the cultivation container"	The photobioreactor provides control for the amount of algae will be harvested.	Dr. Aziah
"More effort are needed in order to harvest the grown algae which I have to send the photobioreactor to other place in order to harvest the algae"	The photobioreactor equips with harvesting system.	Dr. Aziah
"Cultivating algae in pond exposing the algae to predators such as bacteria and fungus, temperature impacts and sunlight impacts"	The basic needs (light, CO_2, temperature and humidity) can be controlled in the photobioreactor.	[28]
"Microalgae cannot maintain their growth in too low light intensity and too high light intensity. Too high light intensity cause photo-inhibition"	The photobioreactor operates in optimum light intensity.	[22]
"The photosynthetic productivity limited by the availability of light"	The cultivation tank of photobioreactor is transparent which allows good illumination.	[29]
"The task for supplying microalgae cells with carbon dioxide to allow photosynthesis and to remove the produced oxygen from the cultivation medium are the important task"	The photobioreactor allows the gaseous exchanging process occur efficiently.	[30]
"The bubble of air through the bottom provides good mixing for overall and also produce the uniform dispersion for microalgae in medium of culture"	The photobioreactor equip with agitation system.	[5]

The produced need statements are organized into a hierarchy for summarizing the generated needs which seems awkward and difficult to work due to their detail and numbers. The lists of hierarchy consisted of primary needs and secondary needs. Primary needs provided with more general needs while the secondary needs expressed the needs in more details. Table 3.3 shows about the generated hierarchical lists of the lab scale photobioreactor. In the process of organizing the needs into hierarchy, the redundant statements are eliminated and the needs are arranged according to the similarity of the expressed needs. For the lab scale photobioreactor, there are seven primary needs which then furthered for importance weighting process. The relative importance of the needs are showed in Table 3.4.

Table 3.3: The generated hierarchical lists of the lab scale photobioreactor.

Primary needs	Secondary needs
The photobioreactor allows high productivity of algae.	• The basic needs (light, CO_2, temperature and humidity) can be controlled in the photobioreactor. • The photobioreactor equip with agitation system.
The photobioreactor allows proper gaseous (carbon dioxide and oxygen) exchange	• The photobioreactor allows the gaseous exchanging process occur efficiently.
The photobioreactor provides effective and efficient illumination.	• The cultivation tank of photobioreactor is transparent which allows good illumination. • The photobioreactor operates in optimum light intensity.
The photobioreactor requires less space.	• The photobioreactor uses small spaces for high productivity.
The photobioreactor equips with harvesting system.	-
The photobioreactor makes it easy to start to cultivate algae.	• The photobioreactor provides control for the amount of algae will be harvested.
The photobioreactor requires low operational cost.	• Efficient harvesting system in photobioreactor consumes low cost. • Artificial light in photobioreactor consumes low cost of implementation. • The photobioreactor consume low cost as raceway ponds.

The importance weighting process established the relative importance of the needs from customers since the hierarchical lists alone not able to provide any information regarding the relative importance that customers had place on each different needs. The approach used for doing the numerical importance weighting for the primary

needs was relying on the further reading from available research papers. In this research project, researchers also target customers for this developed lab scale photobioreactor. By making the numerical importance based on the information stated in available research papers, indirect interaction with customers occurred.

Table 3.4: The importance weighting process occurred after the process of organizing the generated needs into hierarchy.

No.	Primary needs	Importance weighting
1	The photobioreactor allows high productivity of algae.	4
2	The photobioreactor allows proper gaseous (carbon dioxide and oxygen) exchange	4
3	The photobioreactor provides effective and efficient illumination.	4
4	The photobioreactor requires less space.	3
5	The photobioreactor equips with harvesting system.	5
6	The photobioreactor makes it easy to start to cultivate algae.	3
7	The photobioreactor requires low operational cost.	4

3.2.3 Specifications Preparation

The specifications of developed photobioreactor provided the precise descriptions of what the product has to do. The specifications provide technical specifications which referring to main keys of designing the photobioreactor. A specification provided by a metric and a value. At first, metrics are generated based on the needs and their relative importance. Metrics generated were reflecting as directly as possible of the degree to which the product satisfies the needs from customers. Table 3.5 are presenting about the list of metrics together with the units. The way used for generating the metrics is by considering each need in turn and then considering the characteristics of precise and measurable which may reflect the degree at which the photobioreactor satisfied the need.

Table 3.5: List of metrics and units.

Metric No.	Needs No.	Metric	Importance	Units
1	1,3	Maximum light intensity	4	µmol/m^2s
2	1	Operating temperature	4	^oC
3	1	flow for agitation system	4	ml/min
4	1,4	Working volume	4	ml
5	3	Wavelength of light used	4	unit
6	2	Number of holes for gas exchange	4	unit
7	4	Base size of photobioreactor tank	3	mm
8	4	Height of the photobioreactor tank	3	mm
9	5	Base size of harvesting system	5	mm
10	5	Height of harvesting system	5	mm
11	5	The size of mesh for harvesting	5	µm
12	5,6	Amount of cultivation medium being harvested	5	l
13	6	Amount of cultivation medium left after harvesting	3	ml
14	7	Initial cost for harvesting system implementation	4	RM
15	7	Cost for harvesting algae	4	RM
16	7	Cost per unit	4	RM

The relationships between needs and metrics are then presented in needs-metrics matrix as shown in Table 3.6. Rows in the matrix corresponded to the needs from customers while columns corresponded to the metrics. By generating the matrix, the performance of the metrics influenced the degree to which the photobioreactor satisfied the customer needs. In order for transforming the needs from customers to engineering and technical characteristics, Quality Function Deployment (QFD) method is used. One of the technique which utilizing graphical technique of QFD is House-of-Quality. The example for House-of-Quality is in the needs-metrics matrix as shown in Table 3.6. The key element for the House-of-Quality is this matrix.

Table 3.6: The matrix for needs-metrics.

	Need \ Metric	1 Maximum light intensity	2 Operating temperature	3 flow for agitation system	4 Working volume	5 Wavelength of light used	6 Number of holes for gas exchange	7 Base size of photobioreactor tank	8 Height of the photobioreactor tank	9 Base size of harvesting system	10 Height of harvesting system	11 The size of mesh for harvesting	12 Amount of cultivation medium being harvested	13 Amount of cultivation medium left after harvesting	14 Initial cost for harvesting system implementation	15 Cost for harvesting algae	16 Cost per unit
1	The photobioreactor allows high productivity of algae	●	●	●	●												
2	The photobioreactor allows proper gaseous (carbon dioxide and oxygen) exchange						●										
3	The photobioreactor provides effective and efficient illumination	●				●											
4	The photobioreactor requires less space.				●			●	●								
5	The photobioreactor equips with harvesting system.									●	●	●	●				
6	The photobioreactor makes it easy to start to cultivate algae												●	●			
7	The photobioreactor requires low operational cost.														●	●	●

3.2.4 Collecting Information about Competitive Benchmarking

The information regarding the competitive benchmarking are gathered to provide ideas about how the new lab scale photobioreactor can compete in the marketplace and compete in target specifications. This process is done by looking and searching information about existing products which already in the market. Table 3.7

shows about the information of competitive benchmarking and Table 3.8 shows about the competitive benchmarking that has been arranged in chart based on metrics.

Table 3.7: The information regarding competitive benchmarking.

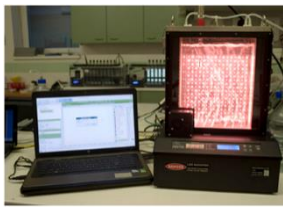
Product	Price (RM)	Feature	Advantages	Limitations
Photobioreactor FMT 150/3000 	94	-Flat-plate type of Photobio-reactor -working volume is 3000 ml -Have cultivation space, LED lighting and monitoring features.	-Suitable for indoor cultivation. - User friendly operation. -Long life light source.	-Extra prices for advanced accessories. -Not equip with harvesting system.
UTEX-Photobioreactor Systems 	667.35	-Annular type Photobio-reactor -Operational volume of 2000 ml. -Glass body -Use air pump.	-Light can penetrate through the glass body. -Suitable for indoor cultures. -Equip with stirring/ agitation equipment.	-Not provide harvesting system. -Artificial illumination requires additional price.
Autoclavable Benchtop Photobioreactor 	12 019	-Vertical type photobio-reactor. -Operational volume is 3000 ml. -Use artificial illumination. -Glass body.	- Lightweight and compact. -Having agitation system. -Suitable for indoor cultures. -Have provision for internal illumination.	- Price is too high. -Do not have harvesting system.

Table 3.8: The chart of competitive benchmarking based on metrics.

Metric No.	Need No.	Metric	Impor-tance	Units	Photo-bioreactor FMT 150/3000	UTEX Photo-bioreactor (basic package)	Auto-clavable Benchtop Photo-bioreactor
1	1,3	Maximum light intensity	4	µmol/ m^2s	1,500	Nil	Nil
2	1	Operating temperature	4	^oC	10 -75	Nil	Nil
3	1	flow for agitation system	4	ml/ min	0.0016 – 10.5	Nil	Nil
4	1,4	Working volume	4	ml	3000	2000	3000
5	3	Wavelength of light used	4	nm	630	Nil	Nil
6	2	Number of holes for gas exchange	4	unit	Nil	Nil	Nil
7	4	Base size of photobioreactor	3	mm	350 (L) × 310 (W)	100 (D)	Nil
8	4	Height of the photobioreactor	3	mm	500	260	Nil
9	5	Base size of harvesting system	5	mm	Nil	Nil	Nil
10	5	Height of harvesting system	5	mm	Nil	Nil	Nil
11	5	The size of mesh for harvesting	5	µm	Nil	Nil	Nil
12	5,6	Amount of cultivation medium being harvested	5	ml	3000	2000	3000
13	6	Amount of cultivation medium left after harvesting	3	ml	0	0	0
14	7	Initial cost for harvesting system implementation	4	RM	Nil	Nil	Nil
15	7	Cost for harvesting algae	4	RM	Nil	Nil	Nil
16	7	Cost per unit	4	RM	94	667.35	12 019

The benchmarking information are being synthesis in order to create and set the target values for the metrics. Target values consist of two useful set of values which are ideal value and another one is marginally acceptable value. The ideal value give the set of value which really desired for the new photobioreactor while the marginally acceptable value is the value that makes the new photobioreactor just barely has commercially viable. The target specifications for the lab scale photobioreactor are

shown in Table 3.9. Target specifications are paramount in generating a suitable concept to be used for setting final specifications. There are 2 ways used for setting target specifications. The ways are:

i. Comparing and considering the information gathered from benchmark products.
ii. Considering the information gathered from published journal and previous research (Refer to Chapter 2, Literature Review for the information).

Table 3.9: Target specifications for the new design of photobioreactor.

Metric No.	Needs No.	Metric	Importance	Units	Marginally Value	Ideal value
1	1,3	Maximum light intensity	4	µmol/m^2s	≥10	≤1500
2	1	Operating temperature	4	^oC	≥15	≤40
3	1	flow for agitation system	4	ml/ min	≥8.3	≤1000
4	1,4	Working volume	4	ml	≤20000	≤2000
5	3	Wavelength of light used	4	Nm	≥630	≤700
6	2	Number of holes for gas exchange	4	unit	1-2	2
7	4	Base size of photobioreactor	3	mm	≤ 350	≥100
8	4	Height of the photobioreactor	3	mm	≤ 500	≥100
9	5	Base size of harvesting system	5	mm	≤ 350	≥100
10	5	Height of harvesting system	5	mm	≤ 500	≥100
11	5	The size of mesh for harvesting	5	µm	≤ 100	≥30
12	5,6	Amount of cultivation medium being harvested	5	ml	≤ 20000	≥2000
13	6	Amount of cultivation medium left after harvesting	3	ml	≤ 750	≥50
14	7	Initial cost for harvesting system implementation	4	RM	≤ 200	≥50
15	7	Cost for harvesting algae	4	RM	≤ 50	0
16	7	Cost per unit	4	RM	≤ 300	≥50

3.2.5 The Generation of Suitable Concept

After setting the target specifications, several concepts can be generated. Product concept provides an approximate description about the technology, working principles and the form of the designed product. The best concept should solve the problems that contribute to the new design of photobioreactor. Thus, morphological chart has been created to provide a structured approach for the process of concept generation. By using this chart, the area of solutions search has been widen and the possibility to generate the most suitable concept increased. Table 3.10 shows about the morphological chart that leads to the generation of possible concepts. The function list provides about features of the photobioreactor and encompasses the major functions of the product. For each function, list of possible solutions are created by looking at available solutions from available products in market or by thinking the new solutions and ideas. Table 3.11 to Table 3.16 shows the concepts that have been generated from morphological chart.

Table 3.10: Morphological chart for generating possible concepts.

Product: Lab scale of photobioreactor					
Function	Solutions				
Cultivate microalgae	Rectangular shape of tank	Cylindrical tank	Oval shaped of tank	Jar shaped of tank	bowl tank
Put the light at correct place	Rectangular shape hole inside the tank	curve inside the tank	Cylindrical shape hole inside the tank	Wall outside the tank	
Illuminate the photobioreactor for photosynthesis	Stripes of LEDs light	Cylindrical fluorescent light	Fluorescent light bulb	LEDs light bulb	
Disperse the microalgae in the cultivation medium	Air pump	Water pump	Rotating gear		
Supply carbon dioxide for photosyhnthesis	Carbon dioxide tank	Air pump			
Harvest the microalgae to get microalgae biomass	Filtration	flocculation	Flotation		