AN INTEGRATED FUZZY ANALYTIC HIERARCHY PROCESS AND LIFE CYCLE OPTIMIZATION MODEL FOR MICROALGAE PRODUCTION

TAN JULLY

FACULTY OF ENGINEERING
UNIVERSITY OF MALAYA
KUALA LUMPUR

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TAN JULLY

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AN INTEGRATED FUZZY ANALYTIC HIERARCHY PROCESS AND LIFE CYCLE OPTIMIZATION MODEL FOR MICROALGAE PRODUCTION

ABSTRACT

Microalgae biofuel have the potential to overcome many of the limitations and present as a newly emerging clean energy that could replace fossil fuels. To produce a sustainable commodity or product, adverse environmental impacts from the overall process cannot be ignored. Development of cost effective processes for microalgae is considered to be the most significant challenge in commercializing microalgae biofuel production. Optimization of sustainable process plant configuration requires the use of systematic assessment methods in assessing on the usage of natural resources, release of pollutants and generation of environmental impact. The challenges in multi-objective optimization (MOO) is in identifying the appropriate aggregation method to integrate the objectives into a single performance index which is typically done by assigning importance weights to the different objectives. Life cycle assessment (LCA) for microalgae had been conducted extensively focused on comparing its environment impacts for microalgae biofuel production. Researches were also been undertaken to identify the feasible use of different methods for microalgae production. However, there is no consensuses on which of these methods are preferable. Novel integrated fuzzy analytic hierarchy process (FAHP) and life cycle optimization (LCO) framework for microalgae production are presented in this thesis. This includes the insight based on LCA studies and the uncertainty in decision making for technologies selection of microalgae production, taken into consideration of MOO technique. FAHP is incorporated into this research to monitor the uncertainty over the decision making process. Three different microalgae cultivation methods (open pond, tubular photobioreactor and flat-plate photobioreactor), four different harvesting methods (sedimentation by flocculation, flotation, centrifugation and filtration) and four different drying methods (sun drying, spray drying, drum drying and freeze drying) are used as case study to illustrate the capability of integrated FAHP-LCO model. These different methods are evaluated under the three selection criteria, i.e.: production capability, economic and environmental concern. They are prioritized using FAHP. Data from the scientific publication and based on theory for material and balance are used in LCA. Commercial optimization software LINGO v14 are used to solve FAHP and LCO equations. The results showed that flat-plate photobioreactor is preferred among others cultivation system when take into the consideration of environment factors (water, energy and carbon footprint) in the MOO. Followed by filtration and sun drying are chosen as best methods for harvesting and drying processes Sensitivity analysis is conducted and provides insights on the robustness of the decision model and enables the understanding of critical criteria that would significantly influence the ranking of the alternatives. The proposed integrated FAHP-LCO approach therefore proven that it can effectively deal with the uncertainty of judgment in the decision making process in the evaluation of microalgae production selection.

Keywords: Microalgae, life cycle assessment, life cycle optimization, multiple objective linear programming, fuzzy analytic hierarchy process

INTEGRASI MODEL FUZZY PROSES ANALISIS HIERARKI DAN PENGOPTIMUMAN KITARAN HAYAT UNTUK PENGHASILAN MIKROALGA

ABSTRAK

Sistem bio bahan api mikroalga mempunyai potensi untuk mengatasi banyak batasan dan muncul sebagai tenaga bersih yang baru untuk menggantikan bahan api fosil. Kesan buruk kepada alam sekitar daripada keseluruhan proses tidak harus diabaikan selain daripada penghasilan produk and komoditi mampan. Pembangunan kos yang efektif untuk mikroalga dianggap sebagai cabaran yang paling penting dalam mengkomersilkan pengeluaran mikroalga bio bahan api. Pengoptimuman konfigurasi proses di kilang memerlukan penggunaan kaedah penilaian yang sistematik berdasarkan penggunaan sumber semula jadi, pengeluaran pencemar dan penjanaan kesan kepada alam sekitar. Cabaran dalam pengoptimuman pelbagai objektif (*MOO*) adalah untuk mengenal pasti kaedah pengumpulan yang sesuai bagi mengintegrasikan objektif ke dalam indeks prestasi tunggal dengan mengenakan nilai kepentingan wajaran kepada objektif yang berbeza. Penilaian kitaran hayat (*LCA*) untuk mikroalga telah dijalankan secara meluas, ia memberi tumpuan kepada analisis perbandingan bagi kesan terhapad alam sekitar semasa pengeluaran mikroalga bio bahan api. Kajian juga sedang dijalankan untuk mengenal pasti penggunaan yang boleh dilaksanakan daripada pelbagai teknologi pengeluaran mikroalga. Walau bagaimanapun, tidak ada konsensus di mana kaedah yang mana satu adalah lebih baik. Integrasi *fuzzy* proses analisis hierarki (*FAHP*) dan pengoptimuman hayat hidup (*LCO*) untuk penghasilan mikroalga adalah novel untuk penyelidikan ini dan dibentangkan di dalam tesis ini. Ini termasuk kajian *LCA* dan ketidakpastian dalam membuat keputusan bagi pemilihan teknologi pengeluaran mikroalga dengan mengambil kira teknik *MOO*. *FAHP* dipilih untuk membuat keputusan dalam penyelidikan ini. *FAHP* adalah untuk memantau ketidakpastian mengenai proses membuat keputusan. Tiga jenis kaedah penanaman mikroalga (iaitu: kolam terbuka, photobioreactor tiub dan plat rata photobioreactor), empat kaedah penuaian yang berbeza (iaitu: pemendapan melalui pemberbukuan, pengapungan, pengemparan dan penapisan) dan empat kaedah pengeringan yang berbeza (iaitu: pengeringan melalui cahaya matahari, pengeringan secara semburan , pengeringan dengan drum dan pengeringan secara pembekuran) telah dipilih dan digunakan sebagai kajian kes untuk memampilkan keupayaan model integrasi *FAHP-LCO*. Keutamaan kaedah proses yang berbeza dinilai di bawah tiga kriteria utama, iaitu pengeluaran, ekonomi dan impak ke alam sekitar. Data daripada penerbitan saintifik dan berdasarkan pengiraan imbangan bahan dan tenaga digunakan dalam *LCA*. Dalam kajian ini , keputusan *FAHP-LCO* menunjukkan bahawa sistem plat rata photobioreactor lebih disukai di kalangan pelbagai sistem untuk proses penanaman yang lain. Diikuti, sistem penapisan dan pengeringan melalui cahaya matahari adalah alternatif terbaik untuk proses penuaian dan pengeringan bagi penghasilan microalgae. Analisis kepekaan digunakan untuk memberi pandangan mengenai keteguhan model dan membolehkan pemahaman sama ada kriteria kritikal yang ketara akan mempengaruhi kedudukan alternatif. Pendekatan *FAHP-LCO* yang dicadangkan dalam kajian ini adalah berkesan untuk berurusan dengan ketidaktentuan penghakiman dalam proses membuat keputusan dalam penilaian pemilihan penghasilan mikroalgae.

Kata kunci: Mikroalga, penilaian kitaran hayat, pengoptimuman hayat hidup, pengoptimuman pelbagai objektif, *fuzzy* proses analisis hierarki

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LIST ABBREVIATIONS

LCA	:	Life cycle assessment
LCI	:	Life cycle inventory
LCO	:	Life cycle optimization
MCDM		Multi criteria decision making
MOO	:	Multi-objective optimization
PBR	:	Photobioreactor
TPBR	:	Tubular photobioreactor
FPPBR	:	Flat-plate photobioreactor
MOLP	:	Multiple objective linear program
CF	:	Carbon footprint
LF	:	Land footprint
WF	:	Water footprint
DD	:	Drum drying
SPD	:	Spray drying
SD	:	Sun drying
FD	:	Freeze drying
AHP	:	Analytic hierarchy process
FAHP	:	Fuzzy analytic hierarchy process
TFN	:	Triangular fuzzy number
TSS	:	Total suspended solid
SETAC	:	Society of Environmental Toxicology and Chemistry

LIST NOMENCLATURES

$\mathbf{A}$	Technology matrix
$\mathbf{B}$	Environment intervention matrix
CR	Consistency ratio
CI	Consistency index
$\mathbf{f}(\mathbf{x})$	Objective function
$\mathbf{g}$	Total value of the environmental footprint
n	Size of matrix
$\mathbf{Q}$	Worst alternative matrix
RI	Random index
w_i	Weight of each criterion i (i = 1, 2, …, n)
$\vec{\mathbf{w}}_{\mathrm{fp}}$	FAHP weight vector
$\mathbf{w}$	Priority vector
$\mathbf{s}$	Gross output or scaling vector
$\mathbf{f}$	Net output vector
$\mathbf{z}$	Pairwise comparison matrix
$\hat{\mathbf{z}}$	Fuzzy pairwise comparison matrix
λ_{max}	Consistency value
δ	degree of confidence for fuzzy scale
L_{ij}	lower boundary of fuzzy set
M_{ij}	middle boundary of fuzzy set
U_{ij}	upper boundary of fuzzy set

LIST OF APPENDICES

CHAPTER 1: INTRODUCTION

1.1 Background Problem

Energy demand is essential factor in sustaining the higher level of activities and living standards. Based on BP Energy Outlook 2016, fossil fuels are expected to remain as dominant source of energy by supplying 60 % of the energy worldwide. However, the study shown that this global primary energy consumption grew only by one percent in 2014 and 2015; respectively well below as compared with the past decade. The supply of energy in recent years has been driven by different factors, such as supply constraint of primary energy resources, increase of emerging economics, climate change, technologies advancement that have increased the range and availability of different fuel options. The current traditional course of fossil fuel consumption is unsustainable, as it releases greenhouse gases (GHGs), particularly CO_2, into the atmosphere (Amaro *et al*., 2011; Peralta-Ruiz *et al*., 2013).

The focuses on sustainable sources such as renewable energy and biofuel in substituting fossil fuels and subsequently reduce the emissions of greenhouse gases. Study shown that renewable energy has grows robustly in power generation to approximately of 3 % for the global primary energy consumption, compared with 0.8 % a decade ago (BP, 2016). Even though the drastic drop of the price of fossil fuels in 2015 with 47 % decline since 1986, the demands over renewable energy is set to grow as the recent pledges made over United Nation COP21 Climate Change Conference in December 2015. It is clearly seems that with the pledge on environmental and climate policies has encourage a swift to lower usage of carbon fuels. An anticipation of 14 % of renewable energy demand is expected (BP, 2016).

The energy security concern and environmental issues have prompt to the extensive research on the alternative energy sources for the production of biofuels over the past years. It is predicted that the world energy demand to increase by as 53 % from recent levels by year 2030 (Talebian-Kiakalaieh *et al*., 2013). Biofuels produced from agricultural crops or waste resources have gained interest as a low-carbon alternative for producing liquid fuels, especially for use in motor vehicles and other transportation applications. Feedstocks for biofuel production include commercial crops like corn, sunflower, soybean, rapeseed, oil palm, as well as crop residues or biomass (Balat and Balat, 2009). Production of global biofuels grew from 16×10^9 L in 2000 to more than 100×10^9 L in 2011 (Zhang *et al*., 2013). Among emerging biofuel feedstocks, microalgae is one of the most promising due to its high yield (i.e.: fuel production per hectare) and fast growth rate (Avagyan, 2008).

Biofuels from microalgae biomass are being regarded as the most suitable alternative energy in today’s global and economical series of developments. Microalgae stands as the substantial option of biofuel feedstock due to able to reduce the greenhouse gases as it utilizes large amount of carbon dioxide during the cultivation process (Singh *et al*., 2011). The interest of microalgae has grown in their triglyceride content, which can be converted into biodiesel (Harun *et. al*., 2010). Microalgae are photosynthetic microorganisms that are fast growing and strong survivor even in extreme ecological environment because of their unicellular or simple multicellular structures (Mata *et al*., 2010; Oncel, 2013). Growth of microalgae depends on the availability of sunlight, carbon dioxide, initial concentration of microalgae and nutrients (Vasumathi *et al*., 2012). Microalgae are effective at converting solar energy into biomass via photosynthesis. Much of the interest in their use as a biofuel feedstock is the result of their high photosynthetic efficiency compared to terrestrial plants (Demirbas and Demirbas, 2011).

The unicellular structure of microalgae results in high photosynthetic efficiency and rapid growth, which has benefits for large-scale cultivation systems (Aslan and Kapdan, 2006). These advantages give rise to the opportunity to produce considerable quantities of microalga biofuels comparable to the other biofuel resources.

The technology for the production of first-generation biofuel from commercial food crops (e.g., sugarcane, corn, and palm oil) is already mature, and is subject only to economic constraints; one major issue is the conflict between food and fuel use. The global demand for liquid biofuel had tripled between 2004 and 2014; this trend has arguably affected the prices of food products (Rosegrant *et al*., 2008). The second generation biofuel is from waste biomass (e.g., agricultural and forest residues) and from non-food crop feedstock can potentially reduce this “food-versus-fuel” competition (Davis *et al*., 2011). However, production technologies for second generation biofuel are still relatively immature. The technological immaturity suggests potential gains in efficiency and cost effectiveness (IEA Bioenergy, 2008). Microalgae as the third generation source of biomass does not compete with conventional agriculture and produce high biofuel yield per unit of terrestrial area due to high photosynthetic efficiency (Chisti, 2008). Nevertheless, converting this promising feedstock into biodiesel is energy intensive, which in turn contributes to the system carbon footprint (Connell *et al*., 2013).

The entire process life cycle for the production of biofuel from microalgae has been explored since the blooming of the worldwide concern towards environment issues. This process includes the microalgae cultivation, harvesting, drying to the production of dried biomass. The selection of the microalgae species is also essential in determining the lipid content and its productivity. Microalgae can be cultivated via many methods and equipment. In generally, it can be carried out in an open pond system or closed system.

In the closed system, microalgae able to cultivate in vary photobioreactor, which are bubble column photobioreactor, tubular photobioreactor, or flat plate photobioreactor (Handler *et al*., 2012 and Sevigne Itoiz *et al*., 2012). In addition, some varieties of microalgae require less freshwater for cultivation, as they can use other sources such as wastewater, brackish water or seawater, thus reducing competition for resources required in the production of food crops (Rawat *et al*., 2013). Microalgae can be grown under heterotrophic conditions to achieve higher yields by using carbon sources dissolved or suspended in water (Liang, 2013).

Microalgae cultivation utilizing solar energy are mainly in open systems such as ponds or highly controlled closed photobioreactor (Mata *et al*., 2010; Bahadar and Khan, 2013; Slade and Bauen, 2013). The most widely used microalgae production systems functioning at commercial scale today are open raceway pond, flat plate photobioreactor and tubular photobioreactor (Norsker *et al*., 2011; Vasumathi *et al*., 2012). Making comparison between achievement of open ponds and photobioreactor is not a simple task, as the assessment relied on the types of algae species cultivated and the technique applied has directly impact of the yield (Mata *et al*., 2010).

The harvesting processes for microalgae are centrifugation, filtration, flotation and flocculation-sedimentation. A suitable harvesting alternative should be scalable to handle large volumes of microalgae in commercial processes (Grima *et al*., 2003). Inappropriate selection of a harvesting alternative may cause substantial problems, affecting the downstream processing in terms of cost and equipment efficiency. As for drying process, there are also many available methods such as: drum drying, freeze drying, spray drying or sun drying. Due to the energy consumption incurred in removing water content, drying process causes major economic issues, and accounts for up to 30 % of the total production cost (Chen *et al*., 2011). The common methods for drying of microalgae are sun drying, spray drying, drum drying or freeze drying.

1.2 Problem Statement

Nevertheless, there are still questions that remain about the best pathway for the production of microalgae biomass for fuel production (Handler *et al*., 2014). Some works on microalgae derived biofuels have focused on the improvement or selection of the various processing steps starting from the production of feedstock up to fuel conversion (Quinn and Davis 2015). A holistic evaluation of the environmental impacts of microalgae derived biofuels can be accomplished using life cycle assessment (LCA). LCA is a tool used to analyze the overall environmental impact of the product from the initial stage of raw material acquisition until the end of life of the product. It is a quantitative tool for analyzing the impacts related to a product or service from the initial stage of raw material acquisition to the end of life or disposal of the product (Guinée 2002). LCA enables the comparison of environmental performance between products and processes which perform the same function (Guinée 2002). Several studies of LCA for the different process paths for biodiesel/biogas production from microalgae have been conducted in the past years.

Despite improvements in the cultivation and processing of microalgae, the overall sustainability of algal biofuels remains controversial (Azadi *et al*., 2014). Technologies need to be assessed based on environmental impacts, quantified via metrics such as energy, water and carbon footprints. De Benedetto and Klemeš (2009) also proposed that carbon footprint, water footprint, energy footprint and workplace footprint be evaluated in the context of streamlined LCA as input for strategic decision-making. Čuček et al. (2012) conducted a comprehensive review of footprint analysis tools for monitoring impacts on sustainability. Razon (2014) discussed the importance of the nitrogen cycle and its interplay with other footprints. These methods enable the comparison of different technologies, which will then facilitate the selection of the most promising ones. Numerous papers dealing with the optimization and environmental assessment of biomass energy supply chains have been published.

Life cycle optimization (LCO) methodology is based on the combination of LCA with mathematical programming, which was first proposed by Azapagic and Clift (1998) and applied to industrial boron production (Azapagic and Clift 1999a). The approach based on the matrix formalism of Heijungs and Suh (2002) was later extended into a LCA optimization model by Tan *et al*. (2008) using fuzzy linear programming. Many other studies have also been done by incorporating multi-objective optimization (MOO) approach to identify the optimal point with regards to the different objectives, such as total environmental footprints (Čuček *et al*., 2014) as well as actuarial risk estimates of fatalities (Ramadhan *et al*., 2014). Wang and Work (2014) also proposed a robust formulation for LCO. However, one of the challenges in MOO is in identifying the appropriate aggregation method to integrate the objectives into a single performance index, which is typically done by assigning importance weights to the different objectives. Different promising technologies for microalgae cultivation, harvesting, dewatering and conversion of biomass have been investigated (Tan *et al*., 2016).

This research work extends the works on LCA for microalgae production by developing an integrated fuzzy analytic hierarchy process, FAHP with life cycle optimization (FAHP-LCO) framework for determining the optimum system design. By taking into account the importance or preference weights of multiple environmental footprints (i.e. energy, water and carbon footprint) (Ho, 2008), FAHP is incorporated in the decision to model the “fuzziness” or the uncertainties arising from vagueness involved during the value judgment elicitation. One the other hand, there is a notable gap in the literature on the LCO of microalgae production systems. For example, searching the Scopus database using “life cycle optimization” as key word yields 161 published documents; however, filtering further using “microalgae cultivation” as an additional search parameter results in only one conference paper. Thus, a significant research gap can be identified in this specific application of LCO.

1.3. Research Objective

The main objective of the research is to develop a novel integrated fuzzy analytic hierarchy process and life cycle optimization for the selection of best alternative for microalgae production from cultivation, harvesting and drying system. Generally, the research objective can be classified as following:

i. To identify the environmental footprints for cultivation, harvesting and drying system of microalgae production using LCA.
ii. To prioritize the alternatives for cultivation, harvesting and drying system via FAHP.
iii. To integrate LCA and FAHP into a decision making model in order to optimize alternatives’ selection based on the desired criteria.

1.4. Scope of Studies

In general, the approach for incorporating LCA into system optimization comprises of four main steps, which are: performing the LCA study, implementing the FAHP pairwise comparison study, then formulating the MOO problem in the LCA context; and finally performing the MOO and choosing the best compromise solution.

This research focuses on the following scopes:

i. Develop the FAHP-LCO framework model
ii. Perform LCA for the cultivation, harvesting and drying process
iii. Construct the AHP decision structure. Alternatives for each cultivation, harvesting and drying process options are identified.
iv. Pairwise comparisons. The value judgment is then represented in fuzzy scale.
v. Perform the LCO by integrating the priority weights with the optimization model.
vi. Conduct sensitivity analysis

1.5 Contribution of Research

Previous studies on LCA were focused mainly on cultivation system for microalgae, biofuel production from microalgae. Very less work were done for the entire cultivation to drying system assessment. At the end of the research, this work would be able to contribute to the insight of alternative selection for cultivation, harvesting and drying processes. The past research works were mainly focused in comparing its overall environmental impacts without taking into consideration of the priority of the environmental, technology or economic concerns. This research is able to provide significant input on how the selection of criteria can be embedded into the LCA by AHP. Meanwhile, the solution of FAHP provides strong justification on the decision making as it is capable to facilitate the uncertainty judgement during the analysis. As conclude, this thesis certainly able to provide understanding of the integrated FAHP-life cycle optimization (FAHP-LCO) model framework for microalgae production.

1.6 Organization of the Thesis

The thesis is presented based on the flow as shown in Figure 1.1. Chapter 1 provides the insight and the motivation of conducting the research, it covers the background study of the research area, understanding the problem statement, define the objective of the research and lastly present the significant of the research to the reader. Chapter 2 details the literature review of the research area. The content of the literature review includes the different type of microalgae production system, which what are the advantages and disadvantages. This information are essential as it later support the methodology of the research. The understanding of the decision-making tools: LCA, AHP and FAHP are needed as they are the key elements for the development of the multi-objective optimization framework.

The details methodology for the integrated FAHP-LCO are presented in Chapter 3. The details of the guided steps are presented in Chapter 4 and Chapter 5 whereby illustration of the case study will able to provide clearer understanding. Chapter 4 presents the FAHP-LCO for cultivation system and Chapter 5 for harvesting and drying system. In both chapters, it covers LCA, FAHP and LCO for the best system selection. Finally, Chapter 5 concludes the research as to ensure the objectives are met. The potential future work that can be extended from this research is recommended.

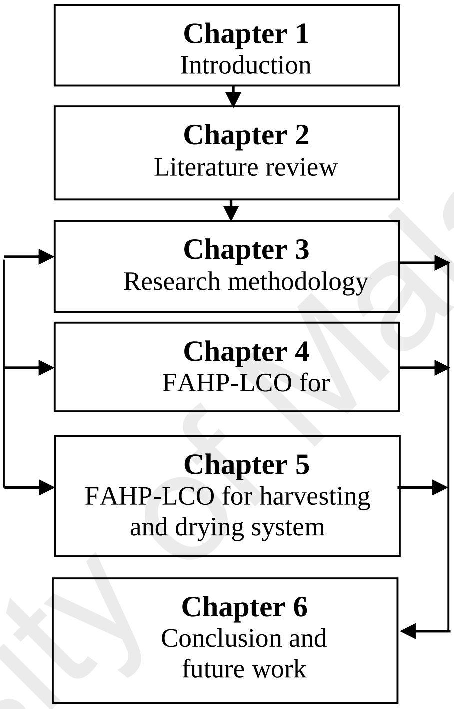

Figure 1.1: Thesis organisation chart

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Chapter 2 presents the background studies of the microalgae production, analytic hierarchy process (AHP), fuzzy analytic hierarchy process (FAHP), life cycle assessment (LCA) and life cycle optimization (LCO). Marine algae, specifically microalgae and its environment impact are reviewed. Various technologies involving in the cultivation, plantation, harvesting and production of microalgae are studied. Since 1970's, researchers have switched the direction that marine algae capability as an ideal feedstock for biofuel production because it would not compete with food production compared comparable to those of conventional (fossil) fuels. Algae biofuels are no sulphur, non-toxic and biodegradable. On the other hand, the studies also shown that marine algae shows it ability to use concentrated carbon dioxide from industrial sources i.e., smokestacks by the absorption of CO_2 by the growing organisms (Lardon *et al.*, 2009; Marsh, 2009). Since then, environmental impact assessment tools i.e. LCA, net energy, water balance and nutrient balance are further described on its application. Many issue to be looked into in the investment of this business to understand the commercial viable of algae based biofuel production, which may include: technology, biological innovation from its cultivation, harvesting, dewatering and extraction process (Singh and Gu, 2010).

2.2 Marine Algae

Marine algae can be classified as macroalgae and microalgae which growing in aquatic environment (Carlsson *et. al.*, 2007). Macroalgae or commonly known as seaweed, are a large and simple photoautotrophic organisms, ranging from unicellular to multicellular forms. They are visible marine algae with fast growing and the sizes can reach up to 60 m in length (McHugh, 2003). Generally, seaweed is classified according to their pigments such as the commonly seen seaweed in brown, red and green color (McHugh, 2003). Meanwhile, microalgae refer to the microscopic and photosynthetic organisms. The increase in interest in marine algae application in various field of industries such as human food, animal food, agriculture, aquaculture, fine chemicals extractions, and renewable energy have led to tremendous growths in the marine algae industry (Borowitzka, 1992). According to FAO (2014), approximate of 25 million tons of seaweed and other aquatic plants are harvested in year 2012. The report stated that the annual production of seaweed and aquaculture was doubled since year 2010 to 2012, which is expecting to continue grown.

Microalgae are classified as third generation biofuel feedstocks, which are desired because of their high lipid, carbohydrate and protein content (Srirangan *et al.*, 2012). The interest of converting microalgae into various products (such as methane, biodiesel from microalgae oil extraction and bio-hydrogen and etc.) have been brought to attention in the past few years due to the increase of concerns about global warming associated with fossil fuel use (Chisti, 2007). Wastewater treatment system able to provide nutrients for microalgae growth in the form of organic compounds (Mata *et al.*, 2010). Although biofuel is potentially CO_2 neutral (Coyle, 2007), the adverse environmental impacts of converting this promising feedstock into biodiesel being energy intensive (Connell *et al*., 2013) cannot be ignored.

2.3 Microalgae

Microalgae are organisms ranging in size from 1-50 μm that grow in salt water or fresh water environments (Demirbas, 2010). Growth of microalgae depends on the availability of sunlight, carbon dioxide, and nutrients (Vasumathi *et al*., 2012). Microalgae are effective at converting solar energy into biomass via photosynthesis as it has simple cellular structure. The aqueous living environment allows them to have sufficient access to water, CO_2 and other nutrient (Carlsson *et. al.*, 2007). The molecular formula for microalgae biomass is $CO_{0.48}H_{1.83}N_{0.11}P_{0.01}$ (Chisti, 2007). Minimum nutritional requirement can be estimated using the approximate molecular formula of the microalgae biomass. Noted that the molecular formula is approximation for the microalgae biomass for material and energy calculation. Photosynthesis reaction of microalgae biomass is shows in Equation 2.1 (Chisti, 2007)

$$100\ CO_2 + 223\ H_2O + 11\ NH_4^+ + HPO_4^{2-} \xrightarrow{\text{Light}} C_{100}O_{48}H_{183}N_{11}P + 112.5\ O_2 + 154\ H_2O \qquad \textbf{Equation 2.1}$$

There are more than 30,000 known species of microalgae. The commonly known microalgae are *Chlorella*, *Dunaliella*, *Cyanophyceae*, *Chlorophyceae*, *Spirulina* and etc. Microalgae been used indigenously for the past centuries as to produce food for human, animal feed, fine chemicals, production of essential fatty acids (Harun *et. al.*, 2010) as well as to be aquaculture feeds, pharmaceutical, cosmeceutical, and agriculture fertilizer (Watanabe and Saiki, 1998; Zhang *et al.*, 2002).

Microalgae production not only being features as food and feed, but also on their use in liquid waste treatment, specifically in water reclamation from sewage. The cultivation and utilization of microalgae being progressed from the past as ancient local traditions, then scientific-technological development and finally green technology trend in sanitary engineering (Soeder, 1980). The presence of microalgae able to increase the degradation of pollutants, improve CO_2 balance, reduce the energy demand and reduce the O_2 supply during aerobic process in the effluent treatment (Harun *et. al.*, 2010).

The interest to convert microalgae to renewable biofuel, methane from the anaerobic digestion of microalgae biomass, biodiesel from microalgae oil extraction, and bio-hydrogen have brought into attention on the past few years due to the escalation of oil price and the concern of global warming that associated with fossil fuel burning (Chisti, 2007). Larkum *et al.*, (2012) also noted that microalgae have significant potential for biofuel production due to their high content of oil and fatty acids. It is made up from 80 % of lipid content (Suali and Sarbatly, 2012). It is neutral lipids with high degree of saturation which suitable as the feedstock for biodiesel production (Rawat *et al.*, 2013). The study showed that microalgae's lipid has high energy content, which is twice the energy stored per carbon atom than carbohydrates (Rawat *et al.*, 2013). This has surpassed all the agriculture crops for biofuel production. Marine microalgae such as *Nannochloropsis* sp. contain high levels of lipids, ranging from 31 to 68 % dry weight (Chisti, 2007). Apart from the triglycerides, *Nannochloropsis* sp. has other valuable products such as proteins, which comprise approximately 30 wt% of the dry cell, and various types of metabolites, such as carbohydrates (Radakovits *et al.*, 2012). Microalgae are capable of rapid growth, with life cycles as short as a few days, thus enabling rapid start-up for biomass production (Sheehan *et al*., 1998). As with terrestrial crops, microalgae cultivation not only produces the biomass, but also reduces greenhouse gases through CO_2 fixation during the cultivation (Singh *et al*., 2011).

Unlike the first generation biofuel feedstocks, the production of biodiesel from microalgae will not compromise the production of food from other crops. Larkum *et al*., (2012) also note that microalgae have significant potential for biofuel production due to their high content of oil and fatty acids. Chisti (2007) discussed that microalgae produce significantly higher oil yield per unit land area compared to other major oil crops. Most traditional biofuels, such as ethanol from corn, wheat, or sugar beets, and biodiesel from oil seeds, are produced from classic agricultural food crops that require high-quality agricultural land for growth (Demirbas, 2009). Table 2.1 shows that microalgae produce significantly higher oil yield per unit land area compared with other major oil crops. The data shows land usage needed for meeting 50 % of fuel demand of the United States is dramatically smaller for microalgae than for other feedstocks (Chisti, 2007; Hu *et al*., 2008; Mata *et al*., 2010).

The data shows that microalgae oil yield ranging from 58,700 L/ha to 136,900 L/ha based on its different biomass weight percentage (30 to 70 %). Thus, microalgae produces an average of 97,800 L/ha over a year as compare with other agriculture feedstocks. For instance, microalgae produces approximately 570 times over corns' oil in an equivalent of land size. Taking into the consideration of this significant oil yield, microalgae have become the subject of research interest as potential feedstock for producing biofuels and other biochemical products (Guldhe *et al*., 2014).

Most traditional biofuels, such as ethanol from corn, wheat, or sugar beets, and biodiesel from oil seeds, are produced from classic agricultural food crops that require high-quality agricultural land for growth (Demirbas, 2009).

Table 2.1: Comparison data of oil yield and land area needed for different sources of oil crops (Chisti, 2007).

Type of crop	Oil yield (L/ha)
Corn	172
Soybean	446
Canola	1,190
Jatropha	1,892
Coconut	2,689
Oil palm	5,950
Microalgae	58,700 – 136,900

In summary, microalgae have the advantages as compared to other feedstocks as listed below:

i. It is easy to cultivate with the presence of sunlight and nutrient from the water (Aslan and Kapdan, 2006; Mata *et al.*, 2010).

ii. Microalgae capability to adapt and growth in different environment condition (Mata *et al.*, 2010).

iii. Less land area is needed with higher growth and production rates (Hu *et al.*, 2008; Mata *et al.*, 2010).

iv. The production of microalgae can be combined with other pollution controls (wastewater treatment or CO_2 emission sequestration) (Mata *et al.*, 2010; Park *et al.*, 2011).

v. It has shorter reproduce time and its growth cycle ranging from few hours to few days (Sheehan *et al.*, 1998).

Microalgae production includes cultivation, harvesting, and drying processes. Figure 2.1 shows the overall marine microalgae production process. Marine microalgae production consists of cultivation, harvesting and drying in order to produce dried microalgae. Short life cycle also allow near continuous harvesting (Larkum *et al*., 2012). However, microalgae production needs large quantities of water (Sevigne Itoiz *et al*., 2012).

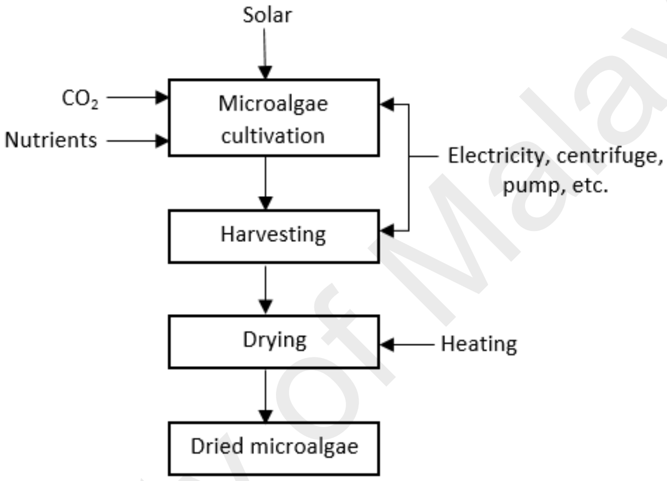

Figure 2.1: **Flow diagram of marine microalgae production**

2.4 Cultivation System of Microalgae

Abiotic, biotics and operation factors are the key influencing factors to the microalgae growth rate (Posten, 2009 and Mata, *et al.*, 2010). Abiotic factors includes of the quantity and quality of the light, nutrient concentration, temperature, CO_2 and O_2 concentration, pH, salinity of the water. Meanwhile, biotic factors indicate the presence of the pathogens and its competition with the microalgae in the system. Lastly, the operational factors are mixing rate, dilution rate, pond depth and frequency of harvesting.

CO_2, light, water and inorganic salts are the requirements for photosynthetic growth of microalgae. Temperature within 20 to 30 ºC needs to be maintained. The culture must make available the inorganic elements that form the microalgae cells. Nitrogen, phosphorus, iron and sometimes silicon are the essential elements needed. However, not all the added phosphorus is bioavailable as phosphorus might chemically react with metal ions and consequently phosphorus need to be supplied in significant amounts. Alternatively, seawater complemented with viable phosphate fertilizers, nitrate and some other micronutrients can be utilized for cultivating marine microalgae. Besides that, water channeling from neighboring land area's runoff water or wastewater treatment plants able to provide the nutrients for microalgae cultivation (Demirbas, 2010). The solar energy is readily available in tropical country where having sufficient sunlight throughout the whole year (Ugwu *et al*., 2008) or by applying artificial light source for indoor cultivation (Suali and Sarbatly, 2012).

Open system and closed system are two main cultivation systems of microalgae. The most widely used microalgae production systems functioning at commercial scale today are open pond, flat-plate photobioreactor and tubular photobioreactor (Norsker *et al*., 2011; Vasumathi *et al*., 2012). Making comparison between achievement of open system and closed system is not a simple task, as the assessment relied on the types of algae species cultivated and the technique applied to evaluate the yield (Mata *et al*., 2010). Open system or also known as open ponds system are more affordable and lower energy consumption than photobioreactor. It can make by natural waters (lakes, lagoons, ponds) or artificial pond or containers. It is easier to construct. However, open ponds system is subjected to contamination and water losses due to evaporation (Resurreccion *et al*., 2012). The major disadvantages in open system include required of huge land size, uncertainty in controlling over the cultivation condition and poor light utilization by cell.

Compared with open system, closed system attracts much interest due to its advantages in cultivation condition control. There are few types of commonly used closed system PBR, i.e.: tubular photobioreactor (TPBR) and flat-plate photobioreactor (FPPBR). Photobioreactor is costly compared to the open ponds due to the needed advance facilities. With better control over the closed system, the higher biomass productivities can be obtained and contamination can be easily prevented. Davis *et al*. (2011) reported that closed system has higher capital cost and operating cost as compared to open system. Total energy consumption for the open system and closed system 450 GJ and 729 GJ per year, respectively (Jorquera *et al*., 2010). It is reported variation of 61 % (capital cost) and 33 % (operating cost) as compared to open system.

TPBR has high surface to volume ratio and can be designed up to several hundred thousand in length. The transparent tubing which are arranged in parallel lines enable the homogenous light distribution in TPBR. Sevigne Itoiz *et al*., (2012) showed that in respect to the same microalgae species and similar TPBR system, the outdoor growth system for microalgae had a significant lower production as compared to the indoor growth system, i.e. 0.15 g/L to 0.28 g/L. This is due to the outdoor biomass productivities are naturally depending on weather condition compared to indoor. The blooming of microalgae is impact by the irradiance and temperature of the system, i.e.: increase of irradiance and temperature lead to the increase of the population in the system (Angles, *et al*., 2012). Table 2.2 summarizes the advantages and disadvantages for the application of open and closed system for microalgae cultivation. Section 2.41 and 2.42 further explain the advantages and disadvantages of open and close system, respectively.

Table 2.2: Advantages and disadvantages of open and closed system for microalgae cultivation (Brennan and Owende, 2010; Ugwu, *et al*., 2008)

Culture System	Advantages	Disadvantages
Open System: Open pond, raceway	• Relatively cheap • Good for mass cultivation of algae • Easy to clean • Low energy requirement • Easy maintenance • Suitable for mass production	• Poor biomass productivity • Large land size • Culture easily to be contaminated • Usage of large amount of water • Poor mixing • Poor CO_2 utilization • Poor lighting utilization
Closed System: Tubular Photobioreactor (TPBR)	• Suitable for outdoor culture • Relatively cheap • Good biomass production • Large illumination surface area	• Large land space • Fouling • Gradient of pH in the tubes • Dissolved of O_2 and CO_2 along the tubes • Some degree of wall growth
Closed System: Flat Plate Photobioreactor (FPPBR)	• Suitable for outdoor culture • Economical • High biomass productivity • Large illumination surface area • Good light path • Low O_2 build up • Good for immobilization of algal	• Difficult to scale up • Difficult to control the temperature • Some degree of wall growth • Some degree of hydrodynamics stress for some strains

2.4.1 Open System

Open pond system is a traditional method for mass cultivation of microalgae since 1950s (Demirbas, 2010; Borowitzka, 1999). Researches had been done extensively in the studies of microalgae cultivation in open cultivation systems in the past. The most commonly used open systems are raceway ponds, circular ponds, tanks and shallow big ponds (Ugwu *et al*., 2008). It able to maximize the solar energy capture. The light supplied through the natural solar light penetrate into the water, while CO_2 gas exchange occurs from surrounding atmosphere to the surface of the water. Aeration and nutrient dispersion can be maintained by mixing homogenously with affordable and low energy consuming paddle wheels.

Open systems is low cost of construction and maintenance throughout the cultivation process (Sevigne Itoiz *et al*., 2012). Open ponds are susceptible to contamination at high-risk level. Therefore, only certain microalgae species able to survive under critical environment which is high salinity and critical pH (Ugwu *et al*., 2008; Davis *et al*., 2011; Kumar *et al*., 2011; Suali and Sarbatly, 2012). Monoculture cultivation is attainable by maintenance of severe growth culture, even though only minority of microalgae fit the criteria. For instance, the species *Chlorella* (versatile to nutrient rich media), *Spirulina* (versatile to high alkalinity) and *D. salina* (versatile to very high salinity) flourish under such examples of severe environments. However, prolonged production periods for this method might not certainly eliminate bacterial and other biological contaminants (Lee, 2001).

The inefficient mixing operation in open systems leads to the poor mass transfer rates and thus resulting a low biomass productivity (Brennan and Owende, 2010; Ugwu *et al*., 2008). This is because only 0.03 to 0.06 % CO_2 exists in the atmosphere and this can slow down the mass transfer and effect the cell growth of microalgae (Mata *et al*., 2010). The mass transfer rate can be improved to at least 90 % by connecting a carbonation column where CO_2 can be transformed into the water (Putt *et al*., 2011). Biomass productivity also may be reduced by the insufficiency of sunlight as thick top layer restricted the penetration of light ray (Vasumathi *et al*., 2012). By minimizing the covered top layer thickness of the pond able to ensure the light supply to the culture (Pulz, 2001; Chisti, 2007; Ugwu *et al*., 2008). Thus, elevate the biomass yield.

Another disadvantage is large land area needed for cultivation (Suali and Sarbatly, 2012; Vasumathi *et al*., 2012). Substantial land areas are need in producing large amounts of microalgae, (Mata *et al*., 2010). However, open pond system does not interfere for space with other field crops, as the system can carry out in area with minimal crop production potential, such as lake and pond (Chisti, 2008).

Open ponds are able to generate biomass production at the best price (Leite *et al*., 2013) due to its low set-up and operational costs (Davis *et al*., 2011; Suali and Sarbatly, 2012). They have high net energy production as the systems have lower energy input, maintenance and cleaning are easier to perform as well. Open ponds are the inexpensive method of large scale microalgae biomass production than closed PBR. With its ease of implementation and more durable than closed systems thus open ponds receive substantial attention for the biofuel production which required large amount of biomass production (Ugwu *et al*., 2008; Mata *et al*., 2010; Vasumathi *et al*., 2012).

Study showed that microalgae cultivation using PBR able to yield higher biomass compared to synthesize in raceways pond (Chisti, 2007). This is caused by few factors, namely: temperature variation in the growth media, evaporation losses, low CO_2 concentration, inhomogeneous mixing, and insufficient light penetration. Open ponds have difficulties in controlling temperature fluctuations because of diurnal cycles and seasonal variations. Water loss through evaporation is contributed by shallow pond and large surface area, restricting the application at high cost water areas (Leite *et al*., 2013). Evaporation losses may give remarkable alteration on growth medium's ionic composition with damaging consequences on microalgae growth even though it makes a net contribution to cooling. Potential carbon dioxide shortages due to diffusion into the surrounding might affect the biomass yield due to less utilization of carbon dioxide (Brennan and Owende, 2010; Ugwu *et al*., 2008).

Raceway pond is constructed with a closed loop, eclipse-shaped recirculation channel which is normally about 0.2 to 0.3 m in depth to ensure sufficient exposure to sunlight. They are mechanically mixed with paddle wheels shown in Figure 2.2. Paddle wheels are function as vertical mixing to prevent algae settlement and at the same time to maximize gas exchange within the ponds (Bruton *et al*., 2009). Raceway ponds are shallow to maximize light penetration because optical absorption and self-shading by the microalgae cells restricts light penetration through the microalgae broth (Slade and Bauen, 2013). Raceway passages are constructed from either compacted earth or concrete and mostly lined with white plastic (Chisti, 2007; Brennan and Owende, 2010; Demirbas, 2010; Singh and Sharma, 2012).

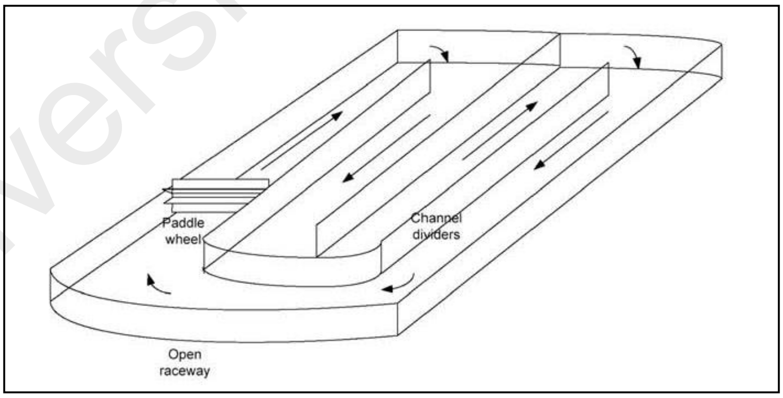

Figure 2.2: Raceway ponds (Jorquera *et al*., 2010)

Raceway ponds are considered as the most cost effective way of microalgae biomass production. It was reported that the productivities of raceway ponds is within 14 to 50 g/m^2/d. They do not come accumulated with O_2 which can jeopardize biofuel production in closed systems (Bahadar and Khan, 2013). Raceway ponds are regarded to be cheaper than PBR as they are inexpensive to construct and easier to function (Chisti, 2007; Bahadar and Khan, 2013). Even though raceways are less costly, the biomass productivity is much lower than PBR because they are poorly mixed, have low light-to-volume ratio and unable to tolerate an optically dark region (Chisti, 2007; Rawat *et al*., 2013). The yield of a raceway pond can be improved by enhancing the CO_2 mass transfer (Putt *et al*., 2011). Apart of receiving CO_2 at the surface air, underwater aerators can be installed to elevate CO_2 content and ensure sufficient CO_2 content in the system. In raceways, evaporation can give the advantage of cooling to the cultivation system. Evaporative water loss in raceway ponds shall be noteworthy. Evaporative losses potentially pose severe impact on culture growth as it causes alteration of ionic composition of the cultivation media. Biomass productivity also can be affected by temperature fluctuation, photoperiod and climate variation because these parameters are beyond control in raceways pond. Bad weather can often stunt algal growth (Singh and Sharma, 2012). Large land space may be needed to meet the preferred production of cultivation because of low productivities. In addition, the thermal power plant releases flue gas that has 12 to 34 % CO_2, depending on the type of the fuels. Diluting the CO_2 concentration will demand operating with great volume of flue gas and rises land space criteria (Vasumathi *et al*., 2012).

Raceway ponds are easily contaminated with unwanted microalgae and microorganisms that can give an impact to the cultivated microalgae (Demirbas, 2010; Singh and Sharma, 2012; Sing *et al*., 2013). Besides that, undesired algae that ingest on microalgae will affect the biomass productivity. Contamination by protozoa and other microalgae may be minimized by stringent selection for the culture’s medium. This restricts the number of suitable species to only a few species in open pond cultivation.

The probability of contamination is often known as a serious constraint of raceway ponds where most of the species cultured in raceway required growing in selective condition (Bahadar and Khan, 2013).

In short, the raceway ponds cultivation system needs expressively less energy for mixing than the photobioreactor designs (Norsker *et al*., 2011). Minimal control upon culture conditions, low productivity, cultures are easily contaminated with other microorganism, require large land space, limited to certain species, and have difficulty in cultivating microalgae for long periods are the drawbacks of raceway ponds for microalgae biomass production (Ugwu *et al*., 2008).

2.4.2 Closed System

The drawbacks of open ponds system have driven researchers' interest in finding the solution to overcome contamination and low yield. Closed system photobioreactor (PBR) of microalgae cultivation such as tubular photobioreactor (TPBR) and flat-plate photobioreactor (FPPBR) have been studied over the past years. It is the alternative cultivation other than open pond system. In closed system, water is circulated by pumps. Higher volumetric biomass can be produced due to nutrient, gas level and artificial light able to be monitored continuously and adjusted accordingly. Closed system reduces the risk of contamination and enables the growth of a single microalgae cell type (monoculture) compare to open systems (Sevigne Itoiz *et al*., 2012).

Cultivation in PBR has high degree of control on the key variable that affect the culture, including pH, temperature, and light intensity and is promising for higher productivities than open systems (Leite *et al*., 2013). Compared with open pond system, PBR is more efficient and produce higher biomass concentration about 2 to 5 g/L. It also has shorter harvest time about two to four weeks, higher surface to volume ratio about 25 to 125 per meters and reduced contamination risks by invading microorganisms or herbivores as it is protected from direct fallout (Bei *et al*., 2008; Davis *et al*., 2011; Lee, 2001). PBR have the potential to cultivate microalgae while providing additional environmental benefits, such as removing nutrients from wastewater or scrubbing power plant flue gases. This can be done when wastewater is used as the cultivation medium for microalgae in PBR or flue gas is injected into the PBR as the CO_2 source for photosynthesis of microalgae. While, flue gas is injected into the PBR as the source for CO_2 to microalgae growth. The absorption of photons from sunlight and transfer of CO_2 from flue gas are determined by the surface area to volume ratio of PBR (Vasumathi *et al*., 2012). The advantages of PBR over open systems able to provide superior control for the culture medium and cultivate variables, (i.e.: pH, temperature, mixing, CO_2 and O_2), and control of water losses. At the same time, PBR also able to minimize the CO_2 reduction, increase the biomass concentration, increase the biomass production yields, provide a safer environment; and control of contaminant or reducing nutrient loss by competing with others microorganisms in the system.

Cultivation of microalgae by PBR can use direct sunlight, artificial light or their combination for microalgae biomass production. It can be carried out either indoors or outdoors. PBR are not exposed to the environment including no contact with the contaminants and gas diffusion. In PBR, cultivation is carried out in a clear tubes or container where the microalgae broth is stirred homogenously from a central reservoir (Slade and Bauen, 2013). O_2 formed during the photosynthesis process is removed by a degassing column in the closed systems (Suali and Sarbatly, 2012). Factors such as light capturing, light reflection, light transmission, and light utilization by microalgae through photosynthesis will determine the efficiency of PBR. An efficient PBR design should be able to receive maximum sunlight and reach the cultivation vessel and fully utilized for microalgae biomass cultivation. Apart from that, it also needs to allow appropriate control on operational parameters so that cultivated cells are able to achieve its maximum productivity. In addition, it should also to minimize energy consumption during operation (Bei *et al*., 2012).

Valuable products such as pharmaceuticals which specifically have to be cultivated in the form of monoculture only can be carried out in PBR (Rawat *et al*., 2013). Mixing provides an advantage in phototrophic systems as mixing and aeration is carried out concurrently. Gaseous exchange within the system can be done by mixing. Artificial light has provided the need of light intensity and photoperiod in order to increase productivity by 25 to 42 % (Amaro *et al*., 2011). PBR enhance the optimization of light path length and also enhance microalgae biomass productivity. A variety of species can be grown in PBR (Davis *et al*., 2011). Unlike open system, PBR allow growths of single microalgae species for longer duration without contact with contamination (Chisti, 2007). PBR are able to give full focus on specific cultivate microalgae species that unable to cultivate in open system by optimizing based on the biological and physiological properties of the strain (Mata *et al*., 2010). It is reported that PBR are able to produce 19,000 to 57,000 L of microalgae oil per acre per year under controlled conditions for high oil content species (Demirbas and Demirbas, 2011).

However, PBR are affected from numerous disadvantages, which required solutions and improvements on the technique. Most of the drawbacks include O_2 accumulation, poor heat distribution system, biofouling, expensive construction and operation cost, and cell damage due to shear stress (Mata *et al*., 2010). The costs involved in PBR systems are considerably higher than open systems and it needs high infrastructure costs (Demirbas, 2010; Bahadar and Khan, 2013). The other costs include the circular system, the CO_2 feed, the cultivation medium feed and the light illumination. Using artificial light to replace sunlight will increase the power usage and higher operating cost (Amaro *et al*., 2011). Fouling and cleaning of both external and internal walls of the tubes are complicated. The dirt on the external wall or algae grown on the internal wall of tubes will prevent lights from penetrating the surface and thus reduce the photosynthesis reaction rate (Bruton et al., 2009).

PBR design is improving very fast to meet the need of industrial production and the operation weakness. Nevertheless, only few types of PBR are able to maximize the sunlight absorption for the microalgae grow. PBR design is the crucial phase in order to achieve the objective for efficient mass cultivation of microalgae. TPBR and FPPBR have been discovered as the most efficient PBR systems for mass production of microalgae biomass, as they provide large surface-area-to-volume ratios (Bei *et al*., 2012). Most outdoor PBR are distinguished by highly exposed illumination surfaces. Researchers showed that flat plate, inclined and horizontal tubular are success type of PBR but they have difficulty to scale up. Other types of PBR are airlift, bubble column and stirred-tank, which have good scalability, and yet limited usage for outdoor cultivation due to low illumination surface areas (Ugwu *et al*., 2008).

2.4.2.1 Tubular Photobioreactor

Tubular photobioreactor (TPBR) is among the most suitable types for outdoor closed system for microalgae cultivation. Generally, TPBR are usually constructed with either glass or plastic tube with airlift system. Figure 2.3 shows the diagram of the horizontal TPBR. TPBR placed in parallel direction or discretely intends to enhance the CO_2 uptake (Chiu *et al.*, 2008). The sunlight is captured in the solar collector or the tubular array. The solar collector tubes diameter is normally less than 0.1 m to allow light penetration to the center of the tube (Chisti, 2007). The growth rate of the culture will decrease with the increase of the tube diameter. Meanwhile, dense culture broth will limit the light penetration because the light coefficient. The solar collector is positioned to maximize sunlight capture. The solar tubes can be arranged side-by-side or directly above the ground to maximize the illumination surface-area-to-volume ratio of the reactor (Demirbas, 2010). Air pump or airlift systems are used to aerate and ensure homogenous mixing of culture in TPBR.

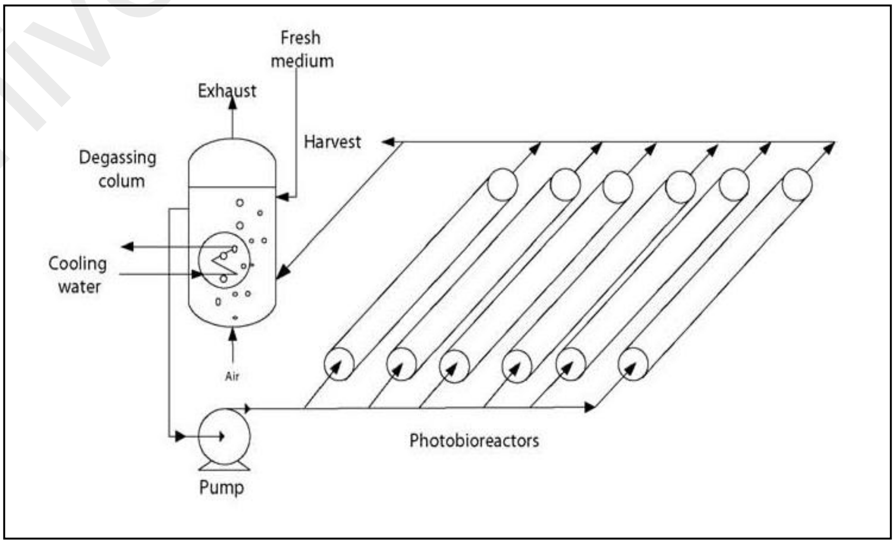

Figure 2.3: Horizontal Tubular photobioreactor (Jorquera *et al.*, 2010)

The scale up of the TPBR poses few constraints. Scale up of the TPBR by manipulating the size of the tubes by its diameter and length (Sastre *et al*., 2007). Increasing the diameter of tubes will decrease the illumination surface to volume ratio which led to the cells at the lower part of the tubes will not have proper light distribution (Ugwu *et al*., 2008). On the other hand, increase of the tubes length give the challenges for excess oxygen accumulation, CO_2 reduction and pH deviation in the systems; thus affect biomass yield directly (Eriksen, 2008). Also, it is difficult to control culture temperatures in most TPBR. It could be expensive and hardly to implement and maintain by installing thermostat to maintain the desired culture temperature (Ugwu *et al*., 2007). Furthermore, long TPBR is characterized by gradient of oxygen and CO_2 transfer along the tubes (Ugwu *et al*., 2007). The increase in pH of the cultures would also lead to frequent re-carbonation of the cultures, which would consequently increase the cost of algal production (Ugwu *et al*., 2007).

2.4.2.2 Flat-Plate Photobioreactor

Flat-plate photobioreactors (FPPBR) (Figure 2.4) is basically a flat and transparent vessel made from materials like glass, plexiglass and polycarbonate. FPPBR receive attention for cultivation of microalgae due to their large illumination surface area (Ugwu *et al*., 2008).

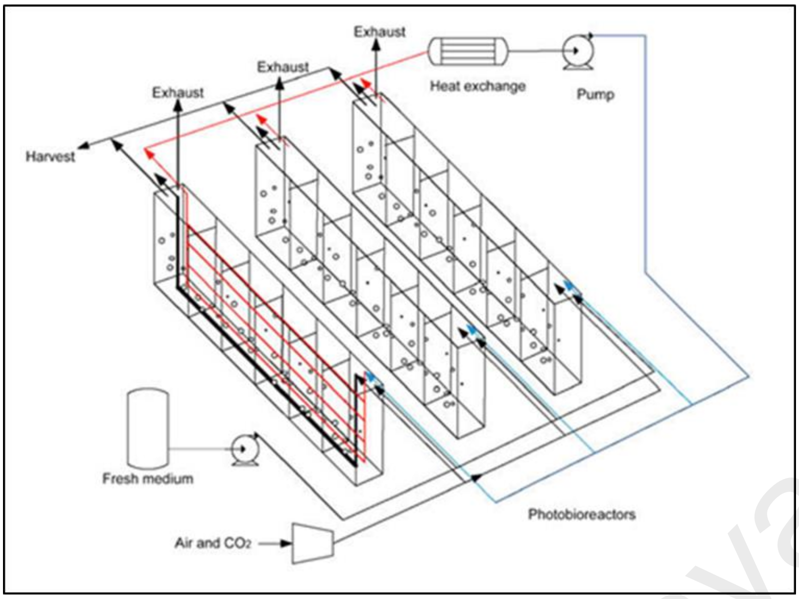

Figure 2.4: Flat-plate photobioreactor (Jorquera *et al*., 2010)

In-situ air stripping is used for well mixing in the PBR. Homogenous stirring can be achieved by bubbling air through perforated tube or mechanically rotation using motor (Kumar *et al*., 2011). The special features of FPPBR are high surface-area-to-volume ratio, a narrow light path and open gas disengagement systems. The FPPBR design can produce a biomass concentration of 2.1 g dry weight per litre (Norsker *et al*., 2011). It has high biomass production due to its large surface area allowing effective solar capture. FPPBR is able to accomplish large scale cultivation as compare to TPBR because of the high photosynthetic efficiency and low accumulation of dissolve oxygen, in return, it required a costly installation and operation charges ((Rawat *et al*., 2013).

FPPBR have low power consumption for mass transfer as compared with TPBR. TPBR has an average of 48 times higher power consumption requirement than FPPBR (53 W/m^3) (Sierra *et al*., 2008). Smaller light path provides sufficient time of exposure thus enhances the higher photosynthetic efficiencies and high density cultures are easily obtained. Dissolve oxygen concentrations rise in FPPBR is comparatively lower than TPBR (Richmond, 2000;

Vasumathi *et al*., 2012). Ugwu *et al*., (2008) suggested that FPPBR is the most suitable technique to cultivate microalgae due to its high photosynthetic efficiencies.

2.5 Microalgae Harvesting

Microalgae with size ranging from one micrometer to two millimeter considered as particles in suspension. The recovery of particles in the suspension, or known as harvesting of microalgae requires solid-liquid separation steps to produce biomass. Some strains are motile and unable to settle down naturally; while some strains tend to agglomerate naturally and to settle down. Microalgae are difficult to harvest due to their density just slightly greater than water and strong negative charge on their surface. At the negative charge surface, the algae cell will remain dispersed. Efficient harvesting is often the key to good economical yield of the overall process (Bruton *et al*., 2009).

Many efforts had been carried out to study the most suitable harvesting system for microalgae which is economical, high efficiency and environmental friendly. The characteristics of the microalgae such as size, density, the desired production quality and quantity are the determining parameter in selecting harvesting method (Olaizola, 2003). The performance of each harvest system can be evaluated based on the rate of water removal (Grima *et al*., 2003), the solids content of the recovered slurry, and the efficiency of the harvesting system (Uduman *et al*., 2010). Furthermore, a suitable harvesting system should be scalable to handle large volumes of microalgae in commercial processes (Grima *et al*., 2003). Inappropriate selection of a harvesting system may cause substantial problems, affecting the downstream operation processes (such as biofuel production) in terms of cost and equipment efficiency.

During microalgae harvesting, biomass will be recovered from the culture medium and large quantities of water will be removed, whereby 200 to 250 g/L of diluted cultures to achieve biomass concentration of 0.5 to 2.5 g/L at the end of the process (Granados, *et al*. 2012). The harvesting process may involve physical, chemical or biological steps to achieve the maximum biomass recovery. In general, physical separation methods are commonly used in harvesting stage. This include sedimentation, centrifugation, or filtration. Sometimes, chemical coagulation/flocculation or flocculation-flotation may be involved in biomass recovery. Addition of chemical aims to enhance the aggregation of the microalgae cell and hence ease the sedimentation or filtration process (Mata, *et al*., 2010). The proper selection of harvesting technology is essential for economically way of producing of microalgae biomass and at the same time to obtain highest biomass recovery (Brennan and Owende, 2010). A comparison of the advantages and disadvantages of the different harvesting alternatives is shown in Table 2.3.

Flotation and sedimentation are separation processes which liquid are constrained in a vessel and particles move freely within the liquid. Flotation and sedimentation are generally apply in open ponds system. Meanwhile, biomass cultivated in closed systems is harvested using filtration or centrifugation (Bruton *et al*., 2009). Pre-treatment may be necessary to improve harvesting yield. Centrifugation process is capable of separating microalgae from liquid media without any difficulties (Mohn, 1988); however, it is also costly, time-consuming and energy intensive when processing large quantities of microalgae (Uduman *et al*., 2010). Filtration process uses a permeable medium that retains solid particles as the liquid component of the slurry is penetrates via as a result of a pressure gradient across the filter medium (Shelef *et al*., 1984). There are many variations of commercial filtration equipment (e.g., pressure filters, vacuum filters, micro strainers, and deep-bed filters). Filter media in microalgae processing may tend to clog and hence require high maintenance and replacement cost. Flocculation involves inducing the formation of larger aggregates from small particles; these flocs can then be separated from the liquid medium by gravity (Vandamme *et al.*, 2010). Coagulants and flocculants such as ferric chloride ($FeCl_3$), aluminum sulfate ($Al_2(SO_4)_3$, and ferric sulfate ($Fe_2(SO_4)_3$) are added to facilitate flocculation (Becker, 1994). However, these chemicals must be selected such that product quality and downstream processing are not adversely affected by their use (Grima *et al.*, 2003). Gravity sedimentation is a separation process that relies solely on gravity to generate clarified liquid and thickened slurry from a given feed (Svarovsky, 1977). On the other hand, flotation is separating particles by attachment of solid particles to air bubbles that carry them to the liquid surface for subsequent mechanical separation (Garg et al. 2012).

Table 2.3: Advantages and disadvantages of different harvesting system

Alternatives	**Advantages**	**Disadvantages**
Centrifugation	• Can handle most algal types (Mohn, 1988) • Rapid cell harvesting (Milledge and Heaven 2012) • Able to handle large volumes at relatively rapid speed (Grima *et al*., 2003) • Available with wide range of centrifuge, i.e.: tubular centrifuges, multi chamber bowl centrifuges, decanter (Shelef *et al.*, 1984) • For high-value product (Grima *et al*., 2003) • Dry solid output: 12-22 % (Shelef *et al*., 1984)	• High capital and operational cost (Uduman *et al*., 2010, Milledge and Heaven 2012) • High energy consumption 8 kWh/m3 (Grima *et al*., 2003) • May cause damage of cell structure due to high gravitational and shear forces (Milledge and Heaven 2012)
Filtration	• Wide variety of filter and membrane types available (Milledge and Heaven 2012) • Dry solid output: 5-27 % (Shelef *et al*., 1984) • Low energy consumption 0.2-0.88 kW/h.m^3 (Shelef *et al*., 1984)	• Prone to fouling and clogging (Shelef et al. 1984) • Relatively slow process (Grima *et al*., 2003) • Species-specific (Uduman *et al*., 2010, Grima *et al*., 2003) • Process efficiency depends on the concentration of the microalgae (Uduman *et al*., 2010) • Size dependency, suitable for large algal cell (Milledge and Heaven 2012) • High operating cost (Grima *et al*., 2003)
Flocculation followed by sedimentation	• Inexpensive (Grima *et al*., 2003, Milledge and Heaven 2012) • Low energy consumption (Uduman *et al*., 2010) 1 kw/h.m^3 • Able to handle large quantity of microalgae culture (Uduman *et al*., 2010) • Applied for wide range of species (Uduman *et al*., 2010) • More than 95 % removal of microalgae (Shelef *et al*., 1984) • More than 80 % of water removal (Grima *et al*., 2003)	• For low-value product (Grima *et al*., 2003) • Low final concentration, solid output: 3-8 % • Uses of chemical may contaminate the final product (Chen *et al*., 2011, Uduman *et al*., 2010) • Effective in low concentration microalgae system (Grima *et al*., 2003) • Sensitive to pH level (Chen *et al*., 2011) • Dry solid output: 0.5-8 % (Milledge and Heaven 2012)
Flotation	• Effective to capture small particles up to 500 μm in aqueous solution using gas bubbles (Chen *et al*., 2011) • Efficient and cost-effective method to harvest algae from wastewater (Wiley *et al*., 2009) • Low space requirements (Barros *et al*., 2015) • Relatively cheaper compared to centrifugation (Sharma *et al*., 2013)	• Species-specific (Milledge and Heaven 2012) • High capital and operational cost (Milledge and Heaven 2012) • Chemical flocculation is used to increase the efficiency of flotation process (Uduman *et al*., 2010) • Dry solid output: 7 % (Milledge and Heaven 2012)

2.5.1 Flocculation and Sedimentation

Sedimentation is a process of solid-liquid separation that separates a feed suspension into slurry of higher concentration and an effluent of substantially clear liquid. Gravity sedimentation under free or hindering settling is used to remove particle which have reasonable settling velocity from a suspension. However, fine particles with few micrometer in diameter, such as microalgae may need flocculation to form larger particles which posse a reasonable settling velocity (Shelef *et al.*, 1984). According to Mohn (1980), addition of flocculants into the settling tank improves the microalgae biomass sedimentation. During this process, microalgae suspension will able to be concentrated to 1.5 % total suspended solid (TSS). Shelef and Sukenik (1984) reported that microalgae harvesting by flocculation with sedimentation is expensive (relatively to high energy requirement) as compared to clarification or sedimentation without addition of flocculants.

Flocculants are category into two groups which are inorganic and polymeric organic flocculants. Inorganic flocculants are polyvalent metal ions such as Al^{3+} and Fe^{3+} which form polyhydroxy complexes at suitable pH and polymeric organic flocculants which are anionic, cationic and non-ionic. Polyelectrolyte is non-ionic, synthetic and natural polymers polymeric flocculants (Shelef *et al.*, 1984). The most effective flocculants are aluminium sulphate ($Al_2(SO_4)_3$) and ferric sulphate ($Fe_2(SO_4)_3$) (Oswald, 1988). Addition of inorganic flocculants in the system will produces large volume of sludge will prevent the growth of microalgae and leads to low productivity yield.

In addition, addition of inorganic flocculants in the harvesting process is unacceptable for the microalgae biomass products usage in human food, aquaculture, agriculture fertilizer or animal feed. Recent studies showed that chitosan is recommended as flocculants due to it is produced from natural resources, which is safer to handle and not impact to the biomass quality (Ahmad *et al*., 2011; Beach *et al*., 2012).

2.5.2 Filtration

During filtration, pressure drop must be applied across the medium in order to force fluid to flow through. Depending upon the required magnitude of pressure drop one or more of the following driving force may be employed which are gravity, vacuum, pressure or centrifugal. A conventional filtration process is most appropriate for harvesting of relatively large (>70 mm) microalgae (Brennan and Owende, 2010; Grima *et al.*, 2003). Conventional filtration system operates under pressure or suctions such as filter press, rotary drum vacuum or pressure filter. On the other hand, the recovery of smaller algae cell (<30 μm), membrane technology can be employed. In generally, membrane technology is cheaper than applying centrifuges and is known to be not energy intensive. It is a very promising technology for harvesting and additionally offers the advantages of almost complete retention of biomass as well as potential disinfection via removal of protozoa and viruses (Bilad *et al.*, 2012). Membrane technology is also favor due to no chemicals such as coagulants or flocculants are required, thus preventing their accumulation in the biomass or the recycled streams that exist in the process (Bilad *et al.*, 2012).

The disadvantages using filtration to clarify algae pond effluent is the filter media size sufficient to retain all the algae tend to clogged rapidly, requiring frequent backwashing. As the result, filter size has to be increased to reduce the clogging but leads to the solid content of the biomass stream decreases. Mechanical process such as moving belt or rotating cylinder principle at the filters can be applied as an expensive solution in order to obtain high concentration cultures (Oswald, 1988).

2.5.3 Flotation

Entrapped gases by dissolved gases compressed in the water and then released can enhance flotation of particles. The success of flotation depends on the stability of the suspended particles. The lower the instability the higher the air particles contact (Shelef *et al*., 1984). The flotation process is faster than sedimentation process. The capital and operating costs of flotation process are low. Compared to sedimentation, the biomass is settled down in the tank; whereas, during flotation process, biomass is collected at the surface of the pond (Bruton *et al*., 2009). The floated biomass have high content of water-free solids as compared to others method.

2.5.4 Centrifugation

Most species of microalgae can be separated from the culture medium by centrifugation (Oswald, 1988). The sedimenting centrifuge is an imperforate bowl which suspension is fed in with high speed of rotation. The recovery of the biomass in sedimenting centrifuge depends on the settling characteristics of the cells, the residence time of the cell slurry in the centrifuge, and the settling depth. Settling depth can be kept small through the design of the centrifuge. The residence time of the slurry in the centrifuge can be controlled by controlling the flow rate (Grima *et al.*, 2003). During the centrifugal process, the feed is subjected to centrifugal forces which make the solids move through the liquid. Centrifugation is normally high in capital and operation costs, but the efficiency is much higher as compared to natural sedimentation (Bruton *et al*., 2009). The common centrifugal devices are: self-cleaning plate centrifuge, nozzle centrifuge, hydro-cyclone and decanter. Operation cost (relatively to the energy consumption) and efficiency of the methods should be evaluated parallels in selecting the device for microalgae harvesting.

2.6 Microalgae Drying

During the algal biomass drying process, slurry is dried from 12 to 15 % moisture content in the drying process. Drying of wet biomass is necessary to increase the viability of biomass storage, downstream processing such as lipid extraction, food processing and etc. Drying process possess major economic concern as it comprise an estimation of 75 % of the overall processing cost during microalgae production (Mohn, 1978). Total capital cost and total energy consumption are varying for each drying method. The specifications of the drying method selection depend on the scale of operation and the uses of the dried product.

Table 2.4 summarizes the advantages and disadvantages of different drying methods. Drying methods may include natural sun drying or using advanced techniques like freeze drying, drum drying, or spray drying. Sun drying is potentially the most economical, but is suited only to places with good weather conditions (Zhang *et al*., 2014). On the other hand, spray drying is suitable to dry algae mass for application as human food (Soeder 1980). Spray drying can cause deterioration of the microalgae pigment due to high temperatures (Brennan and Owende 2010). Freeze drying is widely used in the pharmaceutical and food industries, but is too expensive in the large scale production process low-value products (Grima *et al*. 2003). Finally, in drum drying, the microalgae slurry is spread on the surface of a heated, rotating drum and dries into solid flakes to be scraped off using a stationary blade; the drum is typically heated with steam from the inside.

Table 2.4: Advantages and disadvantages for different drying methods

Alternatives	Advantages	Disadvantages
Sun drying	• Low capital costs as does not require fossil fuel energy (Zhang *et al*. 2014)	• Slow drying process (Guldhe *et al*. 2014) • Require large areas of land size for drying • Weather dependent (Milledge and Heaven 2012) • Degradation of biomass due to long residence time (Milledge and Heaven 2012) • Not suitable for products for human consumption (Shelef *et al*. 1984)
Spray drying	• Established process used in food industry (Soeder 1980) • Preferable method to produce high value microalgal products (Brennan and Owende 2010) • Rapid drying process (Nindo and Tang 2007) • High drying efficiency (Nindo and Tang 2007) • Powdered product requiring no further size reduction (Grima *et al*. 2004) • Rapid process (Grima *et al*. 2004)	• High capital and operational cost (Brennan and Owende 2010) • Significant deterioration of microalgae pigments (Brennan and Owende 2010,) • Low thermal efficiency (Grima *et al*. 2004)
Drum drying	• Effective for drying high-viscosity liquid (Nindo and Tang 2007) • Sterilizing the product (Shelef *et al*. 1984) • Fast and effective (Chen *et al*. 2010)	• High energy efficiency (Tang *et al*. 2003) • Rupture of cellulosic cell
Freeze drying	• Established process used in food industry (Grima *et al*. 2003) • Able to produce high-quality product (Nindo and Tang 2007)	• Very expensive for large scale commercial recovery (Grima *et al*. 2003) • High capital and operating cost (energy) (Grima *et al*. 2004)

2.6.1 Sun Drying

Sun drying is the most traditional methods for drying process. Sun drying is considered as the best to dry wet algal biomass (Zhang *et al*., 2014). It is also as the most economical option to dry algal biomass (Brennan and Owende, 2010). Sun drying can be carried out either by circulation and accumulation of sun heated hot air collector or direct exposure of solar radiation to the slurry. The concentrated algae slurry is exposed to the sun for drying by spreading them on the plastic sheets lined trays. The efficiency of sun drying method is depending on the surface area exposed to the sun, thickness of the layer to be dried as well as the weather of the environment.

2.6.2 Spray Drying

Spray drying involves gas or droplet mixing and drying from liquid droplets whereby the atomized water droplets are sprayed downward into a vertical tower and hot gases pass downward and dried product are collected at the bottom of the tower (Show *et al*., 2003). It is a very fast process and drying can be completed within few seconds. Spray drying was considered as the most suitable method for production of algae for human food (Soeder, 1980). The process efficacy is high, but the high pressure atomization of the water droplets could rupture the algal biomass cells.

2.6.3 Drum Drying

Drum dryer is being widely used for all the liquid food processing process (Tang *et al.*, 2003). A thin layer of liquid or slurry material is fed onto the internally steam-heated outer surface of rotating drums and water is evaporated. The time of exposure to high temperature surface is short thus reducing the risk of cell rupture or damaging of dried biomass. The method is not suitable for the product which is unable to form thin film. This method has low productivity rate as compared to spray drying method. The energy requirement for the process is also high thus gives higher operating cost.

2.6.4 Freeze Drying

The fundamental principle of freeze-drying is sublimation process. In generally, freeze drying process involves three major steps: freezing, ice sublimation, removal of unfrozen water and finally formation of dried cake (Tang.*et al*., 2004) During freeze drying, substances are not exposed to high temperatures; thus the freeze-dried products preserve their initial nutritious characteristics, shape and texture, however it is significantly more expensive (Shelef and Sukenik, 1984). Grima *et al*. (2003) reported that the application of freeze drying in drying algal biomass production is not economically. It is time consuming and energy intensive process (Tang.*et al*., 2004)

2.7 Analytic Hierarchy Process (AHP)

Analytic hierarchy process (AHP) was originally introduced by Saaty (1979) and has been widely applied in various industries (Vaidya and Kumar, 2006). It is especially advantageous for decisions that require integration of quantitative data with less tangible, qualitative consideration such as value and preferences, especially in situations where there are important qualitative aspects that require consideration in conjunction with varying measureable quantitative factors (Noh and Lee, 2003). The AHP method requires the pairwise comparison matrix, **z** (see Equation 2.2) of size *n* to be populated with fuzzy judgments which approximate the solution ratios ($\frac{w_i}{w_j}$), i.e., the intensity of importance or preference of one element over the other element within the same level with respect to a common element in the upper level. The ratio $\frac{w_i}{w_j}$ indicates the relative importance of criteria in the *i*th row over the criteria in the *j*th with respect to the goal. These weights (w_i) are typically computed with eigenvector method using the Saaty's fundamental 9-point scale (Saaty, 1979) (Table 2.5). Note that the weighing of criteria / sub criteria will depend on the value judgment of experts whose trade-off among these criteria / sub criteria is made explicit in the prioritization of alternatives.

$$\mathbf{z} = \begin{bmatrix} \frac{\mathbf{w_1}}{\mathbf{w_1}} & \frac{\mathbf{w_1}}{\mathbf{w_2}} & \cdots & \frac{\mathbf{w_1}}{\mathbf{w_n}} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{\mathbf{w_i}}{\mathbf{w_1}} & \frac{\mathbf{w_i}}{\mathbf{w_2}} & \cdots & \frac{\mathbf{w_i}}{\mathbf{w_n}} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{\mathbf{w_n}}{\mathbf{w_1}} & \frac{\mathbf{w_n}}{\mathbf{w_2}} & \cdots & \frac{\mathbf{w_n}}{\mathbf{w_n}} \end{bmatrix} \qquad \textbf{Equation 2.2}$$

Table 2.5: Fundamental scale of pairwise comparison (Saaty, 1979)

Intensity of importance on an absolute scale	Definition	Explanation
1	Equal importance	Two activities give equal contribution to the objective
3	Moderate importance of one over another	Experience and judgment strongly incline one activity over another
5	Strong importance	Experience and judgment strongly incline one activity over another
7	Very strong importance	An activity is strongly inclined and its dominance showed in practice
9	Extreme importance	The evidence inclining one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between the two adjacent judgments	When compromise is required
Reciprocals	If activity *i* has one of the above numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*	

The priorities of the alternatives are computed by aggregating the weights throughout the hierarchy. Consistency ratio (CR) (Equation 2.3) is calculated to determine the consistency of the judgments made during the pairwise comparison.

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}}$$ **Equation 2.3**

whereby CI is consistency index and RI is random index.

Given as CI can be determined as Eq. 2.4

$$CI = \frac{\lambda_{\max} - n}{n-1} \qquad \textbf{Equation 2.4}$$

Where $\lambda_{\max}$ is the maximum eigenvalue of the matrix; n is the size of the matrix.

RI is random index, fixed value based on Saaty (2003) based on Table 2.6. Saaty computed the consistency index through a simulation of 50,000 times of *n*-by-*n* reciprocal matrix **z**, with random value from the 17 values {1/9, 1/8, . . . , 1, 2, . . . , 8, 9}. Then, each entries of **z** below the diagonal by taking reciprocals were filled up and to compute the CI. The average value is called as RI. The higher the size of the matrix, the CR value will tends to be smaller. CR that is lesser or equal to 0.10 is considered consistent of their input data and acceptable of the AHP value. However, if CR is more than that acceptable value, inconsistency of the judgments within the matrix has occurred and the evaluation process should be reviewed.

Table 2.6: Random Index (Saaty, 2003)

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

2.8 Fuzzy Analytic Hierarchy Process (FAHP)

Fuzzy analytic hierarchy process (FAHP) is to incorporate in the decision modelling of the “fuzziness” or the uncertainties arising from vagueness involved during the value judgment elicitation. It is often unrealistic and difficult to give precise numerical values in pairwise comparisons, due to complexity and uncertainty involved in the prioritization process (Promentilla *et al*. 2008). CR Equation 2.3 is determined based on the random value and consistency ratio, which solely dependent to the size of matrix and its maximum eigenvalue. Thus, fuzzy set theory is used to deal with the uncertainty and vagueness, based on its capability to represent the uncertainty in the data (Zadeh, 1965). Application of fuzzy sets in the context of optimization of processing pathways has been reported extensively in literature (e.g., Liew *et al*. 2013). However, instead of using a single crisp value to approximate the solution ratio $\frac{w_i}{w_j}$, a fuzzy scale is used to represent the value judgments $\hat{\mathbf{z}}_{ji}$ as triangular fuzzy numbers $< \hat{U}_{i,j}, \hat{M}_{i,j}, \hat{L}_{i,j} >$ that will populate the pairwise comparison matrix as shown in Equation 2.5.

$$\hat{\mathbf{z}} = \begin{bmatrix} (1,1,1) & \hat{z}_{12} & \cdots & \hat{z}_{1n} \\ \hat{z}_{21} & (1,1,1) & \dots & \hat{z}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \hat{z}_{n1} & \hat{z}_{n2} & \cdots & (1,1,1) \end{bmatrix} \text{ where } \hat{\mathbf{z}}_{ji} = \frac{1}{\hat{z}_{ij}} = \langle \frac{1}{\hat{U}_{ij}}, \frac{1}{\hat{M}_{ij}}, \frac{1}{\hat{L}_{ij}} \rangle$$ **Equation 2.5**

For example, if $\hat{\mathbf{z}}_{ji}$ is perceived to be more or less equal, it is represented by the triangular fuzzy number $\left\langle \frac{1}{1+\delta}, 1, 1+\delta \right\rangle$ whereas if one element is perceived to be more important or preferred over the other, $\hat{\mathbf{z}}_{ji}$ is represented in the following fuzzy scale as summarized in Table 2.7.

Table 2.7: Summary of fuzzy scale

Fuzzy number, $\hat{\boldsymbol{z}}_{ji}$	**Linguistic scale for comparison of Criteria**	**Linguistic scale for comparison of Alternatives**
$\left\langle \frac{1}{1+\delta}, 1, 1+\delta \right\rangle$	More or less equally important	More or less equally preferred
$\langle \max(1, 3-\delta), 3, \min(9, 3+\delta) \rangle$	Moderately more important	Moderately preferred
$\langle \max(1, 5-\delta), 5, \min(9, 5+\delta) \rangle$	Strongly more important	Strongly preferred
$\langle \max(1, 7-\delta), 7, \min(9, 7+\delta) \rangle$	Very Strongly more important	Very strongly preferred
$\langle \max(1, 9-\delta), 9, \min(9, 9+\delta) \rangle$	Extremely more important	Extremely preferred

An $\hat{\boldsymbol{z}}_{ji}$ representing a judgment of “moderately more important” could be represented by a fuzzy number <1, 3, 6> if δ is set to 3. Note that δ is the degree of confidence of the decision maker wherein the higher the value of δ shows the lower degree of confidence. Zhu *et al*. (1999) stated that as δ increases, the degree of fuzziness increases and the degree of confidence decreases.

Figure 2.5 illustrates the graphical representation of the fuzzy scale as triangular fuzzy number (TFN) used in this case study. These are based on the variation of widths to reflect the ambiguity of judgment and confidence level as reported in the literature. For example, Geldermann *et al*. (2000) used zero and one as weak and strict preference in measuring the fuzzy outranking relation; meanwhile Tan *et al*. (2014) suggested FAHP with a linguistic scale for low, moderate and high degrees of confidence to reflect the spread of the distributions of fuzzy numbers. The fuzzy numbers used in Figure 4 are modified from the scale of Tan *et al*. (2014), using a value of one, two and three for δ to represent the high, moderate and low degree of confidence in the value judgment, respectively.

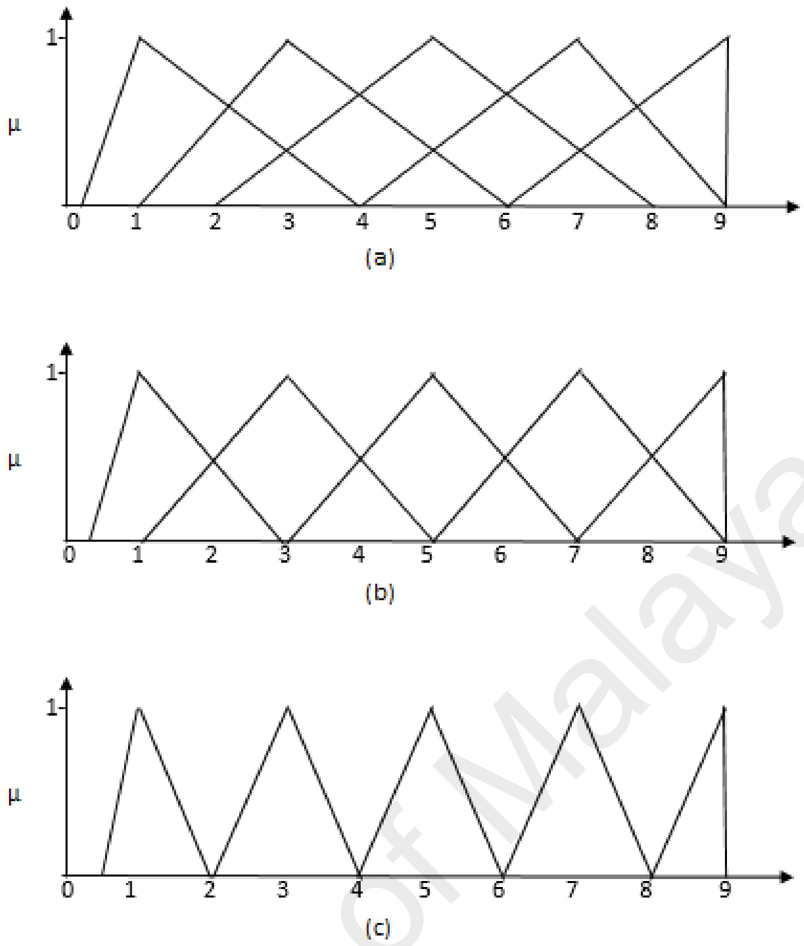

Figure 2.5: Fuzzy AHP linguistic scale for (a) low (fuzzy scale at δ = 3), (b) moderate (fuzzy scale at δ = 2) and (c) high (fuzzy scale δ at = 1) degrees of confidence

The weights that approximate the solution ratio in the pairwise comparison matrix are computed using the following nonlinear programming (NLP) formulation (Promentilla *et al*. 2014) as shown in Equation 2.6 to 2.11 to determine the fuzziness of the system

$$\max \lambda; \qquad \textbf{Equation 2.6}$$

subject to:

$$\lambda(M_{ij} - L_{ij})(w_j) - w_i + w_j L_{ij} \leq 0 \qquad \textbf{Equation 2.7}$$

$$\boldsymbol{\lambda(M_{ji} - L_{ji})(w_i) - w_j + w_i L_{ji} \leq 0\ ;} \qquad \textbf{Equation 2.8}$$

$$\boldsymbol{\lambda(U_{ij} - M_{ij})(w_j) + w_i - w_j U_{ij} \leq 0\ ;} \qquad \textbf{Equation 2.9}$$

$$\boldsymbol{\lambda(U_{ji} - M_{ji})(w_i) + w_j - w_i U_{ji} \leq 0\ ;} \qquad \textbf{Equation 2.10}$$

$$\boldsymbol{\sum_{k=1}^{n} w_k = 1\ ;\ w_k > 0} \qquad \textbf{Equation 2.11}$$

This NLP model computes the optimal priority vector (**w**) by maximizing lambda (λ), i.e., a consistency index which measures the degree of satisfaction of all computed pairwise comparison ratios that satisfy within the bounds of the initial fuzzy judgments. Lambda (λ) ranges from zero to one. A value of zero denotes that the fuzzy judgments are satisfied at their boundaries and a value of 1 denotes perfect consistency (Tan *et al.* 2014). The sum of the weights of all considered criteria, $\mathbf{w}_k$ must be equal to one.

2.9 Life Cycle Assessment

The increase awareness of environment impacts associated with product, process or activity has increase the interest to develop methods to understand and address the impact. Life cycle assessment (LCA) was developed as the quantitative and systematic methodology to measure environmental impact. This method is then been undergoes reviewed by the Society of Environmental Toxicology and Chemistry (SETAC) and later by International Standard Organization (ISO 14040) (Guinee *et al.*, 2002). Table 2.8 shows the current development of ISO standards for LCA. The ISO 14000 series provide a comprehensive guidelines for the management system of LCA through its principle, requirements, example, and documentation. LCA is aims to evaluate the environmental burdens associated with the entire life cycle of a product, process or activity (SETAC, 1991), environmental aspects and potential environmental impacts throughout a product's life cycle (i.e. cradle-to-grave) from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (ISO 14040, 2006). LCA provides an effective linkage between economic performance and environmental impact in process and product design or selection stage (Azapagic and Clift, 1999b), it is also important to identify the significant environmental aspects related to a product system with the relatively period of time (Hur *et al.*, 2005). The outcome of LCA is able to identify the opportunities to improve the environmental performance at any point of a product, process or activity (Finnveden *et al.*, 2009). LCA is also essential as the results able to provide information to decision-makers during strategic planning or initial stage of the product development (Azapagic, 1999).

Table 2.8: ISO standards for LCA

ISO Standard	**Content**
ISO 14040	Principle and framework
ISO 14044	Requirements and guideline
ISO 14047	Examples of application of ISO 14042
ISO 14048	Data documentation format

The ISO 14040 (2006) describes the principles and framework of LCA including:

i. Goal and scope definition
ii. Life cycle inventory (LCI)
iii. Life cycle impact assessment (LCIA)
iv. Interpretation

Figure 2.6 shows the general overview of LCA framework based on ISO 14040. It illustrates the inter-relationship of each step in the framework. These phases are often interdependent in the result but will affect to the next phase and its completion.

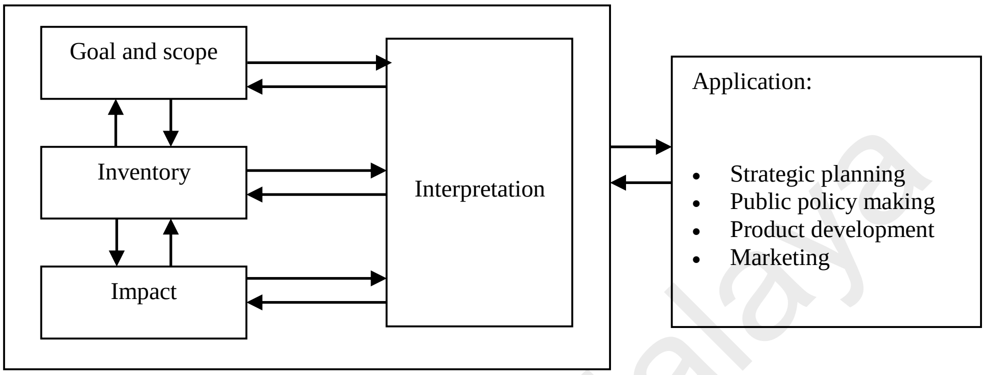

Figure 2.6: Life cycle assessment phase (Guinee *et al.*, 2002)

ISO 14044 (2006) and Guinee *et al.* (2002) in the Handbook on LCA provide detail guidelines to carry out LCA for a specific product. The details of the steps for conducting LCA are based on the mentioned guidelines. The goal and scope definition is step which states and justifies the objective of the LCA study and intended use of the results (Rebitzera *et al*., 2004). Meanwhile, the scope establishes the coverage of the product, process or activity for the LCA study. It includes the identification of system boundaries, technology or strategy choices, and environmental flows and impacts of interest. The function, functional unit, alternative technology or strategies, and reference flows are desired information at the first step. Life cycle inventory (LCI) involves acquiring all relevant data on the unit processes and quantifying all flows connected to the unit processes. Data inventory can be from different resources, such as scientific publication, material and energy balance calculation, on site direct measurement, economic input output table or database in commercial LCA software. In the inventory table, negative sign denotes as inflows and outflows are denoted with and positive values. These data are then put into the mathematical model to calculate the total environmental loading at the specify function unit. The detail of the LCA computation mathematical model are based on matrix equations developed by Heijung and Suh (2002).

LCA mathematical equation is linear equation, which can be presented in the form of vector for a single unit process. In the case of there are involve with large system comprising many different unit processes, the process matrix ($\mathbf{P}_{ij}$) can be formulated, where *i* denotes the number of row and *j* for the number of column. The data collected during the LCI steps need to be distinguished into two parts, one representing the flow within the technology system (technology flows, **A**) and the other representing the flow which related to flow input from the environment (environmental interventions, **B**) and going into the environment (environmental flows, **g**). Then, the functional unit vector, **y** is specified in vector format which able to represents the set of economic flow that corresponding reference functional flow. The final part of the LCI is the environmental flows (**g**) associated with the reference flow (**f**). Equation 2.12 to 2.14 show the basic model for LCI (Heijung and Suh, 2002).

$$\mathbf{As} = \mathbf{f} \qquad \textbf{Equation 2.12}$$

Given that **A** is technology matrix; **s** is the scaling factor and **f** is the functional unit vector. Scaling vector, **s** can be solved matrix multiplication of inverse matrix of **A** ($\mathbf{A}^{-1}$) with **f**.

$$\mathbf{s} = \mathbf{A}^{-1}\mathbf{f} \qquad \textbf{Equation 2.13}$$

Matrix **B** are extensions of the same unit processes in **A** whereby focusing on the environmental flows through the system boundaries. Scaling factor ***s*** is applied to **B** in order to yield **g**, which gives the total quantities of natural resource used and emissions generated by the system.

$$\mathbf{g} = \mathbf{Bs}$$ **Equation 2.14**

The third step in the LCA study is impact assessment. In the impact assessment, the results of the inventory analysis are classified to the relevant impact categories. Example, global warming, toxicity or depletion of abiotic resources are known as *classification*. *Characterization* is calculation of the magnitudes for each impact. The selection of the impact categories is relevant to the objective of the LCA study. The final step of LCA is interpretation. The outcome of the study is evaluated to see if the goals are achieved. Sensitivity analysis is necessary to assess the robustness of the results.

2.10 Life Cycle Assessment of Microalgae Production

Several studies of life cycle assessment (LCA) for the different process paths for biofuel production from microalgae have been conducted in the past years. Table 2.9 shows the summary of the LCA associated with microalgae biofuel production. In many of these studies, microalgae biofuel production LCAs are compiled on each stage by specific technology including microalgae cultivation (i.e.: open pond), harvesting, dewatering, and oil extraction. It also shows that algal biofuels have indicated potential environmental benefits over petroleum-derived diesel under certain circumstances. LCA of microalgae cultivation in open pond system was carried out to compare with the conventional fuels (Lardon *et al*., 2009 and Liu and Ma, 2009). The results show better insight of advantages and drawbacks of algal biodiesel. Similar study had been done by Campbell *et al*. and Collet *et al*. (2011) where LCA for biodiesel from microalgae was compared to other biodiesel feedstock. Microalgae cultivated in open pond system shows that it is more favorable in terms of greenhouse gases emissions compared to the others. Jorquera *et al*., (2010) compared the energy footprint of microalgae production in two different microalgae cultivation methods for open pond system and closed system. For the closed system, different photobioreactor (PBR) cultivation methods were studied. They concluded that open pond showed the highest net energy ratio which may be considered economically feasible for mass cultivation. Razon and Tan (2011) and Sevigne Itoiz *et al*., (2012) conducted the studies on the environmental impacts using different cultivation process paths.

Table 2.9: Summary of different life cycle impact assessment studies for cultivation and harvesting process in microalgae production

Author	**Cultivation Method**	**Summary**
Lardon *et al*., 2009	Open pond	LCA was conducted for two different culture conditions and harvesting methods. Microalgae show as potential energy sources.
Liu and Ma, 2009	Open pond	LCA of microalgae-based fuel methanol was conducted to evaluate its energy efficiency and environmental emission compared with gasoline fuel.
Clarens *et al*., 2010	Open pond	Comparative studies of LCA for switchgrass, canola, corn farming and microalgae were conducted. Conventional crops show lower environmental impacts than algae. However algae performed favorably in total land use.
Jorquera *et al*., 2010	Tubular PBR, Flat plate PBR and open pond	LCA of biomass production from *Nanochrolopsis sp* using three different cultivation methods were conducted. Flat-plate PBR and open pond cultivation show better net energy ratio compared with tubular PBR.
Sander and Murthy, 2010	Open pond	Energy analysis of microalgae dewatering process was conducted and showed high amount of energy required.

Table 2.9: (continue)

Author	**Cultivation Method**	**Summary**
Campbell, 2011	Open pond	LCA study was conducted to compare biodiesel production from algae with canola and ultra-low sulfur diesel. Algae show favorable results in greenhouse gases emissions compared to the others.
Collet *et al*., 2011	Open pond	LCA of biogas production from the microalgae is performed and compared to algal biodiesel and to first generation biodiesels.
Murphy and Allen, 2011	Open pond	A preliminary study of energy and water consumption was studied and provided input to the energy and water management of the overall processes in microalgae production.
Razon and Tan, 2011	Integrated PBR & open raceway pond	Energy deficiency was observed during post-harvest dewatering and oil recovery operation of microalgae production.
Yang *et al*., 2011	Open pond	Life-cycle water and nutrients usage of microalgae-based biodiesel production for the 11 algae strains were conducted.
Beach *et al*., 2012	Not specify	LCA of three different flocculants used in harvesting process were conducted.
Frank *et al*., 2013	Open pond	LCA for the biogas production from microalgae using hydrothermal liquefaction and lipid extraction were evaluated.
Liao *et al*., 2012	Open pond	LCA of microalgae cultivation, harvesting, drying, oil extraction, anaerobic digestion, oil transportation, esterification, biodiesel transportation and biodiesel combustion were done.
Sevigne Itoiz *et al*., 2012	Bubble column PBR	LCA to compare the indoor and outdoor growth of algae in bubble column PBR. Outdoor production system shows better energy consumption and life cycle impact to the environment.
Vasudevan *et al*., 2014	Open pond	LCA for various technology options affected GHG and freshwater consumption for microalgae biofuel production.
Adesanya *et al*., 2014	Hybrid tubular PBR and open pond	LCA from the hybrid system of microalgae cultivation to biodiesel production. Environmental impacts were compared to fossil derived diesel.
Handler *et al*., 2014	Open pond	LCA for cultivation techniques (raceway vs. effluent cultivation) and fuel conversion pathways (pyrolysis vs. oil extraction and hydrotreatment) was conducted.
Quinn *et al*., 2015	Open pond, bioreactor	LCA for four microalgae-to-biofuel production scenarios using process modeling on: baseline scenario, improved microalgae productivity, supercritical CO_2 extraction, and no nutrient recycle.
Soh *et al*., 2014	Open pond	LCA to evaluate varying species/growth conditions (freshwater and marine)

2.11 Life Cycle Optimization

Numerous papers dealing with the optimization and environmental assessment of biomass energy supply chains have been published. A systematic decision making tool based on a mixed integer linear model for the design of sugarcane (Mele *et al*., 2009) and urban energy system (Gerber *et al*., 2011), have been presented. The system integrates environmental ecology, process design, LCA and multi-objective optimization (MOO) (Azapagic, 1999). Meanwhile, Akgul *et al*., (2012) developed a multi-objective modelling framework for the optimization of biofuel supply chains. Čuček *et al*., (2014) used a simplified and more practical version of an objective dimensionality reduction method within MOO to measure sustainability. The typical approach of using various environmental footprints is necessary to aid in general decision-making (De Benedetto and Klemeš, 2009) and assessment of process options (De Benedetto and Klemeš, 2010). A comprehensive review of various footprints was given in Čuček *et al*., (2012), while more updates are given in a recent book chapter (Čuček *et al*., 2015a). Large number of potentially conflicting environmental concern may be problematic in decision-making. This has been shown that representative footprints can be used as proxy for a larger set of footprints due to correlations (Čuček *et al*., 2013). For example, in some cases, carbon footprint can be used as a proxy for energy footprint due to strong correlation between these two metrics. Such reduced sets of footprints can then be combined with conventional profitability measures for comprehensive decision-making (Čuček *et al*., 2014). Čuček *et al*., (2015b) discussed the need to assess other footprints that are important for ecosystem health in regards to water, health, food, and species security (i.e.: nitrogen, phosphorus, biodiversity) and land footprints. These previous works have used such strategies in the context of MOO models; nevertheless, a similar approach can be applied to multi-criteria decision making (MCDM) problems with predefined sets of discrete alternatives.

Ubando *et al*., (2016) developed a decision model via Monte Carlo simulation to show which cultivation system was preferred for conservative (risk-averse) and optimistic (risk-inclined) scenarios. Tan *et al*., (2016) presented the application of fuzzy analytic hierarchy process (FAHP) approach, where the pairwise comparison of the multiple criteria (such as technology capability, cost and environmental impacts) and alternatives were done to prioritize the best method in harvesting and drying of microalgae.

Life cycle optimization (LCO) methodology is based on the combination of LCA with mathematical programming, which was first proposed by Azapagic and Clift (1998) and applied to industrial boron production (Azapagic and Clift 1999a). LCO is comprised of three main steps, which are: performing the LCA study, formulating the MOO problem in the LCA context; and finally performing the MOO which selects the best compromise solution (Azapagic, 1999). The approach based on the matrix formalism of Heijungs and Suh (2002) was later extended into a LCA optimization model by Tan *et al*., (2008) using fuzzy linear programming. Many other studies have also been done by incorporating MOO approach to identify the optimal point with regards to the different objectives, such as total environmental footprints (Čuček *et al*., 2014) as well as actuarial risk estimates of fatalities (Ramadhan *et al*., 2014). Wang and Work (2014) also proposed a robust formulation for LCO. However, one of the challenges in MOO is in identifying the appropriate aggregation method to integrate the objectives into a single performance index which is typically done by assigning importance weights to the different objectives.

Systematic assessment of environmental impacts is needed to ensure sustainable large-scale production of algal biomass. Tan *et al*., (2017) presented a case study to illustrate the application of integrating AHP in LCO context. In this study, the different environmental footprints preference were taken into consideration of the decision making process.

CHAPTER 3: RESEARCH METHODOLOGY

3.1 Introduction

This chapter presents the development of the integrated fuzzy analytic hierarchy approach and life cycle optimization (FAHP-LCO) model framework. The methodology framework is depicted in Figure 3.1. The framework is extended to determine the best cultivation, harvesting and drying option with the optimum target value of preference environmental footprint. A graphical representation of the presented methodology is shown in Figure 3.2. The integrated FAHP-LCO model is formulated as a multiple objective linear program (MOLP), which is able to determine the optimal solution. The methodological framework is shown in Figure 3.1. The framework enables the determination of best cultivation option along with the optimum target value of preference environmental footprints. Identification of the system design goal (the environmental preferences in this case) is essential as it is required in the building of FAHP hierarchy. LCA is integrated into FAHP to assess different alternative technologies. Then, a multiple objective linear program (MOLP) model for the system is developed to minimize the overall environmental impact. Finally, the best technology option can be determined.

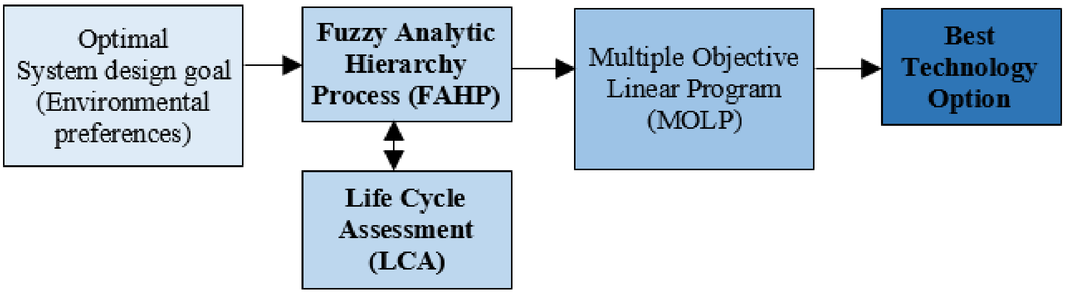

Figure 3.1: Methodology framework of the integrated FAHP-LCO model

A graphical representation of the sequential methodology is shown in Figure 3.2. Using the LCA framework, the boundaries of the system are defined by identifying the functional unit, the processes and technology alternatives, material and energy streams to be included in the analysis, and the environmental footprints to be considered (Step 1). The relative importance of the environmental footprints are then derived using AHP (Step 2). The preference weights are needed to aggregate the footprints into a single environmental score. LCO is then implemented to identify the optimal process design for the system based on the objective function (Step 4), by taking into consideration of the environmental footprint limits or the worst environmental performance in each environmental footprint (Step 3). The integrated FAHP-LCO model is formulated as a MOLP, which is used to determine the optimal solution. The weighted sum form of the composite objective function ensures that the solution is Pareto optimal (Clark and Westerberg, 1983).

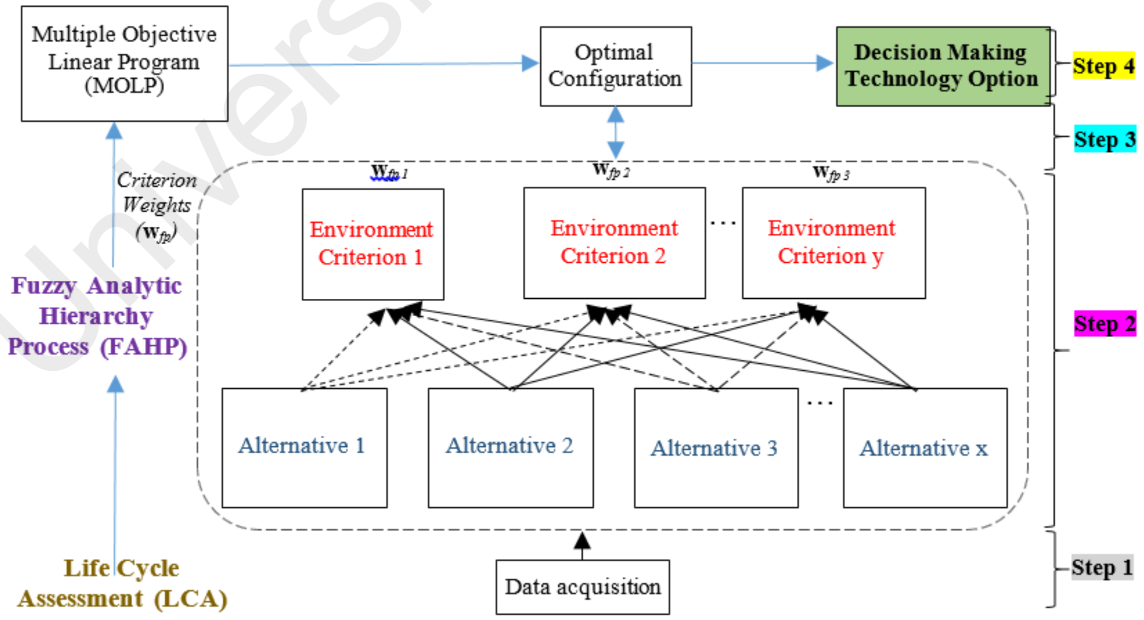

Figure 3.2: Decision modeling framework for identifying the minimum footprints of cultivation options

In summary, the FAHP-LCO is developed in step-by-step procedure as follows:

i. LCA study;
ii. Construct the AHP decision structure and pairwise comparisons;
iii. Perform FAHP;
iv. Conduct LCO and then the integrated FAHP-LCO
v. Choose the best compromise solution

Each of the steps will be discussed briefly in this chapter. The details for the application of the model shown in Figures 3.1 and 3.2 is presented in Chapter 4 and Chapter 5 by the illustration of cultivation system, harvesting and drying system selection. In this project, the model template is built using Microsoft Excel spreadsheet file, and solved using the standard Solver add-in in an Intel® iCoreTM i5-3317U CPU 1.7 Ghz, with 4 GB memory. For the case study described in the next section, the computational time is negligible.

3.2 Life Cycle Assessment

Life cycle assessment (LCA) is used as the quantitative tools to measure the environmental impact for the microalgae production. It is a systematic approach based ISO 14040 (2006). There are four main components in LCA which been discussed based on its background theory the Chapter 2.9. The application of the LCA in this research is mainly to support the illustration and further development of the integrated FAHP-LCO model.

i. Scope and goal definition

It specifies the objective of the assessment as well as provides a description of the product system in terms of the system boundaries and a functional unit. The system boundary for this research is covered from the microalgae cultivation, harvesting and drying processes, with the functional unit target as 1 ton of dried biomass produced at drying process unit. However, the thorough evaluating, process boundaries for the resources fed into the system are also being assessed.

ii. Life cycle inventory analysis

All environmentally relevant material and energy flows of the system are quantification (Jolliet *et al*., 2004). It is understand that the commercial software of LCA such as SimaPro, GaBi are widely been used as assessment tools to collect, analyze and evaluate environment impacts. However, in this research the manual Microsoft Excel spreadsheet are used to compute the LCA. The data are obtained based on scientific publication, online database (EIOLCA.net) and material energy balance calculation of the input-output of the boundaries.

Technologies for production need to be assessed based on environmental impacts such as energy, water and carbon footprints (De Benedetto and Klemes, 2009; Ho, 2008). Based on this, energy, water and carbon footprint are decided as the desired environmental footprints that take into consideration for the microalgae production in this research. Čuček *et al*., (2012) defines various environment footprints as well as diverse tools for footprint evaluation. Energy footprint takes into account energy inputs, such as process energy and electricity, which are obtained from non-renewable resources (Schindler, 2015). Water footprint (WF), which is an indicator of water usage, measures the water used directly and indirectly by consumers or producers at different stages of the supply chain (Hoekstra and Chapagain, 2007; Lee, 2015). It focuses on the amount of water consumed by the system life cycle. Carbon footprint calculates the amount of net greenhouse gases released from a system directly or indirectly. In this work, total CO_2 emissions are used as an approximation of the total carbon footprint. This assumption only considers CO_2 emissions and does not include other greenhouse gases (Lee, 2015).

iii. Life cycle impact assessment

Analysis and compares the environmental impact associated with material and energy of the system. It is able to support the decisions with respect to the product design and development solution.

iv. Interpretation

At this stage, it also shows how significant the environmental impact and contribute to the overall process design compared to each other. This is important in decision making.

The process data can be used to generate the technology matrix **A,** which is an n x m matrix to represent n material or energy flows and m technology matrix processes. It consists of process inputs and outputs of material and energy. The convention used denotes output streams with positive values, and input streams with negative values (Heijungs and Suh, 2002). The intervention matrix **B** is a k x m matrix representing k environmental flows associated to the m processes. The flows represent the interaction of the processes with the environment (i.e. primary energy and water resource consumption and CO_2 emissions). The m technology matrix is arranged from its left to the right, starting of resources by the facility to the main process of the system. The balance equations (Equations 2.12 and 2.14) are as follows:

$$\mathbf{As} = \mathbf{f} \qquad \textbf{Equation 2.12}$$

$$\mathbf{Bs} = \mathbf{g} \qquad \textbf{Equation 2.14}$$

Where the net output vector **f** indicates the amount of material or energy flow that is needed or that exits the system as product, in the context of LCA, this is typically the functional unit. Meanwhile, **s** is the gross output or scaling vector. Equation 2.12 indicates the overall material and energy balance of the system. The processes can be scaled up or down by the scaling vector, **s,** to meet the desired net output vector. When **A** has more columns than rows, Equation 2.12 has excess degrees of freedom, which allows for optimization via selection from alternative technologies or processes. Meanwhile, Equation 2.14 exhibits the interaction of the processes with the environment, where **B** is the intervention matrix and **g** is the environmental footprint matrix. Within this framework, a single process can be represented as vectors **A**(*j*) and **B**(*j*). Figure 3.3 shows an example for the microalgae cultivation process using open pond. Note that zeroes indicate non-existent streams in the respective process. Vector **B**(7) contains only four rows to represent the four process environment flows, i.e. (1) energy, (2) carbon, (3) direct water footprint; (4) indirect water footprint. In this case, the zero values in vector **B**(7) indicate that there are no energy and carbon flows associated with the process and that an input of 80 tons of direct water is needed. Negative and positive values in each process column vector denote inputs and outputs, respectively; further details of these conventions are described by Heijungs and Suh (2002).

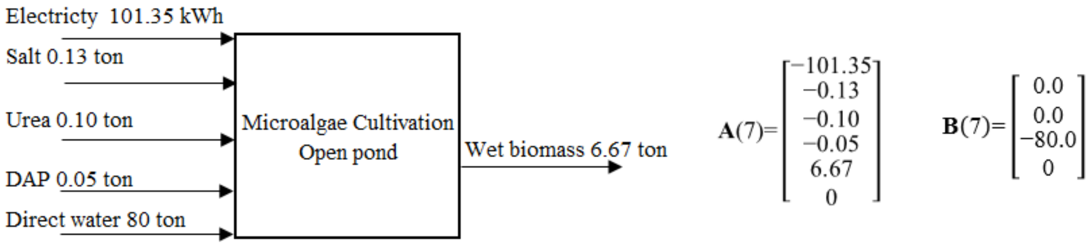

Figure 3.3: Example of column vector representation of a process

3.3 Analytic Hierarchy Process

The second step involves weighting of priorities for the environmental footprint. AHP is the versatile multi-criterion decision making methodology which decomposes the problem structure into a hierarchical model and derives priorities from pairwise comparisons. These priorities are ratio scales derived from value judgments in a pairwise comparison matrix, **z**, as described in Equation 2.2 (Saaty 1990). AHP network is essential as it displays the relationship between the goal, the evaluative criteria and alternatives. The main goal is stated at the first level of the hierarchy. The second level represents the criteria in the hierarchy structure. The criteria are defined based on the needs of the study. Pairwise comparison can be performed between the goal, the evaluative criteria and alternatives within the AHP hierarchy. Equation 2.2 is shows the pairwise comparison in matrix. Table 2.5 is used to provide the AHP scale for the pairwise comparison. Pairwise comparisons based on the expert's judgment are done to derive the relative importance of criteria, sub-criteria and the relative preference of alternatives. Chapter 2 (Section 2.7) brief based on the background theory of AHP based on Saaty (1979). Questionnaires are constructed based on this pairwise comparison technique. Chapter 4 (Section 4.3) and Chapter 5 (Section 5.3) to illustrate the details of the construction of AHP network for cultivation, harvesting and drying process, respectively.

$$\mathbf{z} = \begin{bmatrix} \frac{w_1}{w_1} & \frac{w_1}{w_2} & \cdots & \frac{w_1}{w_n} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{w_i}{w_1} & \frac{w_i}{w_2} & \cdots & \frac{w_i}{w_n} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{w_n}{w_1} & \frac{w_n}{w_2} & \cdots & \frac{w_n}{w_n} \end{bmatrix} \qquad \textbf{Equation 2.2}$$

3.4 Fuzzy Analytic Hierarchy Process

Fuzzy Analytic Hierarchy Process (FAHP) is to incorporate in the decision modeling the “fuzziness” or the uncertainties arising from vagueness involved during the value judgment elicitation. Fuzzy scale is used to represent the value judgments $\hat{a}_{i,j}$ as triangular fuzzy numbers $<\hat{U}_{i,j}, \hat{M}_{i,j}, \hat{L}_{i,j}>$ based Equation. 2.5. Example, $\hat{a}_{i,j}$ representing a judgment of “moderately more important” could be represented by a fuzzy number <1, 3, 6> if δ is set to 3. Note that δ is the degree of confidence of the decision maker wherein the higher value suggests lower degree of confidence. Table 2.7 is the reference to set the fuzzy scale in Chapter 4 (Section 4.4) and Chapter 5 (Section 5.5). A value of 0 denotes that the fuzzy judgments are satisfied at their boundaries and a value of 1 denotes perfect consistency (Tan *et al*. 2014). The sum of the weights of all considered criteria, $\mathbf{w}_k$ must be equal to 1. The weights that approximate the solution ratio in the pairwise comparison matrix are computed using the following nonlinear programming (NLP) formulation (Promentilla *et al*. 2014) as shown in Equations 2.6 to 2.11 to determine the fuzziness of the system.

3.5 Life Cycle Optimization

The third step is to normalize the environmental footprints from the different technology options relative to the performance of the worst alternative matrix, **Q**. This step ensures that all the values are properly scaled, and lie in the interval [0, 1]. The fourth step is performing the LCO by integrating the priority weights with the optimization model, via the objective function, **f(x)**. Equation 3.1 represents the overall result upon performing steps outlined above.

$$\text{minimize } \mathbf{f(x)} = \vec{\mathbf{w}}_{\mathrm{fp}}(\mathbf{Q})^{-1}\mathbf{g} \qquad \textbf{Equation 3.1}$$

The integrated FAHP-LCO model is formulated as a multiple objective linear program (MOLP), which is able to determine the optimal solution. Multiple objective optimization models can be integrated with AHP to determine priorities (Olson 1988). Some hybrid approaches are described in a review by Ho (2008). In such approaches, criterion weights of the environment footprint, $\vec{\mathbf{w}}_{\mathrm{fp}}$, are measured using the FAHP technique. In order to satisfy this optimization model, the limitations of the linearity assumption are the following: 1) the input and output data are constant, 2) the relationship between objective function and constraints are linear, and 3) the value of variables must be non-negative. Note that the resulting model is a linear program, for which a global optimum can be readily determined without significant computational issues.

3.6 Sensitivity Analysis

Sensitivity analysis is conducted to examine how variations in criteria weights influence the selection of option by changing the respective footprint weights. This is done by parametrically adjusting the weight of one footprint, while keeping constant the relative proportions of all the other criteria.

3.7 Summary

By performing the systematic framework in analyzing the cultivation, harvesting and drying system of microalgae production. The application of the integrated FAHP-LCO framework in microalgae enables the optimum alternative selection. This research methodology is to serve as important benchmarks for overall improvement of industry in the decision analysis.

CHAPTER 4: AN INTEGRATED FUZZY ANALYTIC HIERARCHY PROCESS AND LIFE CYCLE OPTIMIZATION MODEL FOR CULTIVATION OF MICROALGAE

4.1 Introduction

This chapter presents the results and discussion of an integrated fuzzy analytic hierarchy process (FAHP) and life cycle optimization (LCO) model for microalgae cultivation system. The results of the research are expected to be presented in four main sections: Section 4.2 presents the life cycle assessment (LCA) for cultivation of microalgae for different system; Section 4.3 shows AHP network for the cultivation processes, followed by Section 4.4 which performs FAHP to obtain the priority ranking of different cultivation system. Lastly, Section 4.6 is to integrate both FAHP and LCO results in order to obtain optimum selection for the system. The sensitivity analysis is presented in this section to show the robustness of the model to the changes of the preferences.

4.2 Life Cycle Assessment (LCA) for Cultivation System

4.2.1 Goal and Scope

LCA is typically conducted either to compare technology alternatives and identify the best option or to identify hot spots within the product's life cycle. In this project, the goal is to determine the optimal technology alternative that which minimizes the overall environmental impact. A functional unit of one ton of dry microalgae biomass produced is used as the basis for the calculations. The integrated FAHP-LCO framework is used to select which is the best among the four microalgae cultivation systems. The life cycle system includes inputs of material and energy from microalgae cultivation to microalgae dry biomass production.

Functional unit is defined as the physical quantity of output that is used as a basis to normalize all other computations throughout the LCA. It also enables different systems to be treated as functionally equivalent (Guinée 2002). To compare microalgae cultivation alternatives in this study, all the data are normalized to a functional unit of one ton of dry biomass. It is the net output vector **f** indicated in Equation 2.12. One ton of dry microalgae biomass is used as the functional unit in this project.

4.2.2 Life Cycle Inventory

This step, involves setting the system boundaries, designing the flow diagram with unit processes, and collecting the data for each of these processes in order to complete the final LCA calculations. The process data is often organized around the unit processes, providing information on the material and energy input and output flows, as well as environmental inputs and outputs. The process data are typically quantified in relation to a reference flow (e.g., one ton of material or 1 kWh of electricity). Data sources used here include previously published data from literature and from EIOLCA.net (Carnegie Mellon University Green Design Institute 2013). The technology matrix (**A**) and the environment intervention matrix (**B**) are obtained. The inventory of the data is divided into two stages. Stage one is data collection for the technology matrix (**A**) and the environment intervention matrix (**B**) of the resources inputs (i.e., urea, salt, diammonium phosphate (DAP) and electricity) into the main systems. These upstream systems can then be represented as a single consolidated process within the LCO model. The inventory of the data is divided into two stages. Stage 1 is to estimate the environmental flow (**g**) from cradle to gate (i.e.: from resources to the gate of the production), for 1 ton of: (i) urea, (ii) salt, (iii) DAP and (iv) 1 kWh of electricity, then stage 2 gate-to-gate analysis. The system boundary is illustrated in Figure 4.1.

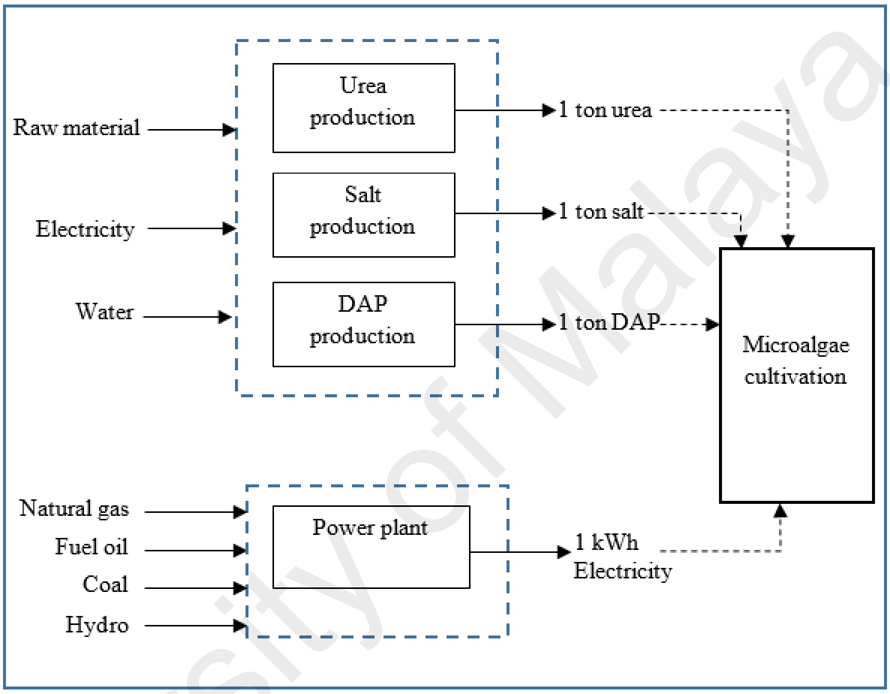

Figure 4.1: Partial LCA of key upstream inputs

The data sources for the background processes, such as electricity generation and chemicals production are presented in Table 4.1. It is based on the system boundary of Figure 4.1. These data are normalized to the production of one ton of chemical or 1 kWh of electricity in order to fit into the matrix calculation. At this stage, assumption and limitation of the processes are:

i. The environmental flow for the chemicals production are based on Economic Input-Output Life Cycle Assessment (EIO-LCA) method by estimating the materials and energy resources required based from economy activities of the chemical (Carnegie Mellon University Green Design Institute, 2013).

ii. U.S. 2002 Benchmark and agriculture industry are selected for the EIO-LCA database to estimate the data (Carnegie Mellon University Green Design Institute, 2013).

iii. Power plant electricity generation is based Malaysia electricity in Year 2010 fuel mix generation grid: coal (36.5 %), fuel oil (0.2 %), natural gas (55.9 %), hydro (5.6 %) and others (1.8%) (Ali *et al*., 2012).

iv. Thermal efficiency for coal (35 % - Malaysia, year 2008), (Shekarchian *et al*., 2011), hydro (90 %) (Turkey, year 2001) (Evan *et al*., 2009), fuel oil (43 %) and natural gas (57.5 %) (Singapore, year 2008) (Tan *et al*., 2010).

v. CO_2 emission (kg/kWh) for electricity generation are: coal (1.18), fuel oil (0.85), natural gas (0.53) and no emission of CO_2 for hydro system (Mahlia, 2003). It is assumed that the type of coal is bituminous coal.

vi. Water consumption (Fthenakis and Kim, 2010) by assumption having the same fuel mix generation grid as mentioned in iii.

Table 4.1 : Data source for the evironmental footprint for background processes

Environmental footprint	Source
Generates 1 kWh electricity:	
Energy efficiency	Tan et al., 2010; Mahlia, 2003; Shekarchiana *et al*., 2011
Electricity generation	Shekarchiana *et al*., 2011
Indirect water consumption	Fthenakis and Kim, 2010
CO_2 emission	Mahlia, 2003; Shekarchiana *et al*., 2011
Produces 1 ton of chemical (salt, urea, DAP):	
Energy consumption Indirect water consumption CO_2 emission	(Carnegie Mellon University Green Design Institute, 2013)

Table 4.2 shows the technology and intervention matrices (**A** and **B**) of these background processes. The chemicals production data are obtained through the EIOLCA.net (Carnegie Mellon University Green Design Institute 2013). For instance, 1.49 ton of indirect water consumption for each 1 kWh electricity generated is based on the average of power generation in Malaysia's for Year 2008 electricity generation (Shekarchiana *et al.*, 2011) and the annual indirect water consumption (ton/kWh) for the various type of power plant (Fthenakis and Kim, 2010). The type of energy are mainly based on the combination of coal, fossil fuel, natural gas and hydro power electricity generation.

Table 4.2: Technology and environment intervention matrices for electricity and chemicals production

	Electricity	Salt	Urea	DAP
Process Input (Technology matrix, **A**)				
Electricity (kWh)	1.0	-3055.6	-6388.9	-8333.3
Salt (ton)	0.0	1.0	0.0	0.0
Urea (ton)	0.0	0.0	1.0	0.0
DAP (ton)	0.0	0.0	0.0	1.0
Starch (ton)	0.0	0.0	0.0	0.0
Cellulose (ton)	0.0	0.0	0.0	0.0
Environmental Footprint (Intervention matrix **B**)				
Energy (kWh)	-2.16	0.0	0.0	0.0
CO_2 (ton)	0.001	0.56	0.004	0.005
Indirect Water (ton)	-1.49	-41.3	-62.8	-81.5

The use of FAHP-LCO model is illustrated by a simplified case study involving microalgae cultivation system. The case study is intended solely as an illustrative example for the purposes of explaining the general methodology proposed in Chapter 3. Hence, the life cycle system is a small one, with just four different cultivation systems, six material or energy flows and four environmental flows.

There are four cultivation systems considered: (1) open pond, (2) TPBR, and (3) FPPBR. The alternative systems are generated based on literature review. The material and energy inputs per ton of dry biomass produced by different cultivation options are presented in Table 4.3. These data are normalized to the production of one ton of dry biomass in order to fit into the matrix calculation. Note that the material and energy requirements in harvesting process (as shown in Table 4.3) are similar for all the four alternatives.

Table 4.3 : Technology and intervention matrices for one ton of dry biomass production

	Cultivation (Open Pond)	Cultivation (TPBR)	Cultivation (FPPBR)	Harvesting & Drying
Process Input (Technology matrix, **A**)				
Electricity (kWh)	-279.53 [a]	-555.72[a]	-178.1 [b]	-134.0 [b]
Salt (ton)	-0.13 [b]	-0.13 [c]	-0.13 [c]	0
Urea (ton)	-0.097 [b]	-0.096 [c]	-0.096 [c]	0
DAP (ton)	-0.048 [b]	-0.047 [c]	-0.047 [c]	0
Wet Microalgae (ton)	6.67 [b]	6.67 [c]	6.67 [c]	-6.67
Dry Biomass (ton)	0	0	0	1
Environmental Footprint (Intervention matrix **B**)				
Energy (kWh)	0.0	0.0	0.0	0.0
CO_2 (ton)	0.0	0.0	0.0	0.0
Direct Water (ton)	-79.98 [b]	-3.36 [c]	-0.57 [c]	0.0

[a] Jorquera *et al.*, 2010
[b] Sierra *et al.*, 2008
[b] Zhang *et al.*, 2013

The second stage is to consider the input and output data of the main systems (each single process involves in the operation). The assumptions and limitations of the processes are:

i. CO_2 was sequestered from the atmosphere via photosynthesis during microalgae cultivation. This CO_2 is eventually released to the atmosphere when the final product is used. Hence, the contribution of biomass carbon to system carbon footprint is virtually zero (Handle et al. 2014). The carbon footprint results mainly from the use of fossil fuel within the life cycle system.

ii. The amount of nutrients added are determined based on the nitrogen and phosphorous contents of the algae cell (around 5.5 % N of the algae dry weight and around 1.1 % P of the algae dry weight) (Borowitzka, 1992).

iii. Significant mixing is required during microalgae cultivation. Aeration is used to accomplish appropriate mixing (Zhang *et al.*, 2013).

iv. The amount of water lost due to evaporation depends on the climatic conditions. It is estimated to be 0.88 m^3 for each m^2 of cultivation open pond area per year (Murphy and Allen, 2011).

v. Microalgae biomass concentration of 0.5 kg/m^3 is assumed at the harvesting stage (Borowitzka, 1999).

vi. The water obtained from the dewatering step is sent back to the microalgae cultivation pond for reuse. Thus, the water discharged to the environment during the dewatering process is negligible.

vii. Steam drying system is used for drying wet biomass. This step consumes 134 kWh to produce one ton of dry microalgae biomass (Zhang *et al.*, 2013).

viii. During the dewatering process by centrifugation, dry biomass with solid content of 15 % w/w is obtained (Zhang *et al.*, 2013).

Alternative 1 – Microalgae Cultivation in Open Pond System

Figure 4.2 shows the material and energy input-output flow of the microalgae cultivation in open pond system (Alternative 1). Additional of the nutrients, i.e.: urea, salt and diammonium phosphate (DAP) are added into the pond for the growing of microalgae. Mixing with paddle wheel is performed during the entire cultivation period.

When the algae concentration of the open pond reaches 0.5 kg/m^3, the algae solution will pass through the harvesting screen and the process of centrifugation to get a cake with solid content of 15 % w/w. The water obtained from the dewatering (centrifuge) step is sent back to the algae cultivation pond to be reused.

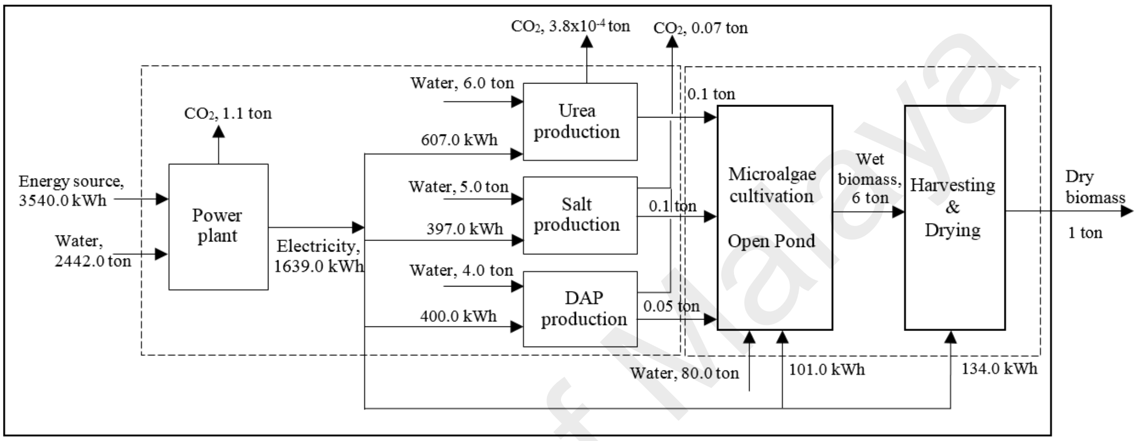

Figure 4.2: Material and energy system boundary for Alternative 1, microalgae cultivation in open pond followed by dry biomass production

Alternative 2 – Microalgae Cultivation in TPBR System

In Alternative 2, microalgae cultivation is performed in tubular photobioreactor (TPBR) system. The process of biomass production from microalgae obtained from TPBR is schematically shown in Figure 4.3. Apart from the cultivation step, other steps of biomass production i.e. microalgae harvesting and dewatering are similar to that of open pond system. In a TPBR cultivation system, sunlight is important as energy source for the photosynthesis process.

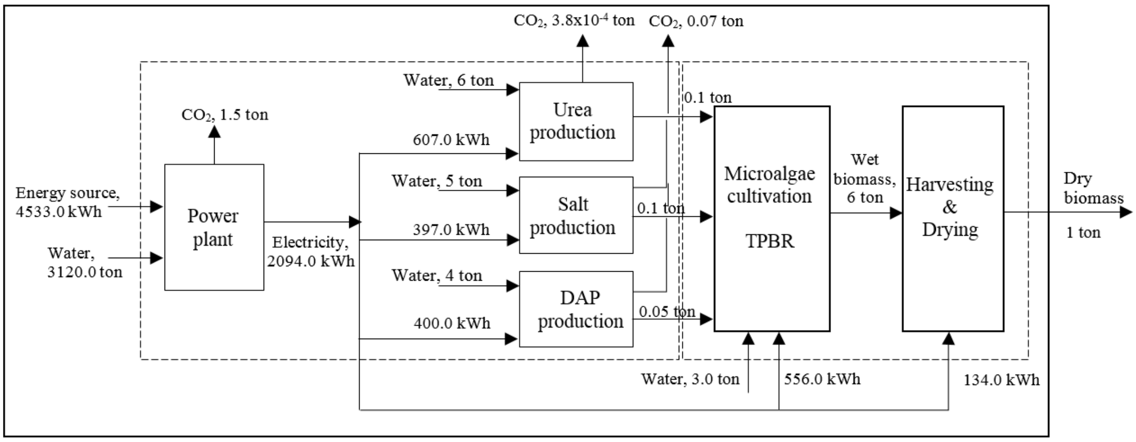

Figure 4.3: Material and energy system boundary for Alternative 2, microalgae cultivation in tubular photobioreactor (TPBR) followed by dry biomass production

Alternative 3 – Microalgae Cultivation in FPBR System

Microalgae cultivation is carried out in flat-plate photobioreactor (FPPBR) as illustrated in Figure 4.4. The energy and water input are lesser as compared to TPBR system. Meanwhile, other resources remain to TPBR system.

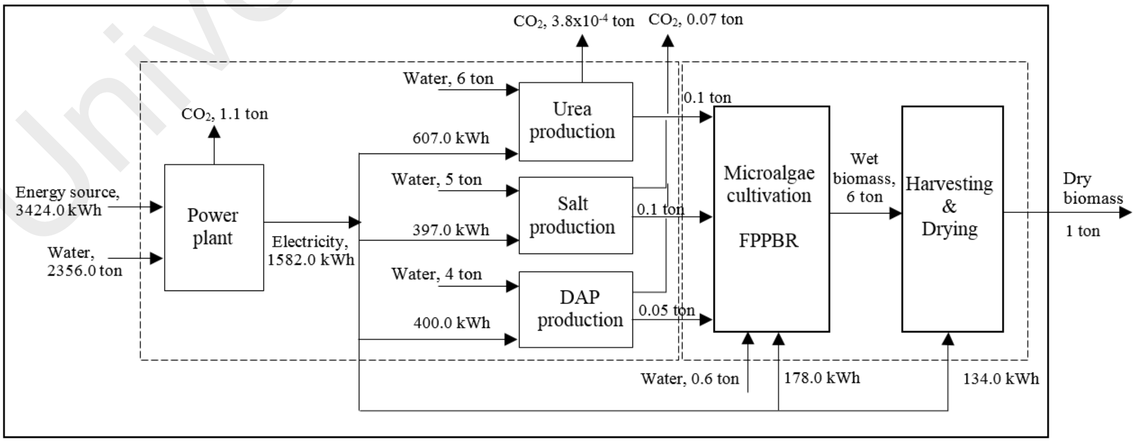

Figure 4.4: Material and energy system boundary for Alternative 3, microalgae cultivation in flat-plate photobioreactor (FPPBR) followed by dry biomass production

The system considers four environment flows, energy, CO_2, indirect water and direct water. Based on the input data to the systems, the matrices in model (Equations 2.12 and 2.14) are determined. Matrices **A** (Equation 4.1) and **B** (Equation 4.2) contain coefficients derived from Tables 4.2 and 4.3.

$$\mathbf{A} = \begin{pmatrix} 1 & -3055.6 & -6388.9 & -8333.3 & -279.5 & -555.7 & -178.1 & -134 \\ 0 & 1 & 0 & 0 & -0.1 & -0.1 & -0.1 & 0 \\ 0 & 0 & 1 & 0 & -0.1 & -0.1 & -0.1 & 0 \\ 0 & 0 & 0 & 1 & -0.05 & -0.05 & -0.05 & 0 \\ 0 & 0 & 0 & 0 & 6.67 & 6.67 & 6.67 & -6.67 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \qquad \textbf{Equation 4.1}$$

$$\mathbf{B} = \begin{pmatrix} -2.2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.0007 & 0.6 & 0.004 & 0.005 & 0 & 0 & 0 & 0 \\ -1.5 & -41.3 & -62.8 & -81.5 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -80 & -3.4 & -0.6 & 0 \end{pmatrix} \qquad \textbf{Equation 4.2}$$

The six rows of **A** correspond to flows of electricity (in kWh), salt (in ton), urea (in ton), DAP (in ton), wet microalgae (in ton) and the dry biomass of microalgae (in ton). The columns one to four are corresponded to the background processes input and output as shown in Table 4.2. Meanwhile, the columns five to seven represent the data for the three cultivation alternative systems: (1) open pond, (2) TPBR, and (3) FPPBR. The four rows in **B** correspond to the flows for energy (in kWh), CO_2, indirect water, and direct water (in ton). The net output or functional unit vector, **f,** specifies a net output of 1 ton of dry biomass in the sixth row (Equation 4.3);

$$\mathbf{f} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{pmatrix} \qquad \textbf{Equation 4.3}$$

4.2.3 Life Cycle Impact Assessment

The environmental footprints being considered are energy, water and carbon footprint. Energy footprint takes into consideration of all kinds of energy inputs, such as process energy and electricity, which are obtained from non-renewable resources such as coal, fossil fuel, hydro and natural gas (Schindler, 2015). Carbon footprint calculates the amount of net greenhouse gases released from a system directly or indirectly. In this project, total CO_2 emissions are used as an approximation of the total carbon footprint; it does not include other greenhouse gases. Although the energy footprint is correlated with the carbon footprint, the correlation is imperfect, and dependent on the carbon intensity of the energy mix of a given location. For example, if electricity comes from renewable sources, then the correlation is much weaker. Water footprint, which is an indicator of water usage, measures the water used directly and indirectly at different stages of the supply chain (Hoekstra and Chapagain, 2007). Equations 2.12 to 2.14 are applied to the technology matrix (**A**) and environmental intervention matrix (**B**) to obtain the final environment impact output (**g**). Table 4.4 shows an example of overall data for a complete matrix for LCA (Scenario 1-open pond). Shaded area is the final impact, **g**.

The calculation of the results can be done in Microsoft Excel (See Appendix A for example).

Table 4.4: Example of complete matrices for LCA (Alternative 1-open pond)

	Electricity	Salt	Urea	DAP	Cultivation (Open Pond)	Harvesting & Drying	Functional unit, **f**
Process Input (Technology matrix, **A**)							
Electricity (kWh)	1.0	-3055.6	-6388.9	-8333.3	-279.53	-134.0	0
Salt (ton)	0.0	1.0	0.0	0.0	-0.13	0	0
Urea (ton)	0.0	0.0	1.0	0.0	-0.097	0	0
DAP (ton)	0.0	0.0	0.0	1.0	-0.048	0	0
Wet Microalgae (ton)	0.0	0.0	0.0	0.0	6.67	-6.67	0
Dry Biomass (ton)	0.0	0.0	0.0	0.0	0	1	1
Environmental Footprint (Intervention matrix **B**)							Impact, **g**
Energy (kWh)	-2.16	0.0	0.0	0.0	0.0	0.0	-3970.18
CO_2 (ton)	0.001	0.56	0.004	0.005	0.0	0.0	1.38
Indirect Water (ton)	-1.49	-41.3	-62.8	-81.5	0.0	0.0	-2758.12
Direct Water (ton)	0.0	0.0	0.0	0.0	-79.98	0.0	-6.67

The environmental footprints of the different technologies are compared to identify the best option alternative as shown in Table 4.5. Negatively signed entries indicate consumption, while those that are positively signed indicate release to the environment. The overall environmental out shown in Table 4.5 indicates that FPPBR is better method compared to TPBR and open pond. FPPBR has less CO_2 releases to the environment among the both closed system. It is approximately 95% less CO_2 to environment, due to its lower energy requirement for the flat-plate system in cultivation. The CO_2 release to the environment is relatively linear with the energy consumption. Note that the shaded data shows the worst performance in each environmental footprint category.

Table 4.5: Summary of environmental output for each process option in cultivation system

Environmental Footprint	Open Pond	TPBR	FPPBR
Energy (kWh)	-3.97E+03	-2.15E+04	-3.72E+03
CO_2 (ton)	1.38	7.13	1.30
Indirect Water (ton)	-2.76E+03	-1.49E+04	-2.58E+03
Direct Water (ton)	-6.67	-3.36	-3.36

4.3 Analytic Hierarchy Process (AHP)

To determine the preference AHP weights of the environmental footprint criteria, pairwise comparison was done using the nine-point scale (as defined in Table 2). The criteria are evaluated in a pairwise manner to determine their relative significance based on expert judgment. The criteria are evaluated in a pairwise manner to determine their relative significance based on expert judgment. The matrix of pairwise comparisons (**z**) of the environmental footprint for the microalgae cultivation is shown in Table 2.5 as expressed in Equation 2.2. The expert considered is someone who is experienced in the field of microalgae biofuel production. Figure 4.5 shows the AHP network designed to achieve the selection of the best alternative for cultivation system of microalgae. It is followed by the intermediate level of evaluating the criteria of cultivation system. There are two intermediate level which are criteria and sub-criteria. Three criteria are identified as the important selection criterion in selecting the best cultivation system for the microalgae production i.e.: production (PDN), economic (ECN) and environmental (ENV). Subsequently, the sub-criteria is referring to the important selecting criteria under the first intermediate level. There are four sub-criteria that effect the production of the microalgae, namely contamination risk (CR), biomass productivity (BP), temperature control (TC) and O_2 inhibition (OI). Water, carbon, energy and land are the four environmental footprints that put into consideration in the selection the microalgae cultivation. Capital cost is the only sub-criteria under the economic consideration. The lowest level in the hierarchy is the alternatives that to be evaluated. The definition for each of the sub-criteria is well defined in Table 4.6. It is important during the pairwise comparison. Finally, open pond, TPBR, and FPPBR are the three cultivation alternatives presented at the lowest level of the hierarchy. These selecting criteria are solely based on the literature review on the importance parameters for the setting of cultivation system.

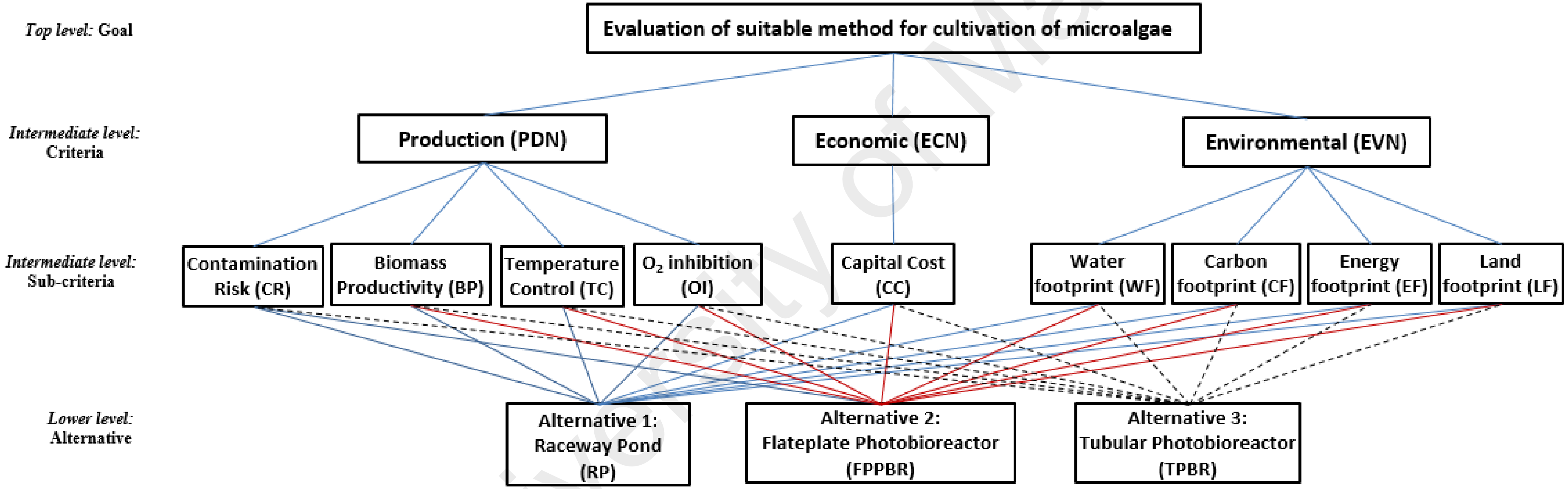

Figure 4.5: AHP decision structure for cultivation system

Table 4.6: Preferences definitions for cultivation system

Criteria	Definition
Productivity:	
Contamination risk	Inherent threat of contamination and pollution by protozoa and undesired microalgae can limit the commercial production of microalgae (Ugwu *et al.*, 2008; Singh & Sharma, 2012; Suali & Sarbatly, 2012).
Biomass productivity	Reported in grams per liter per day. The values of biomass productivity was based on *Nannochloropsis* sp. cultures were grown in artificial sea water and enriched with nutrients as described in the sources (Chini Zittelli *et al.*, 1999; Cheng-Wu *et al.*, 2001; Richmond & Cheng-Wu, 2001).
Temperature control	High productivity can be obtained when the optimal temperature for cultivation is reached (Richmond, 2004). Microalgae can simply adapt to temperatures up to 15 ˚C lower than their optimal, but greater than the optimum temperature about 2 - 4 ˚C can reduce the productivity of the culture (Mata *et al.*, 2010).
Oxygen (O_2) inhibition	High concentration of O_2 can contribute to lower productivity due to photo-oxidative stress (Rawat *et al.*, 2013). High concentration of dissolved O_2 together with strong sunlight can lead to photo-oxidative damage to microalgae cells. The level of O_2 also able to limit the rate of photosynthesis. It is recognized that dissolved O_2 is toxic to microalgae cells (Suali & Sarbatly, 2012).
Environmental:	
Water footprint	Water loss through evaporation, it may affect in ionic composition of the growth medium and potentially damage impacts on culture growth (Pulz, 2001; Rawat *et al.*, 2013).
Carbon footprint	The CO_2 concentration plays a major component to enhance the lipid composition; lipid content and biomass yield (Widjaja *et al.*, 2009). Approximately 45-50% of microalgae cells are made up of carbon, thus microalgae require continual intake of carbon. CO_2 is also often used to maintain a steady pH in the culture system.
Energy footprint	The amount of energy required depends on the rate of growth of microalgae species, types of production systems and environmental conditions. It also includes of the energy consumption for air pumping.
Land footprint	Space needed for a biomass annual production of 100,000 kg/ year
Economic	
Capital cost	Installation costs of the cultivation system

Pairwise comparison for the criteria needs to be done to get the eigenvalue then the priority ranking of the alternatives. This can be done either by the input by the judgments of the professional in the field of relevant or qualitative input after collecting facts and information through literature review. Table 4.7 shows the comparison of the three alternative systems according to the intermediate level sub-criteria. Contamination risk

(CR), temperature control (TC) and O_2 inhibition are the sub-criteria when considering the production (PDN) capability of the system. Meanwhile, the CO_2 losses or carbon footprint (CF) is the sub-criterial under the environmental criteria. It is observed that open pond exposes to extremely high contamination risk as compared to TPBR and FPPBR, which is low in risk. In another words, it is also shows the favor over TPBR and FPPBR as close system for easily handling and controlling. Extensive application of microalgae cultivation in wastewater system in recent years have proven that microalgae is capable to take in inorganic nitrogen and phosphorus for their growth, capable to remove heavy metals as well as some toxic organic compounds (Abdel-Raouf *et al*., 2012). Dissolved O_2 significantly reduced biomass productivity (Jiméneza *et al*., 2003); O_2 inhibits the growth of microalgae as it competes with CO_2 (Raso *et al*., 2012). Low temperature inhibits the active O_2 species (Juneja *et al*., 2012).

Based on Table 4.7, the comparison of the sub-criteria able to provide the judgement and give pairwise scale. The ratio $\frac{\mathbf{w}_i}{\mathbf{w}_j}$ indicates the relative importance of criteria in the *i*th row over the criteria in the *j*th in the column with respect to the goal. These weights ($\mathbf{w}_i$) are typically computed with eigenvector method using the Saaty's nine-point scale (Saaty 1979) (Table 2.5). For instance, pairwise comparison of the different cultivation alternatives with respect to contamination risk can be formulated as following:

i) Is contamination risk more important for open pond as compared to TPBR?
ii) Is contamination risk more important for open pond as compared to FPPBR?
iii) Is contamination risk more important for TPBR as compared with FPPB?

All the pairwise comparison data are then synthesized into matrix form and the values within the matrix are normalized. Then, the weight vector, $\vec{\mathbf{z}}$ corresponding to the pairwise comparison is computed via eigenvector method.

Table 4.7: Comparison of sub-criteria for different cultivation alternatives

	Open Pond (OP)	Tubular photo-bioreactor (TPBR)	Flat plate photo-bioreactor (FPPBR)
Contamination Risk (CR)	Extremely high	Low	Low
Temperature Control (TC)	Difficult to control	Easy to control	Difficult to control
O_2 inhibition (OI)	Lower than Photobioreactor	O_2 dissolves along the tubes in the reactor	Low O_2 build-up
CO_2 losses (Carbon footprint, CF)	CO_2 diffuses to the atmosphere easily	CO_2 diffuses along the tubes in the reactor	Nearly no CO_2 diffusion to the atmosphere
Sources	Borowitzka, 1999; Brennan and Owende, 2010; Carvalho *et al,* 2006; Davis *et al,* 2011; Leite *et al,* 2013; Mata *et al,* 2010; Pulz, 2001; Suali and Sarbatly, 2012; Ugwu *et al*, 2008		

As Table 4.7 serves as the judgement information for the measurement of sub-criteria with cultivation alternatives. The comparative matrix of cultivation alternatives with respect to the different sub criteria (contamination risk, CR; temperature control, TC; O_2 inhibition, OI and carbon footprint, CF) are presented in Tables 4.8 to 4.11. For instance, for the contamination risk (CR), open pond has extremely high risk as compared to TPBR and FPPBR. Thus, in assigning Saaty's nine-point scale, ones can state that TPBR and FPPBR are extremely favoured over open pond, which scaled as nine point. Another example can be provided for carbon footprint (CF) comparative among the alternatives. Literature stated that in open pond, CO_2 diffuses to the atmosphere, thus the carbon capture of CO_2 by microalgae during the photosynthesis process will be very poor. At the end, the CF will be very high as compared to TPBR and FPPBR. It can be scale as 7 as the CF is very important criteria comparing to other systems. On the other hand, FPPBR is nearly zero CO_2 diffusion throughout the process, we can state that its CF is extremely low to the environment as almost all will be consumed in the cultivation process since remain capturing in the photobioreactor. Same adjustment is done for comparing between open pond with TPBR as well as TPBR with FPPBR.

Table 4.8: Pairwise comparison matrix of cultivation alternatives with respect to contamination risk (CR)

	OP	TPBR	FPPBR
OP	1	1/9	1/9
FPPBR		1	1
TPBR			1

Table 4.9: Pairwise comparison matrix of cultivation alternatives with respect to temperature control (TC)

	OP	TPBR	FPPBR
OP	1	1/5	1
TPBR		1	5
FPPBR			1

Table 4.10: Pairwise comparison matrix of cultivation alternatives with respect to O_2 inhibition (OI)

	OP	TPBR	FPPBR
OP	1	5	5
TPBR		1	1/5
FPPBR			1

Table 4.11: Comparison matrix of cultivation alternatives with respect to Carbon footprint (CF)

	OP	TPBR	FPPBR
OP	1	1/9	1/9
TPBR		1	1/5
FPPBR			1

Besides the qualitative judgement, quantitative data obtained from literature also can be used in AHP. AHP weightage of the sub-criteria or criteria can be calculation and normalized directly based on the published data. Table 4.12 summarizes the data for cultivation alternatives in respecting with different sub criteria (i.e.: capital cost (CC), biomass productivity (BP), energy footprint (EF), land footprint (LF) and water footprint (WF)). The energy footprint for the open pond is very low compared to TPBR. It is because open pond usually does not required artificial lighting for the cultivation of microalgae. The biomass productivity of microalgae is linearly increase with temperature (Jiméneza *et al*., 2003). Nevertheless, there are species dependence.

Table 4.12: Summary of quantitative data for cultivation alternatives vs. sub-criteria

Alternative	Capital cost (CC) (RM/kg)[a]	Biomass productivity (BP) (g/l/day)	Energy footprint (EF) (W/m^3)	Land footprint (LF) (m^2)[e]	Water footprint (WF)[g] (ton/dried biomass ton)
OP	127.32	0.035[b]	3.72[e]	25988.25	79.98
TPBR	161.85	0.560[d]	2500.00[f]	10763.20	0.57
FPPBR	163.80	0.270[c]	53.00[f]	10147.00	3.36

[a] Norsker *et al*., 2011; [b] Richmond and Wu, 2001; [c] Wu *et al*., 2001; [d] Chini Zittelli *et al*., 1999; [e]Jorquera *et al*., 2010; [f] Sierra *et al*., 2008; [g] Zhang *et al*., 2001

These relative weights have to be normalized in order to allow them to be analogous to weights defined from the AHP method. The normalized weight is shown in Table 4.13. The values priorities are normalized using Equation 4.4. From the weights of the sub-criterion capital cost (CC), open pond has the highest weight followed by TPBR and FPPBR. This can be interpret from the original value obtained from Table 4.12 whereby open pond has the lower capital cost and so on. These weightages in Table 4.13 are then to be used to calculate the final ranking of the cultivation system at the later section.

$$W_{criteria\ i} = \frac{w_{i,initial\ value}}{\sum_{i=1}^{n} w_{i,initial\ value}} \quad \textbf{Equation 4.4}$$

Table 4.13: The normalized value for each sub-criteria

	Capital cost (CC)	Biomass productivity (BP)	Energy Footprint (EF)	Land footprint (LF)	Water footprint (WF)
OP	0.391	0.040	0.933	0.167	0.006
TPBR	0.309	0.647	0.001	0.404	0.850
FPPBR	0.300	0.312	0.066	0.429	0.144

Besides utilizing facts and information from literature review, one also can provide his expert judgement for the pairwise matrix. Case study in Chapter 5 is highlights the setting up of matrix using experts' input.

Table 4.14 computes the comparative pairwise matrix for the main criteria for production (i.e.: CR, BP, TC and OI) in cultivating microalgae. This is done qualitatively based on literature study.

Pairwise comparative matrix for environmental impacts' sub-criteria (EF, WF, CF and LF) are assessed and shown in Table 4.15. The AHP weights of each sub-criteria is presented in Tan *et al*., 2014. Lastly, Table 4.16 shows the pairwise comparison matrix for main criteria of microalgae cultivation.

Table 4.14: Pairwise comparison matrix of main criteria for production (PRD)

	CR	BP	TC	IO
CR	1	3	1	1
BP		1	1/3	1/7
TC			1	1
IO				1

Table 4.15: Pairwise comparison matrix of environmental impact's sub-criteria for cultivation process (Tan *et al.*, 2014)

	EF	CF	WF	LF	AHP Weight
EF	1	0.5	1	1	0.195
CF	2	1	2	3	0.432
WF	1	1/2	1	1	0.195
LF	1	1/3	1	1	0.177

Table 4.16: Pairwise comparison matrix of main criteria for cultivation process

	PRD	ECN	ENV
PRD	1	1	3
ECN		1	3
ENV			1

4.4 Fuzzy Analytic Hierarchy Process

Fuzziness of the pairwise comparison matrices for microalgae are conducted to ensure the robustness of the qualitative judgement. Degree of confidence, δ is set at 1.0 (high degree of confidence). Figure 4.6 illustrates the graphical representation of the fuzzy scale as triangular fuzzy number (TFN) used in this case study. δ at 2 is set as moderate confidence, whereas δ given in 3 is low confidence level during the pairwise comparison judgement. Fuzzy scale is used to represent the value judgments $\hat{\boldsymbol{z}}_{ij}$ as triangular fuzzy numbers $\langle \hat{L}_{ij}, \hat{M}_{ij}, \hat{U}_{ij} \rangle$ that will populate the pairwise comparison matrix as shown in Equation 2.5.

$$\hat{\mathbf{z}} = \begin{bmatrix} (\mathbf{1},\mathbf{1},\mathbf{1}) & \hat{\boldsymbol{z}}_{\mathbf{12}} & \cdots & \hat{\boldsymbol{z}}_{\mathbf{1n}} \\ \hat{\boldsymbol{z}}_{\mathbf{21}} & (\mathbf{1},\mathbf{1},\mathbf{1}) & \dots & \hat{\boldsymbol{z}}_{\mathbf{2n}} \\ \vdots & \vdots & \ddots & \vdots \\ \hat{\boldsymbol{z}}_{\boldsymbol{n}\mathbf{1}} & \hat{\boldsymbol{z}}_{\boldsymbol{n}\mathbf{2}} & \cdots & (\mathbf{1},\mathbf{1},\mathbf{1}) \end{bmatrix} \textbf{ where } \hat{\boldsymbol{z}}_{\boldsymbol{ji}} = \frac{\mathbf{1}}{\hat{\boldsymbol{a}}_{\boldsymbol{ij}}} = \langle \frac{\mathbf{1}}{\hat{\boldsymbol{U}}_{\boldsymbol{ij}}}, \frac{\mathbf{1}}{\hat{\boldsymbol{M}}_{\boldsymbol{ij}}}, \frac{\mathbf{1}}{\hat{\boldsymbol{L}}_{\boldsymbol{ij}}} \rangle \quad \textbf{Equation 2.5}$$

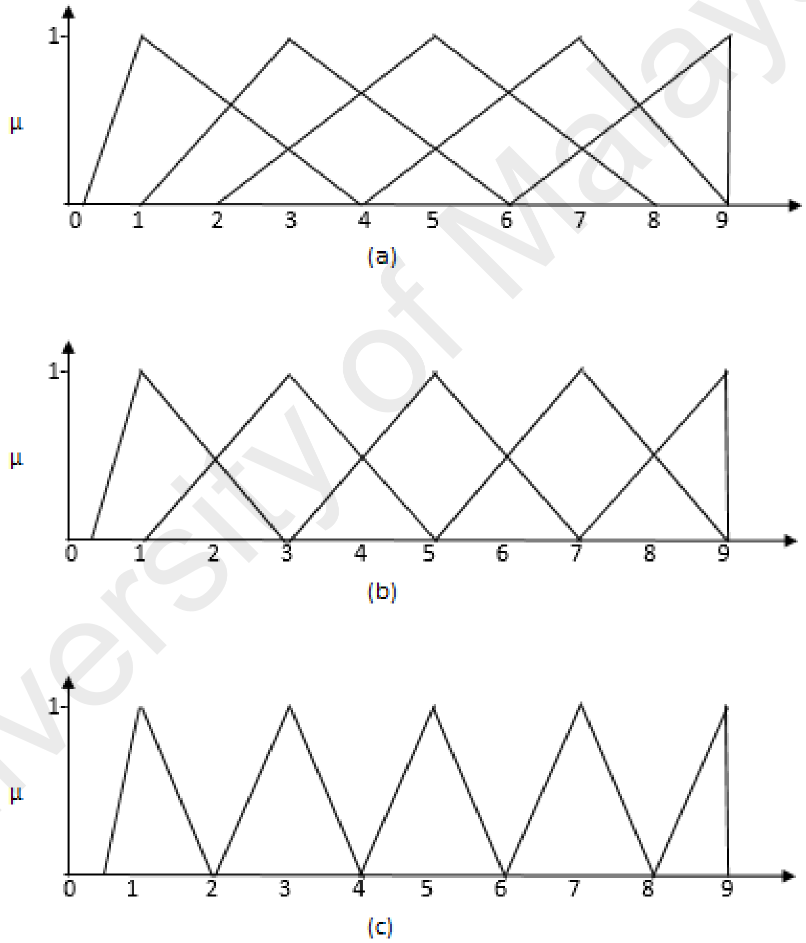

Figure 4.6: FAHP linguistic scale for (a) low (fuzzy scale at δ = 3), (b) moderate (fuzzy scale at δ = 2) and (c) high (fuzzy scale δ at = 1) degrees of confidence

Tables 4.17 to 4.23 describe the TFN pairwise comparison matrix for each of the criteria in the AHP network. Then, the preference fuzzy weights of the criteria, sub-criteria with respect to alternatives are computed based on the degree of confidence. For instance, based on Table 4.8, the degrees of confidence, δ for is set as 1. Next, using Equation 2.5, the fuzzy pairwise matrix can be generated. It can be expressed as Equation 4.5. Using this method, the fuzzy pairwise matrix for sub-criteria contamination risk (CR) can be generated as shown in Table 4.17. Note that the upper limit fuzzy number in the triangular fuzzy number remain at 9 as the maximum of the scale (as indicated in Table 2.7). Similarly, the same approach is applied to other sub-criteria by determine the degree of confidence to set up the fuzzy pairwise matrix as shown in Tables 4.18 to 4.23.

$$\frac{1}{\hat{z}_{12}} = \langle \frac{1}{\hat{U}_{12}}, \frac{1}{\hat{M}_{12}}, \frac{1}{\hat{L}_{12}} \rangle = \langle \frac{1}{9}, \frac{1}{9}, \frac{1}{9-\delta} \rangle \qquad \textbf{Equation 4.5}$$

Table 4.17: Fuzzy pairwise matrix of cultivation alternatives with respect to contamination risk (CR), high degree of confidence (fuzzy scale δ at = 1)

	OP	TPBR	FPPBR
OP	1	(0.11, 0.11, 0.125)	(0.11, 0.11, 0.125)
TPBR		1	(0.5, 1, 2)
FPPBR			1

Table 4.18: Fuzzy pairwise matrix of cultivation alternatives with respect to temperature control (TC), high degree of confidence (fuzzy scale δ at = 1)

	OP	TPBR	FPPBR
OP	1	(0.167, 0.2, 0.25)	(0.5, 1, 2)
TPBR		1	(0.167, 0.2, 0.25)
FPPBR			1

Table 4.19: Fuzzy pairwise matrix of cultivation alternatives with respect to O_2 inhibition (OI) moderate degree of confidence (fuzzy scale δ at = 2)

	OP	TPBR	FPPBR
OP	1	(3, 5, 7)	(3, 5, 7)
TPBR		1	(0.14, 0.2, 0.33)
FPPBR			1

Table 4.20: Fuzzy pairwise matrix of cultivation alternatives with respect to carbon footprint (CF), high degree of confidence (fuzzy scale δ at = 1)

	OP	TPBR	FPPBR
OP	1	(0.11, 0.11, 0.125)	(0.11, 0.11, 0.125)
TPBR		1	(0.167, 0.2, 0.25)
FPPBR			1

Table 4.21: Fuzzy pairwise matrix of main criteria for production (PRD), high degree of confidence (fuzzy scale δ at = 1)

	CR	BP	TC	IO
CR	1	(2, 3, 4)	(0.5, 1, 2)	(0.5, 1, 2)
BP		1	(0.25, 0.33, 0.5)	(0.167, 0.2, 0.25)
TC			1	(0.5, 1, 2)
IO				1

Table 4.22: Fuzzy pairwise matrix of environmental impact's sub-criteria for cultivation process (Tan *et al.*, 2014), high degree of confidence (fuzzy scale δ at = 1)

	EF	CF	WF	LF
EF	1	(0.33, 0.5, 1)	(0.5, 1, 2)	(0.5, 1, 2)
CF		1	(1, 2, 3)	(2, 3, 4)
WF			1	(0.5, 1, 2)
LF				1

Table 4.23: Fuzzy pairwise matrix of main criteria for cultivation process, high degree of confidence (fuzzy scale δ at = 1)

	PRD	ECN	ENV
PRD	1	(0.5, 1, 2)	(2, 3, 4)
ECN		1	(2, 3, 4)
ENV			1

The weights that approximate the solution ratio in the pairwise comparison matrix are computed using the following nonlinear programming (NLP) formulation (Promentilla *et al*. 2014) as shown in Equations 2.7 to 2.12 to determine the fuzziness of the system. If λ is more than this acceptable value, inconsistency of the judgments within the matrix has occurred and the evaluation process should be reviewed. λ is computed for each of the fuzzy pairwise comparison matrix to ensure the consistent in the qualitative judgement using optimisation software LINGO v.14. Consider the fuzzy pairwise comparison matrix in Table 4.17 as an example (Equation 4.6):

$$\hat{\mathbf{z}} = \begin{bmatrix} \mathbf{1} & \mathbf{0.11, 0.11, 0.125} & \mathbf{0.11, 0.11, 0.125} \\ & \mathbf{1} & \mathbf{0.5, 1, 2} \\ & & \mathbf{1} \end{bmatrix} \qquad \textbf{Equation 4.6}$$

By using the upper triangular elements of $\hat{\mathbf{z}}$, the fuzzy model can be written as Equations 4.7 to 4.14 (see Appendix B for LINGO formulation). This non-linear programming model computes the optimal priority vector (**w**) by maximizing lambda (λ), i.e., a consistency index to measures the degree of satisfaction of all computed pairwise comparison ratios that satisfy within the bounds of the initial fuzzy judgments.

max **λ**

subjected to:

$$\boldsymbol{\lambda}\,(\mathbf{0.11-0.11})\mathbf{w_2} - \mathbf{w_1} + \mathbf{0.11w_2} \ \le \mathbf{0} \qquad \textbf{Equation 4.7}$$

$$\boldsymbol{\lambda}\,(\mathbf{0.125-0.11})\mathbf{w_2} + \mathbf{w_1} - \mathbf{0.125w_2} \ \le \mathbf{0} \qquad \textbf{Equation 4.8}$$

$$\boldsymbol{\lambda}\,(\mathbf{0.11-0.11})\mathbf{w_3} - \mathbf{w_1} + \mathbf{0.11w_3} \ \le \mathbf{0} \qquad \textbf{Equation 4.9}$$

$$\boldsymbol{\lambda}\,(\mathbf{0.125-0.11})\mathbf{w_3} + \mathbf{w_1} - \mathbf{0.125w_2} \ \le \mathbf{0} \qquad \textbf{Equation 4.10}$$

$$\boldsymbol{\lambda}\,(\mathbf{0.5-1})\mathbf{w_3} - \mathbf{w_2} + \mathbf{0.5w_3} \ \le \mathbf{0} \qquad \textbf{Equation 4.11}$$

$$\boldsymbol{\lambda}\,(\mathbf{2-1})\mathbf{w_3} + \mathbf{w_2} - \mathbf{2w_3} \ \le \mathbf{0} \qquad \textbf{Equation 4.12}$$

$$\mathbf{w_1} + \mathbf{w_2} + \mathbf{w_3} = \mathbf{1} \qquad \textbf{Equation 4.13}$$

$$\mathbf{w_1} \ge \mathbf{0};\ \mathbf{w_2} \ge \mathbf{0};\ \mathbf{w_3} \ge \mathbf{0} \qquad \textbf{Equation 4.14}$$

By using LINGO v14, it is easy to find optimal solution for the above model with optimal value of 1 for λ and $\mathbf{w}_i$ as (0.05, 0.474, 0.474). Since λ at the value of 1 which denotes its perfect consistency (Tan *et al.*, 2014b). The λ and weightages for other sub-criteria can be generated using the same procedures. The summary of the values can be found in Tables 4.24 to 4.26 (example of LINGO solution is found in Appendix C). Based on this, all the λ have satisfy the criteria. It is concluded that the weighting factor for the FAHP can be then proceed to calculate the priority ranking score and no re-evaluation of the judgement for AHP is needed.

Equations 4.15 to 4.17 are the matrices multiplication of the weights for each sub-criteria in the FAHP network.

$$\boldsymbol{PRD_{overall,j} = \sum_{j=1}^{n}\left[PRD_{sub,i,j}\ W_{PRD,j}\right]} \qquad \textbf{Equation 4.15}$$

$$\boldsymbol{ENV_{overall,j} = \sum_{j=1}^{n}\left[ENV_{sub,i,j}\ W_{ENV,j}\right]} \qquad \textbf{Equation 4.16}$$

$$\boldsymbol{Y_{overall,j} = \sum_{j=1}^{n}\left[MC_{overall,i,j}\ W_{MC,j}\right]} \qquad \textbf{Equation 4.17}$$

Table 4.24: Normalized weights ($PRD_{overall,\,j}$) of cultivation alternatives with respect to each production's sub-criterion

Alternative	CR[a] ($W^{\#}$=0.278)	BP[b] ($W^{\#}$=0.081)	TC[a] ($W^{\#}$=0.278)	OI[a] ($W^{\#}$=0.363)	Normalized weights[c] ($PRD_{overall,\,j}$)
Alt 1: OP	0.05	0.040	0.143	0.714	0.316
Alt 2: TPBR	0.474	0.647	0.714	0.143	0.434
Alt 3: FPPBR	0.474	0.312	0.143	0.143	0.248

[a] Weights from FAHP method (λ = 1.000)
[b] Normalize weights from Table 4.13
[c] Normalized weights from matrix multiplication (Eq. 4.15)
[#] Weights, $\boldsymbol{W_{PRD,j}}$ from FAHP method (λ = 0.5293)

Table 4.25: Normalized weights ($ENV_{overall,\,j}$) of cultivation alternatives with respect to each environment's sub-criterion

Alternative	Energy footprint[a] ($W^{\#}=0.2$)	Carbon footprint[b] ($W^{\#}=0.4$)	Water footprint [a] ($W^{\#}=0.2$)	Land footprint[a] ($W^{\#}=0.4$)	Normalized weights[c] ($ENV_{overall,\,j}$)
Alt 1: OP	0.933	0.052	0.006	0.167	0.242
Alt 2: TPBR	0.001	0.474	0.850	0.404	0.446
Alt 3: FPPBR	0.066	0.474	0.144	0.429	0.317

[a] Normalize weights from Table 4.13
[b] Weights from FAHP method (λ = 1.000)
[c] Normalized weights from matrix multiplication (Eq. 4.16)
[#] Weights from FAHP method (λ = 1.000)

Table 4.26: Normalized overall priority weights ($M_{overall,j}$) of cultivation alternatives with respect to main criteria ($\boldsymbol{MC_{overall,i,j}}$)

Alternative	PRD[a] ($W^{\#}=0.429$)	COST[b] ($W^{\#}=0.429$)	$ENV_{overall}$[c] ($W^{\#}=0.143$)	Normalized Weights[d] ($Y_{overall,\,j}$)
Alt 1: OP	0.316	0.391	0.242	0.338
Alt 2: TPBR	0.434	0.309	0.446	0.382
Alt 3: FPPBR	0.248	0.300	0.317	0.281

[a] Normalized weights Table 2.24
[b] Normalized weights from Table 4.13
[c] Normalized weights Table 2.25
[d] Normalized weighting from matrix multiplication (Eq. 4.17)
[#] weighting from FAHP method (λ = 1.0)

Table 4.27 summarizes the overall priorities and ranking of the alternatives using the proposed method as described in Tables 4.24 and 4.26. The FAHP results show that the preferable cultivation system is tubular photobioreactor (TPBR) with priority weights of 0.382, and then followed by open pond (0.338), lastly FPPBR (0.281). These results are compared with Table 4.5 (LCA results). Table 4.5 shows that FPBBR is more favorable over the system selection based on the single criteria, which is environment footprints in LCA. However, by taking into consideration of multiple criteria in the process design selection using FAHP able to provide wider input. Question is raised up on which system should be selected? This doubtful or argument in decision making for the selection of method can be eliminated by the application of integrated FAHP and LCO, which both of the concerns (the environmental impact results as well as the benefits over alternative methods in the application) can be taken into consideration. LCO for the cultivation system is presented in the following section.

Table 4.27: Overall priorities (**Y**$_{\text{overall, j}}$) and ranking of cultivation alternatives

Alternatives	Overall weights	Ranking
Alt 1: OP	0.338	2
Alt 2: TPBR	0.382	1
Alt 3: FPPBR	0.281	3

4.5 Life Cycle Optimization

Systematic methodologies can be used to calculate the dried biomass produced from microalgae whilst taking into account the environmental impacts considered. The key inputs for the cultivation of microalgae lie on the photosynthetic process which takes up nutrients, energy, water and carbon.

In general, the approach for incorporating LCA into system optimization comprises of four main steps, which are: performing the LCA study (done in section 4.2), implementing the FAHP pairwise comparison study (discussed in section 4.3 and 4.4). Optimization of the LCA can be done by using the existing LCA spreadsheet in excel by using the SOLVER function. Then, formulating the MOO problem in the LCA context; and finally performing the MOO and choosing the best compromise solution. The framework is extended to determine the best cultivation option with the optimum target value of preference environmental footprint. The integrated FAHP-LCO model is formulated as a multiple objective linear program (MOLP), which is able to determine the optimal solution. The integrated FAHP-LCO within MOLP is solved over four main steps. In this section, discussion mainly focuses in formulating the MOO problem in the LCA context.

The third step is to normalize the environmental footprints from the different technology options relative to the performance of the worst alternative, (**Q**)-1. This step ensures that all the values are properly scaled and lie in the interval [0, 1]. Table 4.28 shows the worst scenarios that are used as (**Q**). These are generated based on the environment impact (**g**) during the LCA study for each cultivation system. The data in Table 4.4 is inversed to get $(\mathbf{Q})^{-1}$ for further usage on the LCO.

The fourth step is performing the LCO by integrating the priority weights with the optimization model. Equations 4.18 to 4.21 represent the overall formulation of MOO. The environmental footprints of the different technologies are compared to determine the worst environmental performance in each environmental footprint considered as shown in Table 4.5. The shaded data shows the worst performance in each environmental footprint category which are then used in the optimization function as $(\mathbf{Q})^{-1}$ in the optimization function to normalize the output data. Alternatively, environmental footprint limits, based from the performance of current technologies, may be identified and used as the normalizing factors.

$$\min = \sum_{j=1}^{n} \vec{\mathbf{w}}_{\text{fp}}\, \mathbf{Y}_j \qquad \textbf{Equation 4.18}$$

Subjected to:

$$\mathbf{F}_j = \sum_{j=1}^{n} \mathbf{A}_{i,j}\, \mathbf{S}_j \qquad \textbf{Equation 4.19}$$

$$\mathbf{g}_j = \sum_{j=1}^{n} \mathbf{B}_{i,j}\, \mathbf{S}_j \qquad \textbf{Equation 4.20}$$

$$\mathbf{Y}_j = \sum_{j=1}^{n} \mathbf{Q}^{-1}\, \mathbf{g}_j \qquad \textbf{Equation 4.21}$$

Where:

$\vec{\mathbf{w}}_{\text{fp}}$: AHP weights from FAHP

$(\mathbf{Q})^{-1}$: Worst scenario of the environmental impact flows

G : Overall environmental impact flows

$\mathbf{F}_j$: Functional unit, which been pre-determined

$\mathbf{S}_j$: Changing variables of the system

The optimization function is to minimize the overall environmental output, where FAHP weights $(\vec{\mathbf{w}}_{\text{fp}})$ in relation with the worst alternative output $(\mathbf{Q})^{-1}$ and environment footprint (**g**) of the cultivation system. It is expressed in Equation 4.22. This model template is built using Microsoft Excel spreadsheet file, with solved using the standard Solver add-in. The LCA data for all the cultivation systems are required to perform the LCO.

$$\text{minimize } f(x) = (w_1 \;\; w_2 \;\; w_3 \;\; w_4)\begin{pmatrix} Q_{1,1} & & & \\ 0 & Q_{2,2} & & \\ 0 & 0 & Q_{3,3} & \\ 0 & 0 & 0 & Q_{4,4} \end{pmatrix}^{-1}\begin{pmatrix} \mathbf{g}_1 \\ \mathbf{g}_2 \\ \mathbf{g}_3 \\ \mathbf{g}_4 \end{pmatrix} \qquad \textbf{Equation 4.22}$$

Table 4.28: Inverse matrix of Worst scenario, $\mathbf{Q}^{-1}$ (from Table 4.5)

Overall environment footprint	Energy (kWh)	CO_2 (ton)	Indirect Water (ton)	Direct Water (ton)
Energy (kWh)	4.656E-05	0	0	0
CO_2 (ton)	0	0.140157402	0	0
Indirect Water (ton)	0	0	6.73E-05	0
Direct Water (ton)	0	0	0	0.149925

The results are further optimized by integrating FAHP weights to determine the environmental concern preference and best process configuration as shown in Table 4.29 (See solution in Appendix E). The integrated FAHP-LCO model has shown that the flate-plate photobioreactor (FPPBR) system is the best technology option, considering the environmental criteria. This is due to the associated weights for water footprint (both indirect and direct water at 43 %, respectively) which are relatively more important when compared with the other environmental footprints.

Table 4.29: Integrated FAHP-LCO optimum solution for cultivation process

Environmental Footprint	FAHP weightage, $\vec{\mathbf{w}}_{fp}$	Normalized Value, $\mathbf{g(Q)}^{-1}$	Optimized Value
Energy (kWh)	0.04	0.173	3.72E+03
CO_2 (ton)	0.10	0.182	1.30E+00
Indirect Water (ton)	0.43	0.174	2.58E+03
Direct Water (ton)	0.43	0.504	3.36

Alternately, LINGO v14 can be used to solve the model (see Appendix D for LINGO formulation).

4.6 Sensitivity Analysis

Sensitivity analysis is conducted to examine how variations in criteria weights influence the selection of option. Figures 4.7 to 4.10 demonstrate the sensitivity analysis by changing the respective footprint weights. This is done by parametrically adjusting the weight of one footprint, while keeping constant the relative proportions of all the other criteria. For instance, Figure 4.7 shows how the environmental output changes when the energy footprint's weight varies from 0 to 1. The environmental output can be compared with Table 4.5 for each process option's output (3718 kWh for energy consumption, 1.3 ton of CO_2 emission, 2583 ton of direct water consumption and 3.4 ton of indirect water consumption). Note that FPPBR remain as the selected system for cultivation system regardless of the changes of weights for each environmental impact criterion. There is no changes in the selection option were observed as the weights of the environmental footprint change between intervals of 0 to 1. This analysis shows that FPPBR remain as sole option for cultivation system whenever the judgement of the preference is changed.

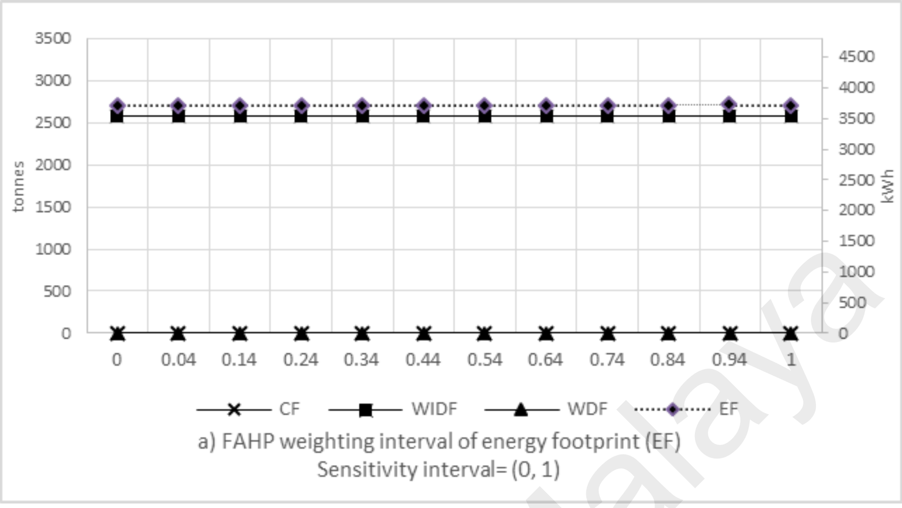

Figure 4.7: Sensitivity analysis for the FAHP weights of environmental footprint for cultivation system at each different footprint's weight interval (0, 1) for energy footprint

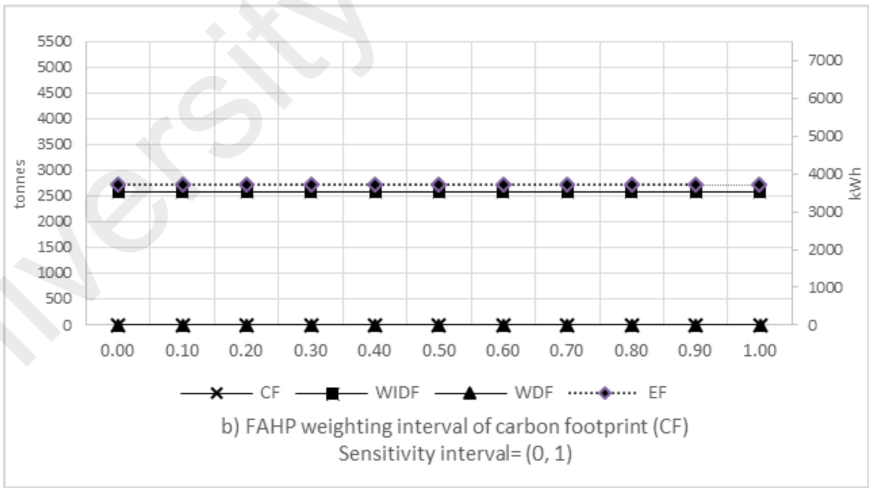

Figure 4.8: Sensitivity analysis for the FAHP weights of environmental footprint for cultivation system at each different footprint's weight interval (0, 1) for carbon footprint

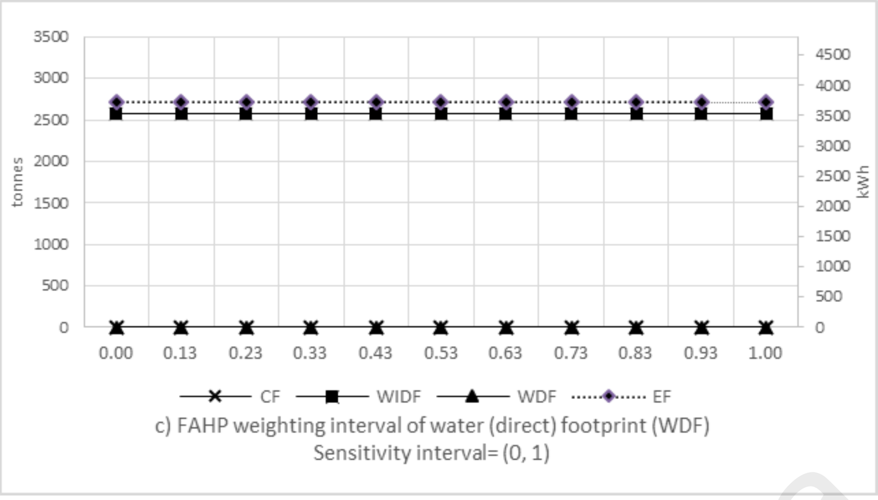

Figure 4.9: Sensitivity analysis for the FAHP weights of environmental footprint for cultivation system at each different footprint's weight interval (0, 1) for direct water footprint

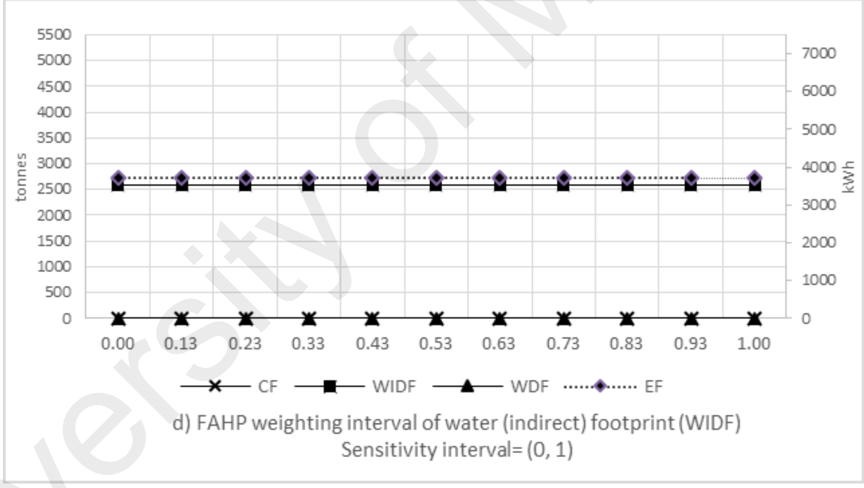

Figure 4.10 Sensitivity analysis for the FAHP weights of environmental footprint for cultivation system at each different footprint's weight interval (0, 1) for indirect water footprint

4.7 Summary

In this chapter, an integrated FAHP-LCO methodology has been developed and applied in the selection of the best technology for the cultivation system of microalgae.

In this approach, FAHP is used to identify the environmental criteria weights, which are then utilized within MOLP model to integrate the energy, carbon dioxide and water footprint limits. The priority weights are systematically elicited from an expert's opinion via FAHP. The proposed modeling framework is then applied to a case study with multiple microalgae cultivation pathways. By solving the model, it is found that the FPPBR cultivation system is the optimum solution. Sensitivity analysis is performed to give insights on the robustness of the decision model particularly with respect to criteria weights.

CHAPTER 5: AN INTEGRATED FUZZY ANALYTIC HIERARCHY PROCESS AND LIFE CYCLE OPTIMIZATION FOR HARVESTING AND DRYING PROCESS OF MICROALGAE

5.1 Introduction

Chapter 5 mainly shows the application of an integrated fuzzy analytic hierarchy process and life cycle optimization (FAH-LCO) for harvesting and drying processes of microalgae. Life cycle assessment (LCA) for each alternative method of harvesting and drying system is carried out, respectively. Then, it is followed by constructing the analytic hierarchy network (AHP) for harvesting and drying system. Fuzzy analytic hierarchy process (FAHP) is developed for evaluating the alternatives in the microalgae harvesting and drying system. An illustrative case study on the harvesting and drying processes is discussed using the FAHP technique. Sensitivity analysis is also performed to study how robust the ranking of the alternatives on the weighting of the criteria. Finally, the FAHP is integrated into the LCO to perform optimization in selecting the best alternative method.

5.2 Life Cycle Assessment for Harvesting System

5.2.1 Goal and Scope

The goal of this LCA is to identify the environmental performance of different harvesting alternatives. Similar with LCA study for cultivation process in Chapter 4, all the data are normalized to a functional unit of one ton of dry biomass. Flate-plate photobioreactor (FPPBR) system is selected in this system based on the MOO decision in Chapter 4 where it stands as the best option. Figure 5.1 illustrates the gate-to-gate system boundary for the LCA. Four alternatives are identified based on recommendations of Uduman *et al*., (2010). They are: (1) centrifugation (CG), (2) filtration (FL), (3) flotation (FT) and (4) flocculation-sedimentation (FS). The results of this LCA are used to facilitate the best alternative selection in the later section.

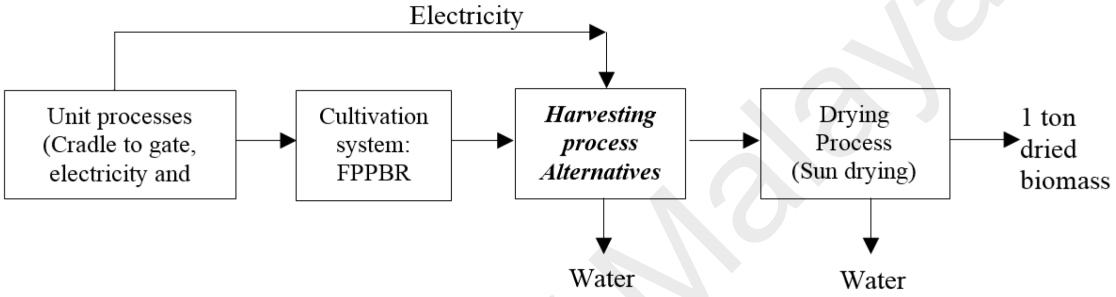

Figure 5.1: Gate to gate System boundary for harvesting alternatives

5.2.2 Life Cycle Inventory

The technology flow (**A**) and the environment intervention (**B**) are obtained with the reference of one ton of dried biomass produced. Assumptions of the harvesting and drying process are necessary to ensure consistency in the LCA and data inventory as shown in Table 5.1. Table 5.2 presents the overall data of the different methods for harvesting process. Noted that sun drying method is adopted as the drying system to produce dried biomass. There is no energy required for natural sun drying. For the dewatering process by all the alternative methods, dried biomass with solid content of 15% w/w (Zhang *et al*., 2013) is fixed to ensure the consistent comparison of the data.

Table 5.1: Summary of the data source for the evironmental footprint for LCI for harvesting process alternatives

	Environmental footprint	Value	Data source
Centrigue	Energy	8 kWh/m^3	(Grima *et al.*, 2003)
	water	12-22 %	(Shelef *et al.*, 1984)
Filtration	Energy	0.2-0.88 kW/m^3	(Shelef *et al.* 1984)
	water	5-27 %	(Shelef *et al.* 1984)
FS	water	1 kw/m^3	(Uduman *et al.* 2010)
	Energy	80 %	(Grima *et al.* 2003)
Flotation	Energy	1 kw/m^3	(Uduman *et al.* 2010)
	water	7 %	(Milledge and Heaven 2012)

Table 5.2: Technology and intervention matrices for one ton of dry biomass production by different harvesting process

	Centrifuge	Filtration	Flocculation-Sedimentation	Flotation
Process Input (Technology matrix, **A**)				
Electricity (kWh)	-279.53 [a]	-8400 [b]	-178.1 [c]	-134.0 [c]
Salt (ton)	0	0	0	0
Urea (ton)	0	0	0	0
DAP (ton)	0	0	0	0
Wet Microalgae (ton)	0	0	0	0
Dry Biomass (ton)	0	0	0	1
Environmental Footprint (Intervention matrix **B**)				
Energy (kWh)	0.0	0.0	0.0	0.0
CO_2 (ton)	0.0	0.0	0.0	0.0
Direct Water (ton)	-79.98 [b]	78.98	78.98	78.98

[a] Grima *et al.*, 2003
[b] Shelef et al. *1984*
[c] Uduman *et al.* 2010

5.2.3 Life Cycle Impact Assessment

Similarly to Chapter 4, Equation 2.12 to 2.14 are applied to the technology matrix and environmental intervention matrix to obtain the final environment impact output. Table 5.3 shows the summary of the overall environmental footprints of the four different technologies.

Table 5.3: Summary of environmental output of each harvesting process option

Environmental Footprint	Centrifuge	Filtration	Flocculation-Sedimentation	Flotation
Energy (kWh)	-1382.0544	-152.021	-17.27568	-172.757
CO_2 (ton)	0.4542864	0.04997	0.00567858	0.056786
Indirect Water (ton)	-954.737256	-105.018	-11.9342157	-119.342
Direct Water (ton)	78.90	78.90	78.90	78.90

5.3 AHP for Harvesting and Drying System

Four alternatives for each harvesting and drying process options were identified. Cost (COST), environmental impacts (ENV) and technology capability (TECH) were defined as the main criteria in the selection of the most preferred option for harvesting process (Figures 5.2 and 5.3). There are three sub-criteria under the environmental impact, i.e.: carbon footprint (CF), land footprint (LF) and water footprint (WF). The definition for each of the criteria and sub-criteria are defined in Table 5.4.

Table 5.4: AHP criteria definitions

Criteria	Definition
Technology Capability	• Efficiency is in the yield at which microalgae effluent is converted into microalgae cake. Process scale up capability is the potential for the process to be scaled to commercial levels of output
Cost	• Operating cost includes: cost of electricity/power, cost of raw materials, cost of replacement of equipment parts, and labor • Cost of investment is the capital cost to set up the process plant.
Environmental Impact	• Carbon footprint is the carbon dioxide released from the process. • Water footprint is the total volume of direct and indirect fresh water used, consumed, and or polluted by the process • Land footprint is the land area occupied by the process

The alternatives for harvesting process are: (1) centrifugation (CG), (2) filtration (FL), (3) flotation (FT) and (4) flocculation-sedimentation (FS). A comparison of the advantages and disadvantages of the different harvesting alternatives is shown in Table 2.3. (See Chapter 2, Section 2.5 for detail of the harvesting description)

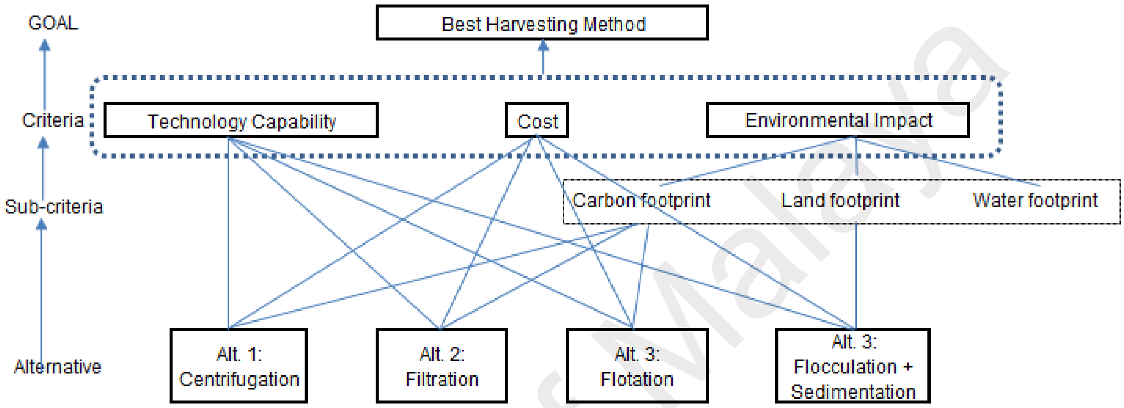

Figure 5.2: AHP decision structure for harvesting process

Likewise, these steps are applied for the selection of the drying process alternatives. The alternatives for selecting the best drying process are: (1) drum drying (DD), (2) freeze drying (FD), (3) spray drying (SPD) and (4) sun drying (SD). Due to the energy consumption incurred in removing water content, drying process causes major economic issues, and accounts for up to 30% of the total production cost (Chen et al. 2011). The requirements for the drying method depend on the scale of operation. In addition, it also depends on the uses of the dried product. Different end product will results in the limitation of choices for the drying alternative. There are some common methods for drying microalgae after secondary dewatering: drum drying, spray drying, sun drying, and freeze drying. Table 2.4 summarizes the advantages and disadvantages of different drying methods. (See Chapter 2, Section 2.6 for more detail on drying process).

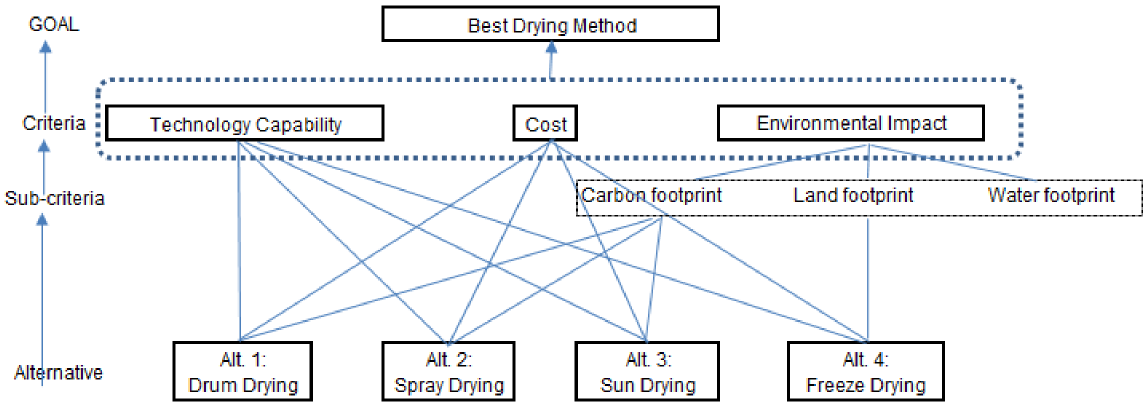

Figure 5.3: AHP decision structure for drying process

Pairwise comparisons based on the expert's judgment are done to derive the relative importance of criteria, sub-criteria and the relative preference of alternatives. Questionnaire was constructed based on this pairwise comparison technique. In this case study, an expert has been consulted based on his technical know-how and vast experience on the research area related to microalgae harvesting and drying processes (See Appendix F for the example of the AHP survey form). For example, such respondent with high confidence perceived that the carbon footprint is very strongly more important than land footprint with respect to the environmental impact criterion for the selection of microalgae harvesting and drying technologies. Note that the weighing of criteria/sub-criteria will depend on the value judgment of experts whose trade-off among these criteria/ sub-criteria is made explicit in the prioritization of alternatives. The AHP weights for the pairwise comparison of all criteria in harvesting selection network are done and to be presented along with the FAHP. The working of the pairwise scale is similar to what been shown in Chapter 4 (Section 4.3). This value judgment is then represented in fuzzy scale.

5.4 FAHP for Harvesting System

The expert performed a pairwise comparison to indicate his preferences. The fuzzy evaluation of the relative importance of sub-criteria with respect to each main-criterion, and the relative preference of alternatives with respect to each sub-criterion are shown in Tables 5.5 to 5.12, respectively. Using commercial optimization software LINGO v14.0 to solve the NLP, the preference weight of the alternatives for harvesting process with respect to the sub-criteria of environment impact (ENV) and main criteria (TECH, COST and ENV) were computed (see Tables 5.13 and 5.14). Note that the λ value is greater than zero indcates the consistency of the judgment in the pairwise comparison matrix. Tables 5.5 to 5.12 are computed based on Saaty's nine scale method. For instance, Table 5.5, the criteria TECH is as importance as criteria COST. Thus, scale 1 is given. However, criteria TECH is moderate importance as compared to ENV criteria. In this case, intensity value of 3 is given. This scale is determine by the expert based on his field of expertise. The expert's indicates his high degree of confidence during the judgement, where δ is set as 1 (refer Figure 2.5). Therefore, the triangular fuzzy representing a judgment of "moderately more important" could be represented by a fuzzy number <0.5, 1, 2> if δ is set to 1. Similarly methodology is applied to others criteria as shown in Tables 5.5 to 5.11. The setting of the fuzzy pairwise comparison matrix is similar method as presented in Chapter 4, Section 4.4.

Table 5.5: Fuzzy pairwise comparison matrix of main criteria for harvesting and drying process

	TECH	COST	ENV
TECH	1	(0.5, 1, 2)	(2, 3, 4)
COST		1	(2, 3, 4)
ENV			1

Table 5.6: Fuzzy pairwise comparison matrix of environmental impact's sub-criteria for harvesting and drying process

	CF	LF	WF
CF	1	(6, 7, 8)	(0.5, 1, 2)
LF		1	(0.125, 0.143, 0.167)
WF			1

Table 5.7: Fuzzy pairwise comparison matrix of harvesting alternatives with respect to technology

	Alt 1: CG	Alt 2: FL	Alt 3: FT	Alt 4: FS
Alt 1: CG	1	(0.5, 1, 2)	(0.167, 0.2, 0.25)	(0.25, 0.33, 0.5)
Alt 2: FL		1	(0.167, 0.2, 0.25)	(0.167, 0.2, 0.25)
Alt 3: FT			1	(0.5, 1, 2)
Alt 4: FS				1

Table 5.8: Fuzzy pairwise comparison matrix of harvesting alternatives with respect to cost

	Alt 1: CG	Alt 2: FL	Alt 3: FT	Alt 4: FS
Alt 1: CG	1	(0.5, 1, 2)	(1,3,5)	(4,5,6)
Alt 2: FL		1	(1,3,5)	(2,3,4)
Alt 3: FT			1	(0.5, 1, 2)
Alt 4: FS				1

Table 5.9: Fuzzy pairwise comparison matrix of harvesting alternatives with respect to Environment's sub-criteria (carbon footprint)

	Alt 1: CG	Alt 2: FL	Alt 3: FT	Alt 4: FS
Alt 1: CG	1	(0.125, 0.143, 0.167)	(0.167, 0.2, 0.25)	(1, 2, 3)
Alt 2: FL		1	(6, 7, 8)	(6, 7, 8)
Alt 3: FT			1	(0.5, 1, 2)
Alt 4: FS				1

Table 5.10: Fuzzy pairwise comparison matrix of harvesting alternatives with respect to Environment's sub-criteria (land footprint)

	Alt 1: CG	Alt 2: FL	Alt 3: FT	Alt 4: FS
Alt 1: CG	1	(0.125, 0.143, 0.167)	(0.5, 1, 2)	(0.33, 1, 3)
Alt 2: FL		1	(6, 7, 8)	(6, 7, 8)
Alt 3: FT			1	(0.33, 1, 3)
Alt 4: FS				1

Table 5.11: Fuzzy pairwise comparison matrix of harvesting alternatives with respect to Environment's sub-criteria (water footprint)

	Alt 1: CG	Alt 2: FL	Alt 3: FT	Alt 4: FS
Alt 1: CG	1	(0.125, 0.143, 0.167)	(0.125, 0.143, 0.167)	(1, 2, 3)
Alt 2: FL		1	(0.5, 1, 2)	(0.5, 1, 2)
Alt 3: FT			1	(0.5, 1, 2)
Alt 4: FS				1

Equations 5.1 to 5.2 are the matrices multiplication of the weights for each sub-criteria in the FAHP network in order to get the final priority weights. Table 5.12 indicates the weights for each of the alternative for harvesting with respect to the environment criteria. Meanwhile, Table 5.12 shows the weights of the main criteria (technology, cost and environmental) relatively to the different harvesting alternatives.

$$\boldsymbol{ENV_{overall,j} = \sum_{j=1}^{n}\left[ENV_{sub,i,j}\, W_{ENV,i}\right]} \qquad \textbf{Equation 5.1}$$

$$\boldsymbol{MC_{overall,j} = \sum_{j=1}^{n}\left[MC_{sub,i,j}\, W_{MC,i}\right]} \qquad \textbf{Equation 5.2}$$

Table 5.12: Normalized weights of harvesting alternatives with respect to each environment's sub-criteria[a]

Alternative	Carbon footprint[b] ($w^{\#} = 0.467$)	Land footprint[c] ($w^{\#} = 0.067$)	Water footprint[d] ($w^{\#} = 0.467$)	Overall Weights $\boldsymbol{ENV_{overall,j}}$
Alt 1: CG	0.100	0.100	0.062	0.082
Alt 2: FL	0.669	0.700	0.374	0.534
Alt 3: FT	0.099	0.100	0.374	0.228
Alt 4: FS	0.099	0.100	0.191	0.142

[a] weighting from FAHP method ($\lambda = 0.999$)
[b] weighting from FAHP method ($\lambda = 1.000$)
[c] weighting from FAHP method ($\lambda = 0.999$)
[d] weighting from FAHP method ($\lambda = 0.043$)
[#] criteria weights based on Table 5.6 ($\lambda = 0.999$)

Table 5.13: Normalized weights of harvesting alternatives with respect to main criteria[b]

Alternative	TECH[c] ($w^* = 0.429$)	COST[d] ($w^* = 0.429$)	ENV ($w^* = 0.143$)	Overall weights
Alt 1: CG	0.119	0.446	0.082	0.254
Alt 2: FL	0.087	0.325	0.534	0.253
Alt 3: FT	0.397	0.132	0.228	0.259
Alt 4: FS	0.397	0.096	0.142	0.232

[b] weighting from FAHP method ($\lambda = 1.0$)
[c] weighting from FAHP method ($\lambda = 0.627$)
[d] weighting from FAHP method ($\lambda = 0.628$)
* criteria weights based on Table 5.5

Table 5.14 summarizes the overall priorities and ranking of the alternatives using the proposed method as described in Tables 5.12 and 5.13. Results show that the most preferred harvesting method is flotation (FT) (with an overall score of 0.259) followed closely by centrifugation (CG) (with an overall score of 0.254). On the other hand, filtration (FL) is ranked third option, and then followed by flocculation-sedimentation (FS). This is mainly due to the cost effectiveness of the dominant alternatives in terms of their lower energy requirement. The ranking of the alternatives is based on the equal importance weighting of technology capability and cost (0.429) provided by the domain expert; whereas environmental impact was rated at a relatively lower weight (0.143).

Table 5.14: Overall priorities and ranking of harvesting alternatives

Alternatives	Overall Score	Ranking
Centrifugation (CG)	0.254	2
Filtration (FL)	0.253	3
Flotation (FT)	0.259	1
Flocculation & Sedimentation (FS)	0.232	4

5.5 FAHP for Drying System

FAHP is conducted to verify the robustness of selection has matches the decision by the experts and LCA results. Similar as FAHP of harvesting system, FAHP methodology been repeated for drying system. Tables 5.15-5.19 show the fuzzy evaluation of the relative importance of sub-criteria with respect to each main-criterion, and the relative preference of alternatives with respect to each sub-criterion.

Table 5.15: Fuzzy pairwise comparison matrix of drying alternatives with respect to technology

	Alt 1: DD	Alt 2: FD	Alt 3: SPD	Alt 4: SS
Alt 1: DD	1	(0.11, 0.11, 0.125)	(0.25, 0.33, 0.5)	(6, 7, 8)
Alt 2: FD		1	(4, 5, 6)	(8, 9, 9)
Alt 3: SPD			1	(6, 7, 8)
Alt 4: SD				1

Table 5.16: Fuzzy pairwise comparison matrix of drying alternatives with respect to cost

	Alt 1: DD	Alt 2: FD	Alt 3: SPD	Alt 4: SS
Alt 1: DD	1	(0.125, 0.143, 0.167)	(0.125, 0.143, 0.167)	(6, 7, 8)
Alt 2: FD		1	(2, 3, 4)	(8, 9, 9)
Alt 3: SPD			1	(6, 7, 8)
Alt 4: SD				1

Table 5.17: Fuzzy pairwise comparison matrix of drying alternatives with respect to Environment's sub-criteria (carbon footprint)

	Alt 1: DD	Alt 2: FD	Alt 3: SPD	Alt 4: SS
Alt 1: DD	1	(0.125, 0.143, 0.167)	(0.250, 0.333, 0.500)	(0.5, 1, 2)
Alt 2: FD		1	(4, 5, 6)	(8, 9, 9)
Alt 3: SPD			1	(2, 3, 4)
Alt 4: SD				1

Table 5.18: Fuzzy pairwise comparison matrix of drying alternatives with respect to Environment's sub-criteria (land and water footprint)

	Alt 1: DD	Alt 2: FD	Alt 3: SPD	Alt 4: SS
Alt 1: DD	1	(0.5, 1, 2)	(0.5, 1, 2)	(0.5, 1, 2)
Alt 2: FD		1	(0.5, 1, 2)	(0.5, 1, 2)
Alt 3: SPD			1	(0.5, 1, 2)
Alt 4: SD				1

Equations 5.1 to 5.2 are the matrices multiplication of the weights for each sub-criteria in the FAHP network in order to get the final priority weights. Table 5.19 indicates the weights for each of the alternative for drying with respect to the environment criteria. Meanwhile, Table 5.20 shows the weights of the main criteria relatively to the different drying alternatives.

Table 5.19: Normalized weights of drying alternatives with respect to each environment's sub-criteria[a] for drying process

Alternative	Carbon footprint[b] ($w^{\#} = 0.467$)	Land footprint[c] ($w^{\#} = 0.067$)	Water footprint[d] ($w^{\#} = 0.467$)	Overall weights
Alt 1: DD	0.083	0.250	0.250	0.172
Alt 2: FD	0.667	0.250	0.250	0.445
Alt 3: SPD	0.167	0.250	0.250	0.211
Alt 4: SD	0.083	0.250	0.250	0.172

[a] weighting from FAHP method ($\lambda = 0.999$)
[b] weighting from FAHP method ($\lambda = 0.4366 \times 10^{-8}$)
[c] weighting from FAHP method ($\lambda = 1.000$)
[d] weighting from FAHP method ($\lambda = 1.000$)
[#] criteria weights based on Table 5.6 ($\lambda = 0.999$)

Table 5.20: Normalized weights of drying alternatives with respect to main criteria[b]

Alternative	TECH[c] ($w^* = 0.429$)	COST[d] ($w^* = 0.429$)	ENV ($w^* = 0.143$)	Overall score
Alt 1: DD	0.11	0.092	0.172	0.353
Alt 2: FD	0.015	0.657	0.445	0.110
Alt 3: SPD	0.109	0.219	0.211	0.090
Alt 4: SD	0.765	0.031	0.172	0.447

[b] weighting from FAHP method ($\lambda = 1.00$)
[c] weighting from FAHP method ($\lambda = 1.00$)
[d] weighting from FAHP method ($\lambda = 1.00$)
[*] criteria weights based on Table 5.5

Tables 5.21 indicate the results of the prioritization method for drying process alternatives. It shows both the aggregate scores and the resulting ranks of the available options. The most preferred method for microalgae drying is sun drying, followed in descending order by drum drying, freeze drying, and spray drying when ones evaluate from the multiple criteria perspective.

Table 5.21: Overall priorities and ranking of drying alternatives

Alternative	**Overall Score**	**Ranking**
Drum drying (DD)	0.353	2
Freeze drying (FD)	0.110	3
Spray drying (SPD)	0.090	4
Sun drying (SD)	0.447	1

5.6 Life Cycle Optimization

The results are for harvesting and drying process are further optimized by integrating FAHP weights to determine the environmental concern preference and best process configuration as shown in Table 5.3 (worst scenario). LCO is done for harvesting and drying system by integrating the priority weights with the optimization model. Equations 4.4 to 4.8 as represent the overall formulation of MOO.

Table 5.22: Worst scenario (**Q**) for harvesting process

Environmental Footprint	Energy (kWh)	CO_2 (ton)	Indirect Water (ton)	Direct Water (ton)
Energy (kWh)	0.000723561	0	0	0
CO_2 (ton)	0	2.201254539	0	0
Indirect Water (ton)	0	0	0.001047409	0
Direct Water (ton)	0	0	0	0.012661433

The integrated FAHP-LCO model has shown that the filtration and sun drying system is the best technology option based on the optimum value (min z = 0). This proven that one can use the MOO to identify best solution for the selection with the integrated of the desire selection criteria, where in this case study, environmental impact is the selection factor.

5.7 Sensitivity Analysis

Sensitivity analysis is conducted to examine how variations in criteria weights influence the selection of harvesting or drying alternatives. The sensitivity analysis is demonstrated by changing the respective criteria weights in harvesting and drying alternatives. This is done by parametrically adjusting the weight of one criterion, while keeping constant the relative proportions of all the other criteria. For example, Figure 5.4 shows how the ranking of alternatives changes when the carbon footprint's weight varies from 0 to 1. It can be seen that when the carbon footprint is not taken into consideration as one of the sub-criteria of environmental impact, flotation (FT) and centrifugation (CG) are still the dominant alternatives but rank reversal occurs between filtration (FL) and flocculation-sedimentation (FS). In contrast, if carbon footprint is considered as the sole criterion for environmental impact, filtration is the most preferred followed by centrifugation, flotation and flocculation-sedimentation. Note that centrifugation (CG) alternative is still ranked second regardless of the changes of weights for each environmental impact criterion. The results also indicate that drying alternatives' ranking is more sensitive as compared to harvesting alternatives for its different environmental impacts (ENV) criteria. This includes carbon footprint, land footprint and water footprint (Figures 5.4 to 5.6 for harvesting's environmental impact criteria; Figures 5.9 to 5.11 for drying's environmental impact criteria) As shown in Figures 5.9 to 5.11, no significant changes in the ranking for drying alternatives ware observed as the weights of the environmental footprint change. In this case, sun drying (SD) and drum drying (DD) remained to be the dominant alternatives.

As for the sensitivity of the ranking of harvesting alternatives on the technology (TECH) criterion, major rank reversal occurred when the relative importance of technology was changed to above 0.43 (see Figure 5.7). Below this value, filtration (FL) was the most preferred alternative whereas flocculation-sedimentation (FS) is the least preferred one. However, flotation (FT) and flocculation-sedimentation (FS) became the most preferred harvesting process and flotation (FT) was least preferred one if the technology criterion is given more weight, i.e., above 0.43. This rank reversal also occurred for the first and second most preferred alternatives for the drying process when the weights of technology criterion was changed to below 0.34 (see Figure 5.12). Above this value, sun drying is the most preferred drying process but became second to drum drying when the weight of technology is below 0.34.

As for the sensitivity of the ranking of harvesting alternatives on the cost criterion, major rank reversal occurred when the importance weight of cost is changed to above 0.43 (see Figure 5.8). Below this value, flotation is ranked first but above this value, centrifugation became the most preferred harvesting process. Likewise, Figure 5.13 shows the sensitivity of the ranking of drying alternatives when the cost's weight varies between 0 and 1. Major rank reversal occurred for the first and second most preferred alternatives when the relative importance of cost is changed to above 0.53. Above this value, drum drying was the most preferred alternative, followed by sun drying (SD), freeze drying (FD) and spray drying (SPD). Below this value, sun drying is the most preferred drying process whereas drum drying became the second preferred alternative. Sun drying (SD) remained to be ranked first when the importance weight of cost criterion is less than 0.53. In addition, drum drying (DD) is ranked third whereas spray drying (SPD) became second if the importance weight of the cost is very small.

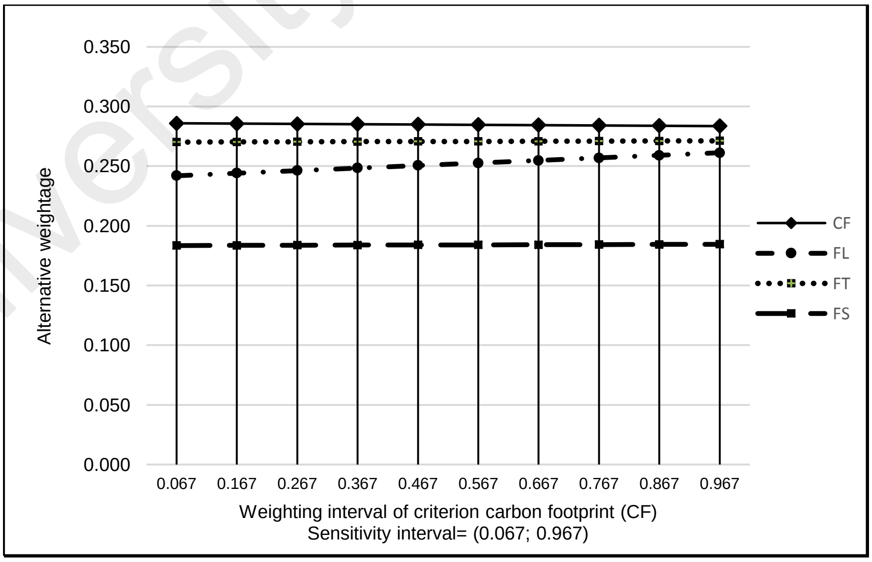

Figure 5.4: Sensitivity analysis of the priority weights of alternatives for harvesting process at carbon footprint's weight interval (0, 1)

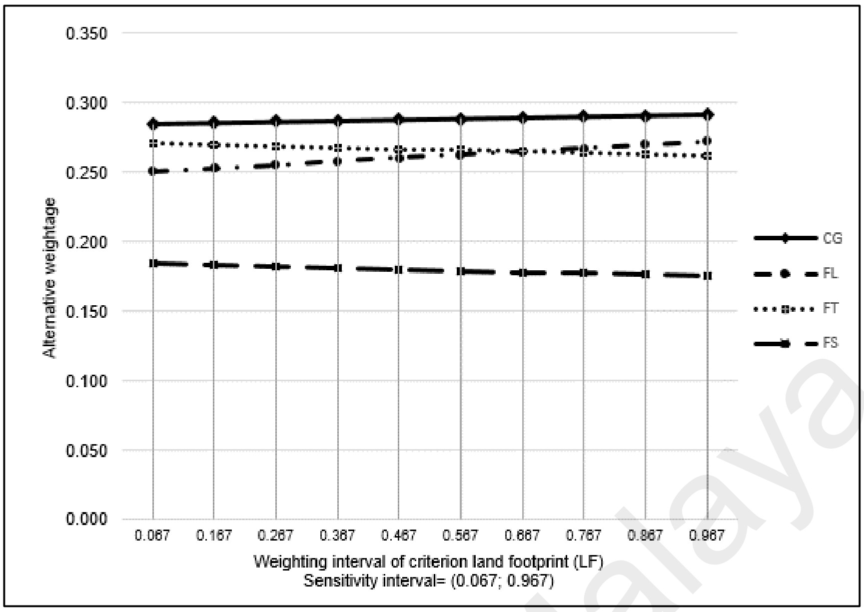

Figure 5.5: Sensitivity analysis of the priority weights of alternatives for harvesting process at land footprint's weight interval (0, 1)

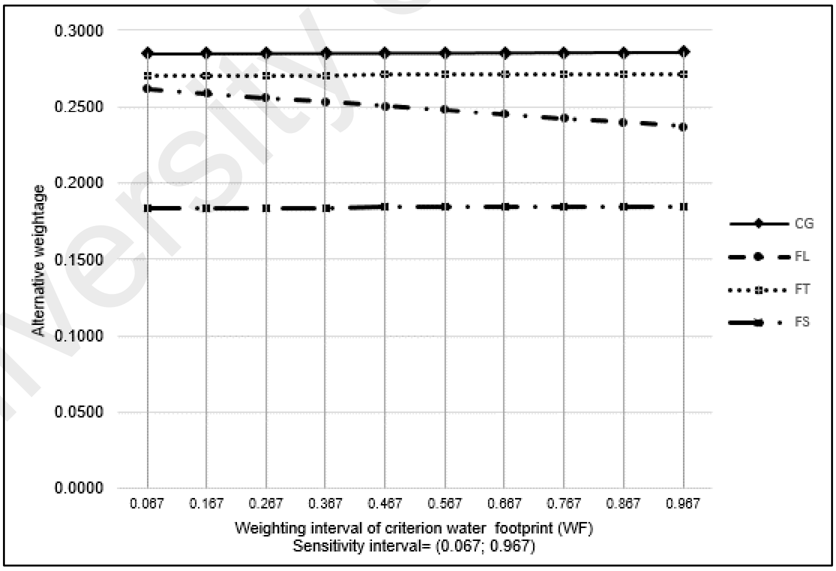

Figure 5.6: Sensitivity analysis of the priority weights of alternatives for harvesting process at water footprint's weight interval (0, 1):

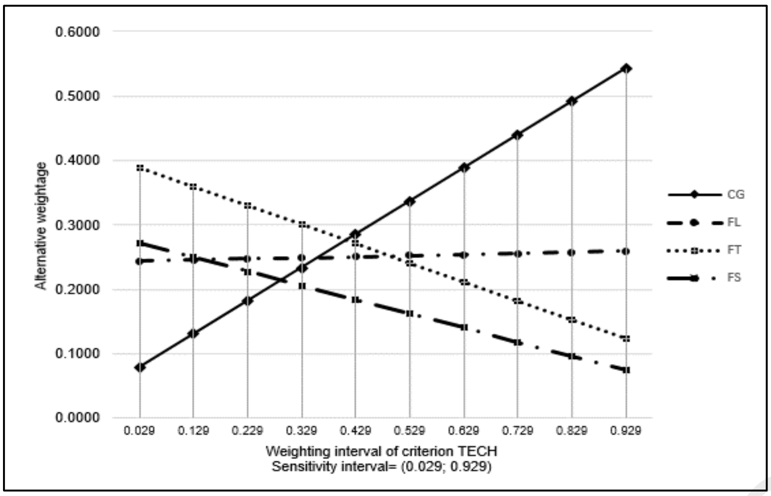

Figure 5.7: Sensitivity analysis of the priority weights of alternatives for harvesting process at TECH's weight interval (0, 1):

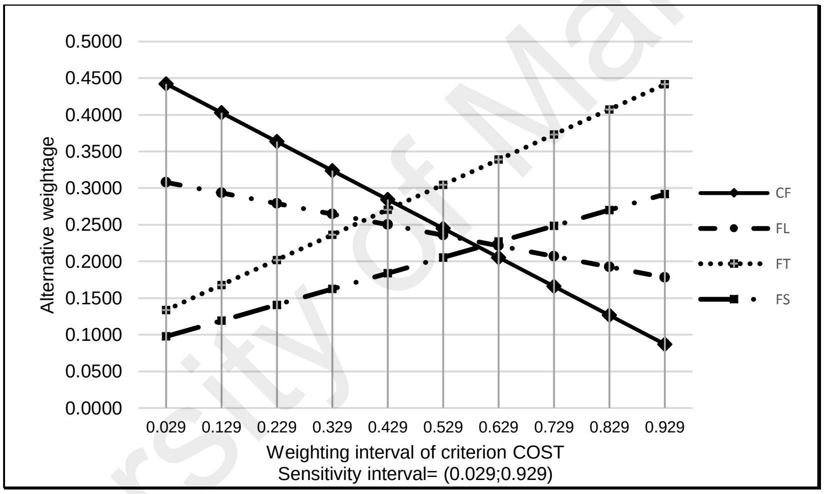

Figure 5.8: Sensitivity analysis of the priority weights of alternatives for harvesting process at COST's weight interval (0, 1):

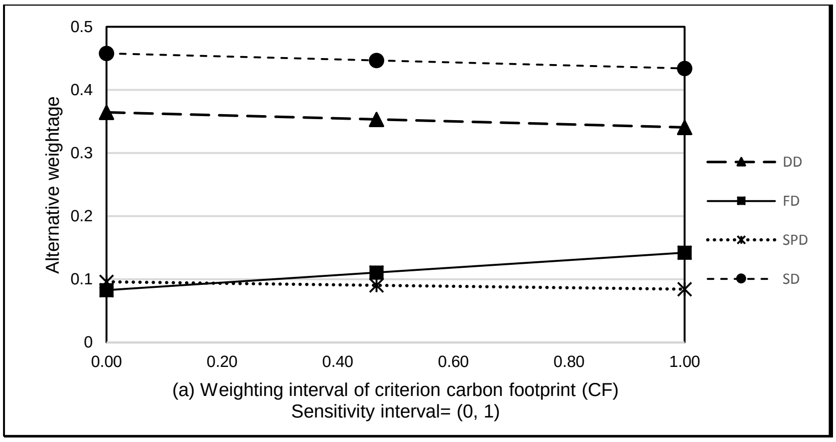

Figure 5.9: Sensitivity analysis of the priority weights of alternatives for drying process at carbon footprint's weight interval (0, 1)

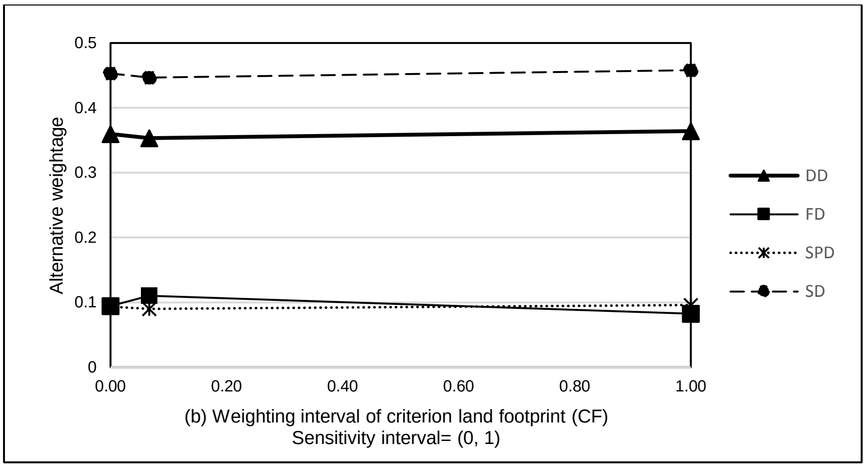

Figure 5.10: Sensitivity analysis of the priority weights of alternatives for drying process at land footprint's weight interval (0, 1)

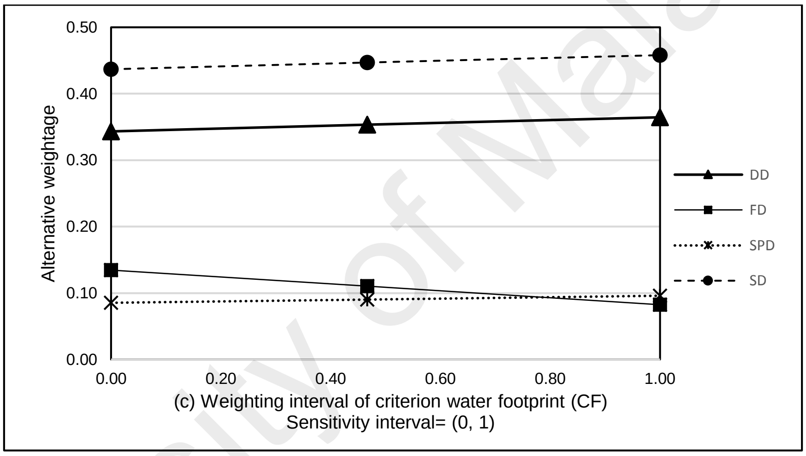

Figure 5.11: Sensitivity analysis of the priority weights of alternatives for drying process at water footprint's weight interval (0, 1):

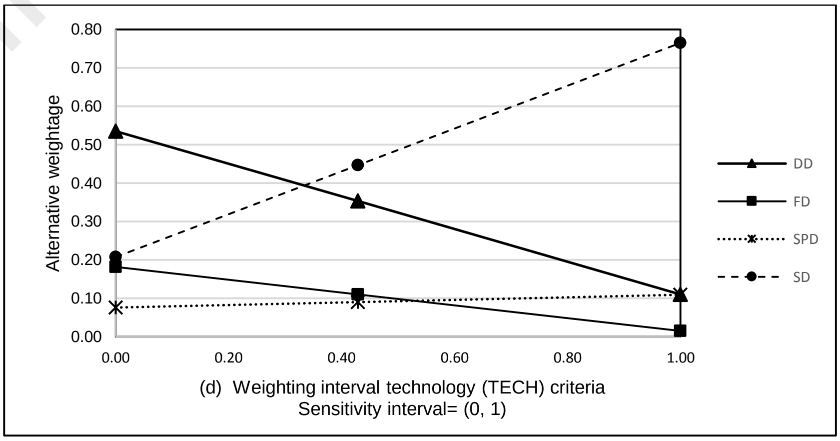

Figure 5.12: Sensitivity analysis of the priority weights of alternatives for drying process at TECH's weight interval (0, 1):

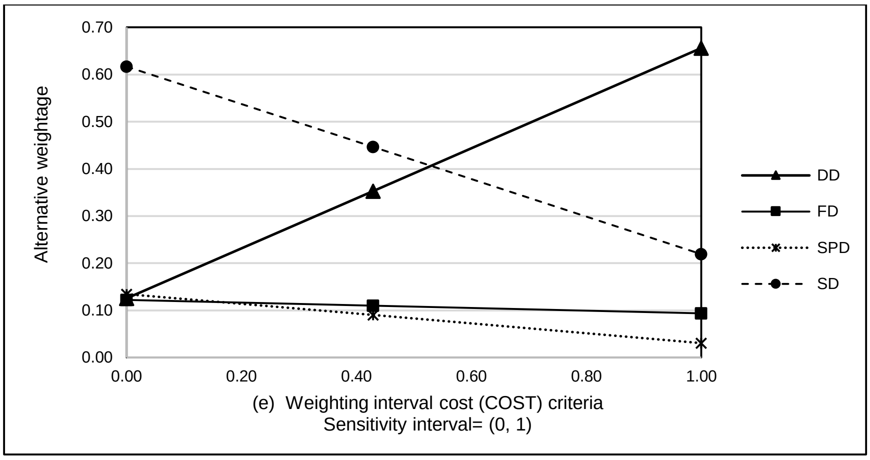

Figure 5.13: Sensitivity analysis of the priority weights of alternatives for drying process at COST's weight interval (0, 1):

Filtration is preferred alternative when carbon footprint and land footprint are the dominating environmental criteria. However, a rank reversal may occur wherein the combination of flocculation and sedimentation becomes the most preferred alternative when decision maker tends to give more weight on the water footprint and technology capability criteria. In the scenario when environmental criteria are given more weight, filtration and freeze drying are the most preferred alternatives for harvesting and drying process of microalgae, respectively.

5.8 Summary

In this chapter, FAHP-LCO model is applied to evaluate and prioritize for the harvesting and drying processes in the microalgae industry. In this case, filtration and sun drying are the most preferred alternative for harvesting and drying process, respectively. Sensitivity analysis is performed to gain insights on the robustness of the decision model and to understand critical criteria that would significantly influence the ranking of the alternatives. Filtration is preferred alternative when carbon footprint and land footprint are the dominating environmental criteria. However, a rank reversal may occur wherein the combination of flocculation and sedimentation becomes the most preferred alternative when decision maker tends to give more weight on the water footprint and technology capability criteria. In the scenario when environmental criteria are given more weight, filtration and freeze drying are the most preferred alternatives for harvesting and drying process of microalgae, respectively.

CHAPTER 6: CONCLUSION

6.1 Conclusion and Significance

In conclusion, the integrated methodology has been developed for selecting the best technology option and process configuration for the production of microalgae. This integrated fuzzy analytic process (FAHP) and life cycle optimization (LCO) is identified as one of the sustainable decision making strategies for the production of microalgae. Several major contributions on FAHP-LCO are offered in this thesis, covering both insight-based and mathematical optimization-based approaches.

The analytic hierarchy process (AHP) is used to identify the environmental criteria weights, which are then utilized within a hybrid multiple objective linear program (MOLP) utilizing an input-output model to integrate the energy, carbon dioxide and water footprint limits. Through AHP, the subjective preferences of an expert are captured in quantitative form. FAHP model is developed and applied to evaluate and prioritize for the cultivation, harvesting and drying processes in the microalgae industry. The model used fuzzy numbers to reflect the ambiguity-type uncertainty and degree of confidence of expert judgment. LCO is based on the combination of life cycle assessment (LCA) with mathematical programming. Realistic case study for both cultivation, harvesting and drying process are solved to illustrate the application of the proposed modeling framework.

This research has successfully conducted the evaluation of different cultivation and harvesting methods of microalgae production using proposed model. Optimization procedure with considers the three environmental aspects, namely, energy, water (both direct and indirect) and carbon footprints. It is concluded that flat-plate photobioreactor cultivation system is the optimum solution, compared to other alternatives. Then, followed by filtration and sun drying as the most preferred alternative for harvesting and drying process.

The proposed model can provide valuable insights in designing the upstream processes of microalgae production prior to technology selection. It also manage to overcome the challenges in multiple objective optimization by identifying the appropriate aggregation method to integrate the objectives into a single performance index. This thesis also can serves as the guides for chemical production multi criteria decision analysis (MCDA) framework which take into consideration of the system parameter either quantitatively or qualitatively. The purpose of MCDA is not always to single out the correct decision but to help improve understanding in a way that facilitates a decision-making process involving risk, multiple criteria, and conflicting interests. It also able to visualize trade offs among multiple conflicting criteria and quantifies the uncertainties necessary for comparison of available remedial and abatement alternatives. This process helps technical project personnel, as well as decision makers and stakeholders, to systematically consider and apply value judgments to derive a most favorable management alternative.

6.2 Future Work

Future work can extend this approach to consider more alternatives or consider the problem in more detail using more sub-criteria elements in the decision structure. It may also be applied for evaluating different areas of microalgae production which includes of biofuel production to solve larger scale decision-making problem. Group decision-making model to integrate inputs of multiple experts with uncertainty analysis is also another possible extension. On the other hand, there are other MCDA methods, such as Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE), and Technique for Order Performance by Similarity to Ideal Solution (TOPSIS) which provides methods for participatory decision making in which stakeholder values are elicited and explicitly incorporated into the decision process. Different MCDA methods have strengths and limitations. No matter which analytical decision tool is selected, implementation requires complex, often impossible trade offs. This complexity is probably one of the main reasons why MCDA is still not widely used in practical applications. However, explicit and structured approaches will often result in a more efficient and effective decision process as compared with the often intuition- and bias-driven decision processes that regulatory agencies are often accused of using in decision making. Performing different MCDA methods able to validate of results. Apart of that, focusing effort directed at integrating MCDA principles and tools with existing approaches, including the use of risk and cost-benefit analysis, will lead to more effective, efficient, and credible decision making.

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