METHODOLOGY FOR ASSESSING THE SUSTAINABILITY OF HOLLOW FIBER MEMBRANE SYSTEM FOR WASTEWATER TREATMENT

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To my sweet little princess, Sofia.

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ABSTRACT

The world's supply of fresh water is finite and threatened by pollution such as the wastewater discharged from industries. Lately, the use of membrane system has received increasing attention for wastewater treatment. Though the membrane performance are usually determined, its performance from the sustainability perspective has received less attention. In line with the Malaysian government policy, the membrane system used for wastewater treatment needs to be scrutinized to ensure its sustainability according to the Triple Bottom Line aspects including environmental, social and economic. Previously, several tools or frameworks have been developed for assessing sustainability. However, most of the available tools assess membrane usage phase only without considering other phases of life cycle. This research aims to identify influencing parameters for assessing the sustainability of hollow fiber membrane system for wastewater treatment. In addition, a methodology for assessing the sustainability of membrane system was developed using fuzzy logic approach. It enables the assessment in the range between *sustainable* and *non-sustainable* membrane system. Life Cycle Assessment model was also developed to analyze the environmental burdens on the membrane system. GaBi software was employed to identify the parameters involved that cross the system boundary. The system boundary selected was from *cradle-to-grave* which consists of materials, fabrication process, transportation, usage and end of life phases. There were 29 parameters selected in the analysis. A Graphical User Interface was constructed using MATLAB platform, which was embedded with fuzzy linguistic calculation. A case study consists of a typical membrane system was successfully assessed by using the developed methodology. The results indicated that the sustainability level of the hollow fiber membrane module was high with an overall index value of 0.73. Fabrication process phase needs more attention in terms of sustainability as its index values were 0.27, 0.31, and 0.58 for environmental, social, and economic, respectively. For validation purposes, the results of the assessment were compared with the existing methodologies called ReCiPe and EcoIndicator99. However, the result from ReCiPe approach was limited to environmental aspect only. As for the social aspect, the findings were compared with the EcoIndicator99 approach. The results showed that the fuzzy evaluation method is able to assess the sustainability level of membrane system at par with the one obtained from EcoIndicator99.

ABSTRAK

Bekalan air bersih adalah terhad dan kini terancam dengan pencemaran air sisa yang dihasilkan oleh industri. Sejak kebelakangan ini, sistem membran semakin mendapat perhatian yang tinggi bagi merawat air sisa. Walaupun prestasi membran biasanya diukur, namun prestasi dari perspektif kelestarian telah mendapat kurang perhatian. Selari dengan dasar kerajaan Malaysia, sistem membran yang digunakan untuk rawatan air sisa perlu diteliti bagi memastikan ianya lestari mengikut aspek *Triple Bottom Line* yang merangkumi aspek alam sekitar, sosial dan ekonomi. Sebelum ini, beberapa alat telah dibangunkan untuk menilai tahap kelestarian. Walau bagaimanapun, kebanyakan alat yang dibangunkan hanya menilai membran pada fasa kegunaan sahaja tanpa mengambil kira fasa-fasa lain dalam suatu kitar hayat. Tujuan kajian ini adalah untuk mengenalpasti parameter-parameter yang mempengaruhi penilaian tahap kelestarian sistem membran gentian berongga untuk merawat air sisa. Tambahan pula, kaedah untuk menilai kelestarian sistem membran dibangunkan dengan menggunakan pendekatan logika kabur. Ia membolehkan penilaian dibuat dalam julat diantara kelestarian dan ketidaklestarian sistem membran. Model Penilaian Kitar Hayat juga telah dibangunkan untuk menganalisis beban alam sekitar terhadap sistem membrane. Perisian GaBi puladigunakan untuk mengenal pasti parameter yang terlibat dalam melintasi sempadan sistem. Sempadan sistem yang dipilih adalah dari *cradle-to-grave* yang merangkumi fasa bahan, proses pembuatan, pengangkutan, penggunaan dan fasa hayat akhir. Terdapat 29 parameter yang dipilih di dalam kaedah ini. Sebuah paparan *Graphical User Interface* telah dibangunkan menggunakan platfom MATLAB, yang mengandungi pengiraan logika kabur menggunakan bahasa kabur. Satu kajian kes melibatkan sistem membran biasa telah berjaya dinilai dengan menggunakan kaedah yang dibangunkan. Hasil kajian menunjukkan bahawa tahap kelestarian modul membran gentian berongga adalah tinggi dengan nilai indek keseluruhan adalah 0.73. Proses fabrikasi memerlukan lebih perhatian dari segi aspek kelestarian dengan nilai 0.27, 0.31, dan 0.58 masing-masing untuk aspek alam sekitar, sosial dan ekonomi. Untuk tujuan pengesahan, keputusan penilaian telah dibandingkan dengan kaedah yang setara iaitu ReCiPe dan EcoIndicator99. Namun, keputusan kaedah ReCiPe adalah terhad untuk aspek alam sekitar sahaja. Untuk aspek sosial, keputusan telah dibandingkan dengan kaedah EcoIndicator99. Hasil menunjukkan bahawa kaedah logika kabur mampu menilai prestasi kelestarian sistem membran yang setara dengan kaedah yang diperolehi dari EcoIndicator99.

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LIST OF ABBREVIATIONS

1D	-	One Dimensional
2D	-	Two Dimensional
3D	-	Three Dimensional
AI	-	Artificial Intelligence
ANN	-	Artificial Neural Network
AP	-	Acidification Potential
BF	-	Bore Fluid
BOD	-	Biological Oxygen Demand
BOM	-	Bill of Material
CH_4	-	Methane
cm	-	Centimeter
CO	-	Carbon Monoxide
CO_2	-	Carbon Dioxide
COD	-	Chemical Oxygen Demand
Cr	-	Chromium
Cu	-	Copper
DALY	-	Disability Adjusted Life Year
DER	-	Dope Extrusion Rate
DfE	-	Design for Environment
EC	-	European Commission
EIA	-	Environmental Impact Assessment
ELCD	-	European Life Cycle Database
EOL	-	End of Life
EP	-	Eutrophication Potential
EQA	-	Environmental Quality Act
EU	-	European Union
FIS	-	Fuzzy Inference System

GA	-	Genetic Algorithm
Gpd	-	Gallon per day
GRI	-	Global Report Initiative
GT	-	Green Technology
GUI	-	Graphical User Interface
GWP	-	Global Warming Potential
H	-	High
HCL	-	Hydrochloric Acid
Hg	-	Mercury
IChemE	-	The Institution of Chemical Engineers
J	-	Joule
KeTTHA	-	Ministry of Green Technology and Water
Kg	-	Kilogram
L	-	Low
LCA	-	Life Cycle Assessment
LCC	-	Life Cycle Costing
LC-CO_2	-	Life Cycle Carbon Dioxide
LC-E	-	Life Cycle Energy
LCI	-	Life Cycle Inventory
LCIA	-	Life Cycle Impact Assessment
LCSA	-	Life Cycle Sustainability Assessment
LinX	-	Life Cycle Index
LM	-	Low to Medium
LWSP	-	Lowell Centre for Sustainable Production
M	-	Medium
mf	-	Membership Function
MH	-	Medium to High
MJ	-	Mega Joule
ml	-	Milliliter
NH_3	-	Ammonia
NMP	-	*N-methyl-2-2-Pyrolidone*
NMVOC	-	Non-methane Volatile Organic Compound
NO_X	-	Mono-Nitrogen Oxide
Pb	-	Lead

PBB	-	*Polybrominated Biphenyls*
PBDE	-	*Polybrominated Diphenyl Ethers*
PO_4	-	Phosphorus
PVC	-	*Poly Vinyl Chloride*
RM	-	Malaysian Ringgit
RoHS	-	Restriction of Hazardous Substances
s	-	second
SETAC	-	Society of Environmental Toxicology and Chemistry
SIRIM	-	Standard and Industrial Research Institute of Malaysia
SLCA	-	Social Life Cycle Assessment
SME	-	Small and Medium Enterprise
SO_2	-	Sulphur Dioxide
SO_X	-	Sulphur Oxide
TBL	-	Triple Bottom Line
TSS	-	Total Suspended Solid
UNCSD	-	United Nation Commission on Sustainable Development
W	-	Watt
WP	-	Waste Potential
WPI	-	Water Price Index
WRc	-	Water Research Centre

LIST OF SYMBOLS

AND	-	Minimum fuzzy operator
OR	-	Maximum fuzzy operator
μ	-	Degree of fuzzy membership function
μ_{high}	-	Fuzzy membership function for high degree
$\mu_{low\ to\ medium}$	-	Fuzzy membership function for low to medium degree
μ_{low}	-	Fuzzy membership function for low degree
$\mu_{medium\ to\ high}$	-	Fuzzy membership function for medium to high degree
μ_{medium}	-	Fuzzy membership function for medium degree
E_{exp}	-	Membrane module expected efficiency
I_{AP}	-	Acidification index
$I_{carcinogen}$	-	Carcinogen index
$I_{economic}$	-	Economic index
I_{energy}	-	Energy index
$I_{environmental}$	-	Environmental index
I_{EP}	-	Eutrophication index
I_{GWP}	-	Global warming index
$I_{heavy\ metal}$	-	Heavy metal index
$I_{human\ health}$	-	Human health index
$I_{maintenance}$	-	Maintenance index
$I_{material}$	-	Material index
I_{price}	-	Price index
I_{risk}	-	Risk index
I_{social}	-	Social index
$I_{sustainability}$	-	Sustainability index
I_{WP}	-	Waste index
L_{exp}	-	Membrane module expected lifetime
n	-	Degree of input variables

$N_i(\chi)$	-	Aggregated membership function
P	-	Membrane price/cost
R	-	Number of fuzzy rule
t	-	Time
v	-	Number of input variables
V_h	-	Membrane module design flux
w	-	Optional weightage
X^*	-	Defuzzified output
χ	-	Fuzzy inputs variable

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CHAPTER 1

INTRODUCTION

1.1 Background of Research

Sustainability is generally acknowledged to be a result of balancing three pillars or triple bottom line (TBL) of sustainability, namely, environmental, social, and economic aspects, as shown in Figure 1.1. According to Fane (2005), to sustain is 'to continue without lessening' and 'to allow to flourish now and in the future'. However, how well do the use of current membrane technologies and their operation stand up to scrutiny based on sustainable criteria? That is why parameters for membrane system need to be identified specifically for membrane system considering all sustainability aspects.

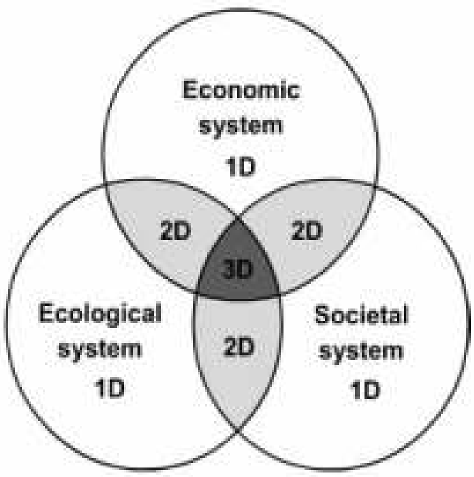

Figure 1.1 Product sustainability concepts (Sikdar, 2003)

Sustainability assessment have been studied by several researchers focusing on setting up the set of criteria or parameters on membrane system (Fane, 2005; Muga and Mihelcic, 2008; Balkema *et al*., 2002) and general products (Azapagic, 2004). They concluded that identified parameters influenced the sustainability assessment. In addition, most of researchers assessed the environmental element, which is part of sustainability focused on membrane system and wastewater treatment processes (Sombekke *et al*., 1997; Parameshwaran *et al*., 2001; Pillay *et al*., 2002; Tangsubkul *et al*., 2006; Fujiwara *et al*., 2006; Fane, 2007; Vince *et al*., 2008; Biswas *et al*., 2008; Mahgoub *et al*., 2010), and other general products (Fava *et al*., 1991; Joshi *et al*., 1999; Olsen *et al*., 2001; Ishii, 2007).

Several researchers expanded the sustainability assessment study by proposing tools or framework for assessing the sustainability focused on general products or services (EcoIndicator95,1995; EcoIndicator99, 1999; Khan *et al*., 2004; Labuschagne, 2005; Hemdi *et al*., 2011; Singh *et al*., 2012). Several frameworks were developed for monitoring the various sustainability indicators for assessing performance of governmental progress (United Nation CSD, 2001) and process industry (Greiner, 2001; IChemE, 2002).

Optimal decision can only be made when the environmental, social and economic elements are all considered in one model (Hockerts, 1999). If products have higher level of sustainability, then these products are expected to minimize the environmental impact during product life cycle and have good functionality to users. In addition, the materials used should fully utilized and not harmful for society. These products also should be designed for easily re-manufacture or recycle. Since our human population and social rates continue to grow, it threatening the sustainability of human kind. Such growth creates high demand on mass production of products that consume considerable amount of materials and energy.

Wastewater discharged from industries flow to natural water stream, causing harmful effect to human kind. Since the current activities eventually will have impacts on the next generation, membrane sustainability level need to be monitored by the manufacturer, designer, and the authority who approve the system installation and operation. The assessment should consider from the early stage of the production until end of product life for minimizing waste and maximizing product recyclability.

1.2 Statement of Problems

Sustainability index has become an important sustainability indicator for product life cycle. That considering environmental, social and economic elements. In the past studies, researchers had focused on environmental sustainability aspects in their researches instead of considering all TBL aspects to evaluate sustainable environmental performance (Sombekke *et al*., 1997; Parameshwaran *et al*., 2001; Pillay *et al*., 2002; Tangsubkul *et al*., 2006; Fujiwara *et al*., 2006; Gibson, 2006; Fane, 2007; Vince *et al*., 2008; Biswas *et al*., 2008; Mahgoub *et al*., 2010). It is noticed that most of the reports show life cycle assessment (LCA) technique has been used to assess sustainability of products or systems. However, the proposed tools or frameworks only consider either single element i.e. environmental element (EcoIndicator95, 1995; Greiner, 2001) or combination of two sustainability elements of TBL (EcoIndicator99, 1999; Singh *et al*., 2012). It is believed that measuring the entire TBL elements is more meaningful since the result of sustainability assessment become more precise in the sustainability perspective. As such, a good sustainability assessment tool should evaluate all TBL elements that consist of environmental, social and economic consideration.

There was a general framework that considers all TBL aspects but the system boundary was limited to *cradle-to-gate* only (Khan *et al*., 2004). It merely covered raw materials and manufacturing process, whereas sustainability requires a wider system boundary from *cradle-to-grave*. In other scenario, there was another general framework but it only covered the end-of-life (EOL) phase (Ullah *et al*., 2014). Since the system boundary of the above general frameworks were limited, the analysis of sustainability assessment tends to provide bias results to another phase life cycle. Both general frameworks do not provide solution *cradle-to-grave* as expected in sustainability assessment.

In the case of sustainability assessment on the membrane system, it is noticed that the investigations only focused on its performance (Rajabzadeh *et al.,* 2008; Yoon *et al*., 2004; Wang *et al*., 1999) rather than the true assessment of sustainability index that covers all three elements. Usually, the measured performance include flux design (Rajabzadeh *et al*., 2008) and membrane fouling system (Yoon *et al*., 2004; Wang *et al*., 1999).

As mentioned earlier, there is hardly found in the literature that reports sustainability assessment of membrane system from cradle-to-grave which covers all the required TBL elements. In addition, earlier assessment tools and frameworks do not indicate clearly the possible weak areas in the entire life cycle of membrane system that needs further improvements. Hence, it is timely a comprehensive methodology for assessing a sustainability of typical membrane system is required.

1.3 Research Questions

The research questions of this research were as follows:

i. What are the parameters involve in the methodology for assessing the sustainability of membrane system for wastewater treatment?

ii. How to assess the sustainability of membrane system for wastewater treatment that includes all three main aspects (environmental, social and economic) in their assessment?

1.4 Research Objectives

The research objectives of this research were as follows:

i. To suggest the parameters involved for methodology for assessing the sustainability of membrane system for wastewater treatment.

ii. To develop a methodology for assessing the sustainability of membrane system for wastewater treatment considering three pillars of sustainability and product life cycle.

1.5 Research Scopes

The scopes of this research were as follows:

i. Three pillars of sustainability aspects, i.e environmental, social and economic were considered in the proposed methodology.

ii. Methodology developed was based on ISO 14040:2006 LCA Framework as the guidelines. The system boundary covered from *cradle-to-grave* including materials, fabrication process, transportation, usage and EOL for wastewater treatment.

iii. Fuzzy logic approach was employed to determine the sustainability level in term of indices of membrane system.

iv. A case study conducted was limited to hollow fiber membrane system in laboratory scale environment.

v. Results of the sustainability assessment using the developed methodology were compared with ReCiPe approach for environmental aspect and EcoIndicator 99 for social aspect. As for economic aspect, result was compared with direct cost.

1.6 Summary of Research Methodology

Figure 1.2 shows the summary of research methodology to perform the research activities. The research methodology is developed to achieve the research objectives and scopes.

1.7 Significance of Research

A new methodology for assessing the sustainability of the membrane system for its entire life cycle phases was proposed in this study. Three important elements of sustainability, namely, environmental, social, and economic, were considered during the development of the methodology. It is expected that the developed methodology would help researchers, manufacturers, and designers to monitor the sustainability level of membrane system. In addition, the weak sustainability areas can be also identified easily using this approach, such as phases that need further improvements. It is believed that such capability is very helpful to produce a sustainable membrane system without sacrificing membrane performance. Using the proposed system, the users are able to reduce excessive time in evaluating sustainability that involving all the three pillars.

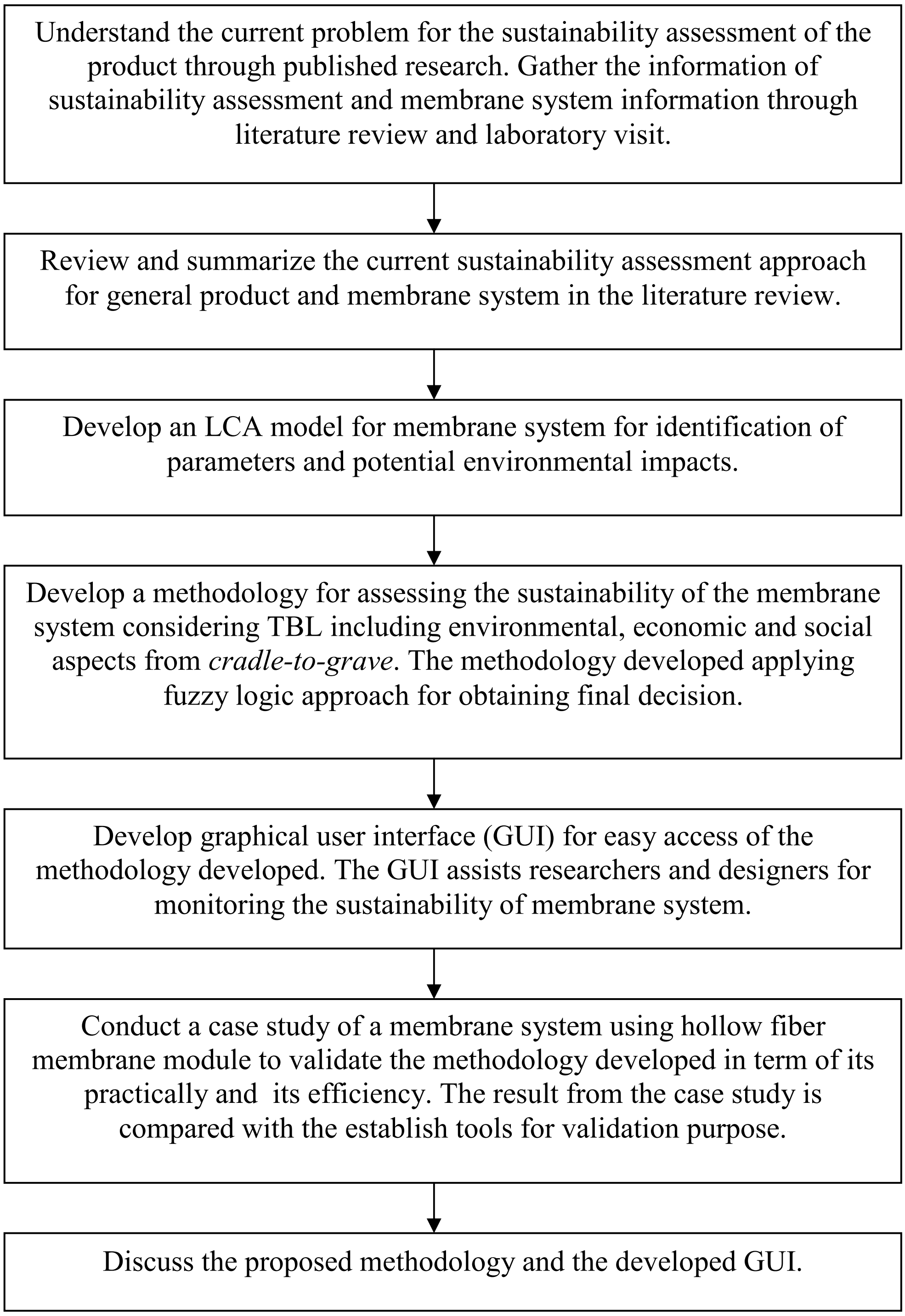

Figure 1.2 Summary of research methodology

1.8 Thesis Structure

This thesis consists of five chapters. Each chapter is briefly described as follows:

Chapter 1 presents the background of the research, membrane system for wastewater treatment, problem definition, research questions, research objectives, summary of research methodology, research scopes, and the significance of the research.

Chapter 2 discusses detailed literature review concerning sustainability concept, and sustainability assessment approach including qualitative and quantitative assessment with the system boundary. This chapter discusses LCA according to ISO 14040 (2006) and membrane system, from *cradle-to-grave* including material, fabrication process, transportation, usage, and EOL. This chapter explores issues on sustainability assessment consisting of sustainability assessment concept in terms of sustainability goals and current method for assessing sustainability. Moreover, sustainability parameters of membrane system during its entire life cycle phases are discussed. In addition, this chapter discusses legislation regarding sustainability and sustainability policy in Malaysia and the life cycle database provided. This chapter also elaborates on artificial intelligence system. Comparison was made between fuzzy logic approach and other approaches.

Chapter 3 explains the development of the methodology for assessing sustainability. The steps of methodology development describes the development of LCA model of membrane system and the determination of parameters, middle-point indices by using fuzzy logic approach, final-point indices, overall sustainability index, and membrane performance index. This chapter also presents the GUI was developed using Matlab software for easy assessment of the proposed methodology.

Chapter 4 describes the application of the developed methodology for the membrane system. In this chapter, a case study was conducted for typical membrane system using hollow fiber membrane module. This chapter begins with product description, followed by LCA study conducted with its results, and calculations for obtaining reference value when evaluating sustainability assessment using the developed methodology. Hence, the results of each sustainability element were presented. Validations were made for each sustainability aspect. Finally, overall view of the research conducted by developing the methodology for assessing the membrane product sustainability was presented such the review of achievements and critical of appraisal of this study.

Chapter 5 summarizes and concludes the research outcomes of the thesis. This chapter summarizes the research objective achieved. Future research opportunities are also discussed at the end of this chapter.

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