ECO EFFICIENCY ASSESSMENT OF DOMESTIC WASTEWATER TREATMENT SYSTEM IN MALAYSIAN URBAN AREAS

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DEDICATION

This thesis is dedicated to my father Mr Hussein Hasan Sabeen and my mother Mrs Salamh Radan, who taught me that the best kind of knowledge to have is that which is learned for its own sake. It is also dedicated to my beloved wife Nada, my children, Emad, Wael and Awael, brothers Aziz, Daiffallah, Ameen, Hassan, Ahmed, Saleh and my sisters Samiah, Jamilah,Hanan, Amal, my uncles Gieeb, Salem and their families who taught me that even the largest task can be accomplished if it is done one step at a time.

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ABSTRACT

The main purpose of wastewater treatment is to protect humans against waterborne diseases and safeguard aquatic bio-resources like fish. However, there are environmental costs associated with attaining the required level of water quality such as greenhouse gas emissions due to energy production and eco-toxicity from sludge applications on land. The goal of this study is to assess the eco-efficiency of large-scale sewage treatment plants (STPs) in urban areas, focusing specifically on variations in treatment technologies. Life cycle assessment (LCA) and cost benefit-analysis (CBA) were the analytical tools used to evaluate environmental and economic impacts, respectively. For the purpose of this assessment, three STPs in the major Malaysian cities of Kuala Lumpur, Penang, and Johor Bahru were chosen. These STPs employed different treatment technologies. The Jelutong STP in Penang used a sequence batch reactor to treat domestic wastewater. The Bunus STP in Kuala Lumpur as well as the Medini STP in Johor Bahru employed Aerobic activated sludge. Based on the STP data, Bunus STP had the highest performance in terms of wastewater pollutant removal through 96% biological oxygen demand, 90% chemical oxygen demand, and 68% phosphorus. Based on the LCA for 1m^3 treated wastewater, STP Bunus Kuala Lumpur had the highest global warming potential(GWP) and acidification potential (AP) at 2.69E-01 kg CO_2-eq and 2.11E-03 kg SO_2, respectively. Jelutong STP had the highest eutrophication potential (EP) and human toxicity potential (HTP) at 1.47E-02 kg PO_4^{-3} and 5.63E-02 kg DCB-eq, respectively. Medini STP had the highest terrestrial toxicity (TETP) at 2.0E-02 kg DCB-qq. From CBA analysis, Medini STP had the highest operating cost for 1m^3 domestic wastewater treatment with RM 0.635 per day and RM232 per year, followed by Bunus STP with RM 0.311 per day and RM 111.6 per year as well as SBR Jelutong Penang with RM 0.157 per day and RM 57.4 per year. In terms of electricity consumption for 1m^3 domestic wastewater treatment, aerobic activated sludge Medini STP consumed the highest amount of energy at RM1.02 per day. This is followed by Bunus STP at RM 0.27 per day and Jelutong with RM 0.19 per day. The LCA and CBA framework developed for Bunus plant 1 m^3 domestic wastewater flow rate (as a hypothetical example) minimized the environmental impact of GWP by 25%, EP by 3%, AP by 26%, TETP by 3%, and HTP by 3%. In addition, the suggested scenario maximized the benefit of 1m^3 domestic wastewater by RM 2.17 per day. The study revealed very different impacts for the three plants, drawing attention to the importance of treatment process choice. The integration of LCA and CBA using the developed framework improve the sustainability of domestic wastewater treatment system in Malaysian urban areas.

ABSTRAK

Tujuan utama rawatan air kumbahan adalah untuk melindungi manusia daripada penyakit bawaan air dan untuk melindungi sumber hidupan bio akuatik seperti ikan. Walau bagaimanapun, terdapat kos persekitaran yang berkaitan bagi mencapai tahap kualiti air yang diperlukan seperti pelepasan gas rumah hijau akibat pengeluaran tenaga, dan ketoksikan-eko dari aplikasi enapcemar ke atas tanah. Matlamat kajian ini adalah untuk menilai kecekapan eko loji rawatan kumbahan (STP) berskala besar di kawasan bandar, dengan memberi tumpuan khusus kepada variasi dalam teknologi rawatan. Penilaian kitaran hayat (LCA) dan analisis-manfaat-kos (CBA) adalah alat analisis yang digunakan masing masing untuk menilai kesan alam sekitar dan ekonomi. Bagi tujuan penilaian ini, tiga STP di bandar utama Malaysia iaitu Kuala Lumpur, Pulau Pinang dan Johor Bahru telah dipilih. STP ini menggunakan teknologi rawatan yang berbeza. STP Jelutong di Pulau Pinang menggunakan reaktor kelompok turutan untuk merawat air kumbahan domestik. STP Bunus di Kuala Lumpur dan STP Medini di Johor Bahru menggunakan enapcemar aktif. Berdasarkan data STP, STP Bunus menunjukkan prestasi yang tertinggi dalam penyingkiran pencemaran air sisa melalui 96% permintaan oksigen biologi, 90% permintaan oksigen kimia dan 68% fosforus. Berdasarkan LCA untuk $1m^3$ air kumbahan dirawat, STP Bunus Kuala Lumpur menunjukkan potensi pemanasan global (GWP) dan potensi pengasidan (AP) masing-masing pada 2.96E-01 kg CO_2-eq dan 2.11E -03 kg SO_2. STP Jelutong mempunyai potensi eutrofikasi (EP) dan potensi toksisiti manusia (HTP) paling tinggi masing-masing Pada 1.47E-02 kg PO_4^{-3} dan 5.63E-02 kg DCB-eq. Medini STP mempunyai ketoksikan terestrial tertinggi (TETP) pada 2.0E-02 kg DCB-eq. Dari analisis CBA, STP Medini mempunyai kos operasi tertinggi untuk rawatan air kumbahan domestik $1m^3$ dengan RM 0.635 sehari dan RM232 setahun diikuti oleh STP Bunus dengan RM 0.311 sehari dan RM 111.6 setahun serta SBR Jelutong Penang dengan RM0.157 sehari dan RM57.4 setahun. Dari segi penggunaan elektrik untuk rawatan $1m^3$ air kumbahan domestik, AS STP Medini menggunakan jumlah tenaga tertinggi sebanyak RM1.02 sehari. Ini diikuti oleh STP Bunus pada RM 0.27 sehari dan STP Jelutong dengan RM 0.19 sehari. Rangka kerja LCA dan CBA yang dibangunkan untuk loji Bunus $1m^3$ kadaran air kumbahan domestik (sebagai contoh hipotesis) meminimumkan kesan alam sekitar GWP sebanyak 25%, EP sebanyak 3%, AP sebanyak 26%, TETP sebanyak 3 % dan HTP sebanyak 3%. Di samping itu, senario yang dicadangkan memaksimumkan manfaat $1m^3$ air sisa domestik sebanyak RM 2.17 sehari. Kajian ini menunjukkan impak yang sangat berbeza untuk ketiga-tiga rawatan yang menarik perhatian kepada kepentingan pemilihan jenis rawatan. Mengintegrasikan LCA dan CBA menggunakan rangka kerja yang dibangunkan meningkatkan kelestarian sistem rawatan air sisa domestik di kawasan bandar Malaysia.

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LIST OF ABBREVIATIONS

AP	-	Acidification Potential
AS	-	Activated Sludge
BAF	-	Biological Aerated Filter
BCR	-	Benefit Cost Ratio
BL	-	Baseline Scenario
BOD	-	Biological Oxygen demand
CBA	-	Cost Benefit Analysis
CC	-	Climate Change
CML	-	Centre for Environmental Studies Methodology
COD	-	Chemical oxygen demand
DWWT	-	Domestic wastewater treatment
DWWTP	-	Domestic wastewater treatment Plant
DWWTS	-	Domestic wastewater treatment system
EP	-	Eutrophication Potential
FDP	-	Fossil Depletion Potential
FOFP	-	Photochemical Oxidant Formation Potential
FU	-	Functional unit
GC-MS	-	Gas Chromatography–Mass Spectrometry
GHG	-	Green Gas Emission
GW	-	Grey Water
GWP	-	Global Warming Potential
HFCW	-	Horizontal Flow Constructed Wetland
HTP	-	Human toxicity Potential
IDEA	-	Intermittent Decanted Extended Aeration
IPCC	-	Intergovernmental Panel on Climate Change
ISO	-	ISO - International Organization for Standardization
IWK	-	Indah Water Konsortium
JPP	-	Jabatan Perkhidmatan Pembetungan
KW	-	Kilowatt
LCA	-	Life Cycle Assessment

LCC	-	Life Cycle Costing
LCI	-	Life cycle inventory
LCIA	-	Life cycle Impact Assessment
NPV	-	Net present Value
PMFP	-	Particulate Matter Formation Potential
PPCPs	-	Pharmaceuticals Personal Care Products
PPM	-	Parts Per Million
PV	-	Present Value
RBCs	-	Rotating Biological Contactors
SA	-	Sensitivity Analysis
SBR	-	Sequencing Batch reactor
SS	-	Suspended Solid
TETP	-	Terrestrial Toxicity Potential
TSS	-	Total Suspended Solid
UASB	-	Ultra-High Rate Fluidized Bed
VFCW	-	Vertical Flow Constructed Wetland
VSSF	-	Vertical subsurface flow
YRW	-	Yellow Reduced Water
YW	-	Yellow Water

LIST OF SYMBOLS

Cd	-	Cadmium
CH4	-	Methane
CO_2	-	Carbon dioxide
H_2O_2	-	Hydrogen peroxide
Hg	-	Mercury
N_2O	-	Nitrogen Oxide
NH3	-	Ammonia
NH4	-	Ammonium
NO_2	-	Nitrite
NO_3	-	Nitrate
OH	-	Hydroxide
P	-	Phosphorus
PO_4	-	Hydrogen Phosphate
TN	-	Total nitrogen

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CHAPTER 1

INTRODUCTION

1.1 Problem Background

Malaysia has a long history of environmental pollution due to rapid economic development and population growth (Hezri, 2014). The current Malaysian population is estimated to be 31,127,247 million, most of which are concentrated in urban areas. The contributes to environmental problems through the generation of domestic wastewater (Meters, 2014). The amount of sewage has rapidly increased due to the migration of citizens from rural to urban areas. This has made sewerage networks more become extensive in Malaysia. Furthermore, water consumption has increased, with the volume of wastewater generated by municipal and industrial sectors in Malaysia estimated to be 2.97 million cubic meters annually (Mat *et al.,* 2013; Cann *et al.,* 2013; Dhama *et al.,* 2013).

In recent years, domestic wastewater in urban areas has become a noticeable source of environmental pollution. In addition, human well-being could be at risk because of diseases such as cholera and E coli that can quickly spread without adequate sewage treatment. Electricity consumption for domestic wastewater treatment is a major source of global warming. This is due to the high rate of energy consumption (Ozgun *et al.,* 2013). High energy consumption, operation, and technology maintenance costs can reduce the quality of treated wastewater, which further affects human health and the environment. Also, discharged wastewater will increase Eutrophication Potential (EP) and Terrestrial Eco Toxicity (TETP) while negatively impacting soil, vegetation, and human health. Therefore, the provision of environmental and economic sustainable wastewater treatments is very important.

Hong *et al.* (2009) reported that the inadequate treatment of wastewater leads to disposal of effluent with high organic content such as Chemical Oxygen Demand

(COD), Biological Oxygen Demand (BOD), nitrite, nitrate, Total Nitrogen (TN), and phosphorus. This contributes to eutrophication and increases the pollutions of water bodies, soil, and waterways, which further affects human health and the environment. On the other hand, the remnants of domestic and wastewater treatment (sludge) have many substances that damage the soil and subject the environment to heavy metals (Mara, 2013; Maldonado *et al.*, 2008). This increases the impact of Terrestrial Toxicity (TETP) on the ecosystem. This study assesses the environmental impact of domestic wastewater treatment systems in Malaysian urban areas.

The CML2001 Life Cycle Impact Assessment (LCIA) method using the Gabi6 database was used to determine what technology has the highest and lowest impact on human health and the environment. Normalization and result weighting for CML 2001 was done based on global references to obtain a single impact score for available emissions based on the Gabi6 database. Cost Benefit Analysis (CBA) was used to assess the operation costs, energy use, fuel consumption, chemical substances, maintenance, wages, and economic gain. The eco-efficiency framework was done through a combination of Life Cycle Assessment (LCA) and Cost Benefit Analysis (CBA). CBA was selected instead of LCC because CBA reflects benefits while LCC reflects costs. The minimization of the environmental impact and cost of domestic wastewater treatment plants was supported by both scenarios. The first scenario produced electricity using biogas and bio solids while the second scenario reused effluent water to produce fertilizer and annamox process bacteria. This minimized the environmental impact and cost of domestic wastewater treatment systems. The developed framework proposed the best solution for the environmental and economic sustainability of domestic wastewater treatment systems in Malaysian urban areas.

1.2 Problem Statement

Environmental pollution from wastewater disposal is a concern in many nations around the world. Wastewater effluent contains high-levels of organic substances that have a significant environmental impact on water bodies, rivers, and waterways. Developing countries like Malaysia face serious wastewater pollution problems that affect water bodies, groundwater, human health, and the environment (Adnan *et al.,* 2012). The technology presently in use is an aerobic process that consumes large amounts of energy (Azimi and Rocher, 2017). This technology also has a high Global Warming Potential (GWP) due to the adverse negative impact and high rate of energy consumption, which reflects a high rate of fuel consumption. The current technology in use increases energy consumption (Soares *et al.*, 2017). According to Grzes *et al.* (2014), wastewater handling represent 54% of Greenhouse Gas Emissions (GHG). Mohd Safuan *et al.* (2014) reported that the common way of disposing sludge on land or sea is costly and environmentally harmful. Converting sludge to useful energy is cheap and has negative environmental consequences due to the energy consumption of drying sludge.

Wastewater treatment in many places around the world is characterized by high surplus biomass, high operation costs, and high maintenance costs (Soares *et al.*, 2017). This process emits gases such as carbon dioxide and methane that play an important role in Global Warming Potential (Gu *et al.,* 2017; Li *et al*., 2017; Plants, 2000; Qiu *et al.,* 2010; Vigneswaran *et al.,* 2009). Furthermore, substances such as ammonia, nitrogen, COD, BOD, nitrates, aluminium, ferric salts, lime, and residual phosphorus precipitation from wastewater treatments have contributed greatly to environmental pollution (Semerjian and Ayoub, 2003). For the environmental impact and cost of domestic wastewater treatment systems to be reduced there is a need for new domestic wastewater treatment processes. Eutrophication (EP) and Terrestrial Toxicity Potential (TETP) are the main parts affected by increases or decreases in domestic wastewater treatment process efficiency (McNamara, 2016).

High energy consumption in term of grid costs comes from fuel consumption and contributes to climate change though the emission of CO_2 and CO (Gu *et al.*, 2017). In addition, high operational and maintenance costs for current wastewater treatment technologies had led to the use of cheap materials and equipment that affects the quality of treated wastewater. Attempts to increase the efficiency of these technologies in removing pollution has led to a high rate of energy consumption, which consequently affects the environment as well as firm and government costs.

Inefficiencies in existing technologies in removing waste pollution (in terms of performance, environmental impact, and cost) created the research gap addressed by this study. Cornejo (2015) and Lim *et al.*, (2008) studies on wastewater, Combined Life Cycle Assessment (LCA), and Life Cycle Costs (LCC) have reduced the cost and environmental impact of wastewater treatments. Previous studies have revealed that the use of LCC did not reflect wastewater benefits (Koul and John, 2015; Rodriguez-Garcia *et al.*, 2011). The advantage of using CBA instead of LCC is that CBA reflects wastewater benefits. Therefore, research on the use of domestic wastewater that accommodate its benefits, reduces environmental damage, maximizes pollution removel efficiency, and reduces costs is lacking. Studies that integrated the effect of LCA and CBA for domestic wastewater treatment sustainability is lacking. This study developed a framework for minimising the cost and impact of domestic wastewater treatment system, which is novelty of the study. Integrating LCA and CBA provides a solution for improving the environmental and economic efficiency of domestic wastewater treatment systems in Malaysian urban areas.

1.3 Study Objectives

The aim of this research is to assess the environmental and economic sustainability of domestic wastewater treatment systems using LCA and CBA. This study developed framework for minimising the cost and impact of domestic wastewater treatment systems. This was done by integrating LCA and CBA. The objectives of this research are as follows:

(a) To collect inventory input and output data for different domestic wastewater treatment systems in Malaysian urban areas.

(b) To analyse the potential environmental impacts of different domestic wastewater treatment systems using the LCA approach.

(c) To assess the cost and economic feasibility of the domestic wastewater treatment systems in Malaysian urban areas.

(d) To develop an eco-efficiency framework for sustainable domestic wastewater treatment systems that minimizes environmental impact and cost.

1.4 Study Scope

The study scope consisted of three domestic wastewater treatment plants in Malaysian urban areas. Domestic wastewater treatment plants were selected based on daily domestic wastewater generation, plant scale, and wastewater treatment efficiency. The first part assesses the potential impact of domestic wastewater treatments in terms of environment and economic aspects in three Malaysian urban areas (Kuala Lumpur, Johor, and Penang). The system in Bunus Kuala Lumpur and Medini Johor Bahru were aerobic activated sludge system. While the system in Jelutong Penang was sequencing batch reactor. The system boundary of this study was from gate to gate.

Sampling was conducted to collect primary data that was compared with data with from Indah water Konsortium IWK. Secondary data was collected from IWK (data average). Data collection in the three urban areas took approximately five months to finish. Some data such as the construction cost of the selected plants was taken from Jabatan Perkhidmatan Pembetungan (JPP). Other secondary data such as the cost of one person equivalent for the Bunus Kuala Lumpur plant was collected from the literature.

The purpose of this assessment was to minimize the environmental impact of Domestic Wastewater Treatment (DWWT) in urban areas. This was achieved by the use of soil reclamation, recycling, and domestic wastewater reuse in addition to current domestic wastewater practices (DWW disposal). Besides, electricity and biogas was produced from the methane in domestic wastewater. Data for the study was taken from Indah Water Konsortium (IWK). The second part of this study compared the environmental impact of adopted technologies and economic aspects (chemical and biological treatments) such as sequence batch reactors, and activated sludge. LCA was used to assess the environmental impact of domestic wastewater treatment and the used technologies while CBA was applied to assess economic costs.

The selection of wastewater treatment plant sites was done based on their location in urban areas, their use of non-conventional wastewater treatment technologies, and the quality of their effluent wastewater. Another consideration was done the environmental impact of the $1m^3$ of wastewater. This study integrated LCA and CBA instead of LCC because CBA reflect wastewater benefits. The study considered the cost and present values of the selected plants based on a plant life span 30 years. The selection of a 30 year life span was best in terms of benefits because past 30 years maintenance increases and benefits decrease.

Cost estimation was done co-operatively with IWK. Microsoft excel was used to calculate the cost and the economic feasibility of domestic wastewater. The third part analysed the potential environmental impact of domestic wastewater system inputs and outputs from different points of view (Materials, chemical substances, energy requirements, and environmental impact). The obtained data was imputed into Gabi software to analyse the potential environmental impact of domestic wastewater and the technologies use. In summary, the scope of this study achieved the following objectives:

(a) Input and output data for domestic wastewater treatment systems in Malaysia were collected using IWK. Input and output data contained the use of electricity, transportation fuel, COD, BOD, nitrate, nitrite, and phosphorus.

(b) This research covers only domestic wastewater treatment systems in Malaysian urban areas. The Bunus Kuala Lumpur plant, Medini Johor Bahru plant, and Jelutong Penang plant were considered during data collection.

(c) The potential environmental impact assessment of different domestic wastewater treatment systems was limited to the LCA approach.

(d) Analysis of the potential environmental impacts of different domestic wastewater systems was limited to the Gabi6 software.

(e) The fuel consumption costs for the transportation of materials and chemicals within investigated plants were included.

(f) The system boundaries included raw materials and gate to gate wastewater processing.

1.5 Significance of Research

A framework was developed to evaluate the eco-efficiency of wastewater treatment plants. This study minimized the environmental impact and cost of domestic wastewater treatment systems. The integration of LCA and CBA using the suggested framework decreased the environmental impact below the selected environmental threshold values. The developed framework is important to guiding decision makers to choose the best domestic wastewater treatment technologies with the lowest environmental impact and cost. In addition, this research will increase awareness on how to use recycle domestic wastewater for economic gain (fertilizer, soil reclamation, electricity generation, and cooking gas). Furthermore, this research is important for choosing the best solution for sustaining sewage systems without negative odours and pathogens by suggesting the best treatments with the lowest cost and environmental impact. This enhances the balance between human health and environment by reducing pathogens, costs, and environmental impact. The cost of domestic wastewater treatment systems was minimized to less than the selected economic threshold values. Therefore, the suggested framework provided the best solution for increasing the eco-efficiency of domestic wastewater treatment, which enhanced environmental and economic sustainability in Malaysian urban areas.

1.6 Thesis Layout

The layout of this study is structured as follows:

Chapter 1 gives the introductory background. It also highlights the problems associated with the research area. In addition, this chapter outlines the goal and significance of this study.

Chapter 2 discuss previous studies related to Domestic Wastewater Treatment (DWWT) technologies. The analysis-based techniques are presented. Important concepts such as LCA, cost benefits tools, and Gabi software are discussed.

Chapter 3 describes the methodology used in this research. It explains the research tools and processes. It also explains the economic and environmental domestic wastewater analysis using LCA and CBA.

Chapter 4 presents the results of the LCA approach to analyse the potential environmental impact of domestic wastewater treatments and technologies.

Chapter 5 presents the cost estimates done using inventory data, IWK annual reports, and consultations with IWK executives. Costs included operational costs and maintenance as well as daily, monthly, and annual wages. The calculation of these case studies was done in sequence, starting from operation to polymer cost.

Chapter 6 shows the results for the $1m^3$ domestic wastewater flow rate framework in terms of treatment sustainability

Chapter 7 presents the conclusion and recommendations for future research based on the study findings

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