# ASSESSMENT OF PERFORMANCE AND GREENHOUSE GASES EMISSIONS FOR AEROBIC BIOFILM COMBINED REACTOR

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# DEDICATION

This thesis is dedicated to my parents, who have always loved me unconditionally and whose good examples have taught me to work hard for the things that I aspire to achieve.

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# ABSTRACT

Most of the existing sewage treatment plants (STP) in Malaysia are using conventional systems with poor treatment effects, which causes the STPs to become one of the main sources of water pollution. This study aimed to design a novel biological water purification system with a combination of a fixed biofilm reactor and a moving bed biofilm reactor termed as the aerobic biofilm combined reactor (ABCR). The ABCR system has not been reported to treat domestic wastewater apart from industrial wastewater, and no research has been documented on the performance of greenhouse gas (GHG) emissions, power consumptions and space occupation of ABCR system. The objective of this study was to characterize the performance of ABCR and to verify its local adaptability, efficiency, economic and environmental impacts in treating the domestic sewage in Malaysia. Different water intake rates were adopted to verify the system resistance to the fluctuation of organic loading rate, and 10 h was selected to be the designed hydraulic retention time (HRT). This HRT was the minimum HRT to meet the local effluent discharge standard. The power consumption to run the ABCR system was also analyzed during this study, and the results showed an average value of 0.287 kWh/population equivalent. The ABCR system was also compared with the conventional sewage treatment process of extended aeration (EA). The results showed that the ABCR system offered the co-benefits of a higher quality of treated water, greater space saving (51.2 %) and lowered GHG emissions (18.3 %) than that of the EA system. The performance of ABCR system under the selected HRT also showed that the system is suitable for the typical Malaysian domestic sewage treatment to comply with the local discharge standard. The effluent achieved well below the discharge limits for most of the major pollutants, especially on the removal of ammoniacal nitrogen. The ABCR also has a lower power consumption (saving of 21.4 %) and lower sludge generation (85.7 %) as compared to the EA system. The ABCR system could promote the sustainable development of municipal facilities for urban wastewater treatment.

# ABSTRAK

Kebanyakan loji rawatan kumbahan (STP) di Malaysia menggunakan sistem konvensional dengan kesan rawatan yang kurang berkesan, sehingga menjadikan STP sebagai salah satu sumber utama pencemaran air. Kajian ini bertujuan untuk mereka bentuk sistem penulenan air secara biologi menggunakan gabungan reaktor biofilem tetap dan reaktor biofilem bergerak yang dinamakan aerobic biofilm combined reactor (ABCR). Sistem ABCR belum pernah dilaporkan untuk merawat air sisa domestik selain daripada air sisa industri, dan masih tiada kajian yang merekodkan prestasi pelepasan gas rumah hijau (GHG), penggunaan tenaga dan penggunaan ruang bagi sistem ABCR. Objektif kajian ini adalah untuk mencirikan prestasi ABCR dan untuk mengesahkan kesesuaian tempatan, kecekapan, serta impak ekonomi dan persekitarannya dalam merawat kumbahan domestik di Malaysia. Kadar kemasukan air yang berbeza telah digunakan untuk mengesahkan ketahanan sistem ini terhadap kadar turun-naik pemuatan organik di mana 10 jam telah ditetapkan sebagai masa pengekalan hidraulik (HRT). HRT ini merupakan tetapan minimum yang memenuhi piawaian pelepasan efluen tempatan. Penggunaan tenaga bagi sistem ABCR juga dianalisa dan hasilnya menunjukkan nilai purata sebanyak 0.287 kWh/populasi setara. Sistem ABCR juga dibandingkan dengan proses konvensional rawatan kumbahan pengudaraan tambahan (EA). Keputusan menunjukkan bahawa sistem ABCR memberikan manfaat berserta kualiti air terawat yang lebih tinggi, penjimatan ruangan yang lebih besar (51.2 %) dan penurunan pelepasan GHG (18.3 %) berbanding sistem EA. Prestasi sistem ABCR yang dijalankan menggunakan HRT yang dipilih juga menunjukkan bahawa sistem ini sesuai untuk merawat air kumbahan domestik Malaysia bagi memenuhi piawaian pelepasan tempatan. Efluen ini mencapai piawaian pelepasan bagi kebanyakan bahan pencemar utama seperti ammonia-nitrogen. ABCR juga menggunakan kuasa yang lebih rendah (penjimatan 21.4 %) dan penjanaan enapcemar yang lebih rendah (85.7 %) berbanding dengan sistem EA. Sistem ABCR boleh meningkatkan pembangunan mampan dari segi prasarana perbandaran untuk rawatan air sisa di bandar.

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# LIST OF ABBREVIATIONS

| | | |
|---|---|---|
| ABCR | - | Aerobic biofilm combined reactor |
| AL | - | Aerated lagoon |
| A/O | - | Aerobic/Anoxic |
| APHA | - | American Public Health Association |
| APS | - | Aeration pond system |
| BAF | - | Biological aerated filter |
| BioAX | - | Immobilized aerobic biofilm reactor |
| $BOD_5$ | - | 5-day biochemical oxygen demand |
| CAPEX | - | Capital expenditure |
| CBA | - | Cost-benefit analysis |
| $CH_4$ | - | Methane |
| CLS I | - | Class I |
| CLS IIB | - | Class IIB |
| CLS III | - | Class III |
| CML | - | Centrifugal mother liquor |
| $CO_2$ | - | Carbon dioxide |
| COD | - | Chemical oxygen demand |
| DO | - | Dissolved oxygen |
| DOE | - | Department of Environment |
| EA | - | Extended aeration |
| Eff | - | Effluent |
| Eq | - | Equation |
| EQA | - | Environmental Quality Act |
| GGP | - | Green Gas Protocol |
| GHG | - | Greenhouse gas |
| GWP | - | Global warming potential |
| HRT | - | Hydraulic retention time |
| Inf | - | Influent |
| IPCC | - | Intergovernmental Panel on Climate Change |
| IRR | - | Internal rate of return |

| | | |
|---|---|---|
| IWK | - | Indah Water Konsortium |
| MBBR | - | Moving bed biofilm reactor |
| MBS | - | Mass bio system |
| MLSS | - | Mixed liquid suspended solids |
| $NH_3$ | - | Ammonia |
| $NH_3$-N | - | Ammoniacal nitrogen |
| NL | - | Natural levels |
| $N_2O$ | - | Nitrous oxide |
| $NO_3$-N | - | Nitrate nitrogen |
| NPV | - | Net present value |
| NTU | - | Nephelometric turbidity unit |
| O&G | - | Oil and grease |
| OPEX | - | Operational expenditure |
| PE | - | Population equivalent |
| SPAN | - | National Water Services Commission |
| SS | - | Suspended solids |
| STP | - | Sewage treatment plant |
| TP | - | Total phosphorus |
| TSS | - | Total suspended solid |

# LIST OF SYMBOLS

% - percent

ø - diameter (symbol used in engineering)

°C - degree Celsius

cm - centimeter

-eq - equivalent

kW - kilowatt

kWh - kilowatt-hour

L - liter(s)

mg - milligram

mm - millimeter

ppt - parts per trillion

ppm - parts per million

h - hour(s)

m - meter(s)

min - minute(s)

y - year

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# CHAPTER 1

# INTRODUCTION

## 1.1 Research Background

Malaysia is one of the developing countries that face the problems of water pollution,which require innovative technologies to solve the issues. The conventional sewage sources and some old sewage treatment plants (STPs) in Malaysia are among the primary causes of water pollution (Ariffin and Sulaiman, 2015). Advanced sewage treatment processes are anticipated to improve the current STPs in Malaysia.

Water is an essential natural resource that is exposed to increasing anthropogenic pressures. The pressures due to the exponential growth of population and urbanization have urged the balance between the discharge of wastewater and the protection of the receiving water bodies (Kamika et al., 2014). Inefficient management of wastewater treatment plants, such as improper system selection and poor operation management, can lead to the wastage of valuable land resources, long-term environmental deterioration and health problems to human.

Many Malaysian rivers are suffering from sewage pollution (Ariffin and Sulaiman, 2015). Untreated or incomplete treated wastewater flowing into the river or water body will cause eutrophication (Yao et al., 2019). Water eutrophication causes the water body to appear black and smelly, and the concentration of dissolved oxygen (DO) to be deficient due to the algae bloom (Li et al., 2016). Dense cyanobacteria blooms caused by water eutrophication could lead to pH elevation (9 to 10.5). This situation can last for weeks while elevated pH could also exacerbate eutrophication (Gao et al., 2014). The organic matter accumulated in the lower layer of the eutrophication water will release harmful gases (such as methane and hydrogen sulphide) under anaerobic conditions (Wang et al., 2019), and some plankton will produce toxins that will harm the aquatic animals.

The current technology of sewage treatment has been enhanced to remove ammoniacal nitrogen ($NH_3$-N) and phosphorus (P) while eliminating organic pollutants in the water body. Some improved treatment systems, such as the oxidation ditch system and anaerobic-anoxic-aerobic (A-A-O) system, are among popular systems applied for sewage treatment. Both methods have excellent efficiency in removing 5-day biochemical oxygen demand ($BOD_5$), oil and grease (O&G) and suspended solids (SS). The recent improvement of technology has also led to the innovation of more efficient wastewater treatments, including the use of membrane bioreactor technology that has gradually matured and widely applied in the industry. Membrane bioreactor process is a combination of membrane separation and conventional sewage treatment technology.

Membrane bioreactor does not need to consider the sedimentation of sludge, and it can significantly increase the concentration of sludge mixture and increase sludge age (reduce sludge output) (Innoceti et al., 2002).It has a significant effect on the removal of chemical oxygen demand (COD), SS, hospital bacteria and virus (Liu et al., 2010). The potential shortcomings of membrane bioreactor are membrane fouling and its periodic replacement which requires process optimization on operation parameters and backwashing (Kootenaei and Aminirad, 2014).

Malaysia has experienced the continuous improvement of sewage treatment technology and policy in recent decades (Muyibi et al., 2008). Before the 1950s, most of the local sewage was dumped or fertilized after simple storage, and septic tanks were not used until the 1960s. Sewage storage and treatment methods at that time could post a risk to public health. From the 1970s to 2000, Malaysia began to adopt the secondary biological treatment of sewage and activated sludge treatment which started in Peninsular Malaysia. With its large-scale use in the west of Asia, STPs have begun to be built on a large scale.

However, due to the poor treatment effect of some sewage plants or the illegal discharge of untreated sewage into the rivers, pollution in the river has become more serious (Ariffin and Sulaiman, 2015). After the year 2000, the introduction of the tertiary treatment process has further improved sewage treatment technology and increased the amount of treated sewage. Nevertheless, there are still many environmental problems to be solved, such as odour diffusion and sludge disposal. The current situation of conventional sewage collection and treatment can still be divided into two categories according to the degree of intensification. One is the systematic sewage pipeline collection, which is used in the STP for unified treatment. Most cities with new residential areas and the suburban regions of Malaysia currently use this system.

The other one is the septic tank treatment system, which is used in the remote rural or island areas. The functions of urban sewage treatment station system are relatively complete, which can be maintained and managed by the wastewater treatment company such as Indah Water Konsortium (IWK). IWK is responsible for the operation and maintenance of the sewage systems in all states in Malaysia. IWK has the responsibility of approving new sewage pipelines and sewage station systems.

The environmental authority, such as the Department of Environment (DOE) in Malaysia is responsible for monitoring the effluent quality of each sewage treatment system to meet the required standards. Malaysia has relatively mature experience in operation, maintenance and management using the conventional sewage collection and treatment system at present. However, the increasing rate of urbanization, industrialization and population growth urges the implementation of a more efficient sewage treatment system to serve the growing demand for treated water. It is also critical to solve the issue of land shortage and inefficient treatment due to increasing sewage generation (Mat et al., 2013).

Efficient sewage treatment process with high-quality effluent quality can alleviate the shortage of freshwater resources. The reuse of domestic sewage after advanced treatment is a good source of irrigation water (Jaramillo and Resrepo, 2017). Since the urban sewage is not affected by climate, it can be treated and reused in-situ. Based on the original sewage treatment, a tertiary treatment or more efficient treatment process is adopted to ensure the water quality after sewage treatment meets the Malaysian Standard for water reuse. It also expands the scope of application of recycled water and saves limited freshwater resources.

A new technology of sewage treatment system integrating an advanced biological water purification system called Aerobic Biofilm Combined Reactor (ABCR) is designed in this study based on a wastewater treatment pilot-scale case study located in Kuala Lumpur, Malaysia. The ABCR has been used for industrial wastewater treatment in the Northeast Asia, but it was the first time to be introduced in Malaysia for domestic sewage treatment. The verification of the performance of ABCR is essential following the standard procedures set by National Water Services Commission (SPAN) in Malaysia. The ABCR process contains two main bio-treatment reactor. One is the immobilized aerobic biofilm reactor (BioAX), which is a new treatment process based on the conventional biological aerated filter (BAF). Another major bioreactor is a new treatment process called novel mass bio system (MBS), which is an improved and updated treatment process based on the conventional moving bed biofilm reactor (MBBR). Figure 1.1 shows the comparisons between the novel ABCR system and the conventional extended aeration (EA) system.

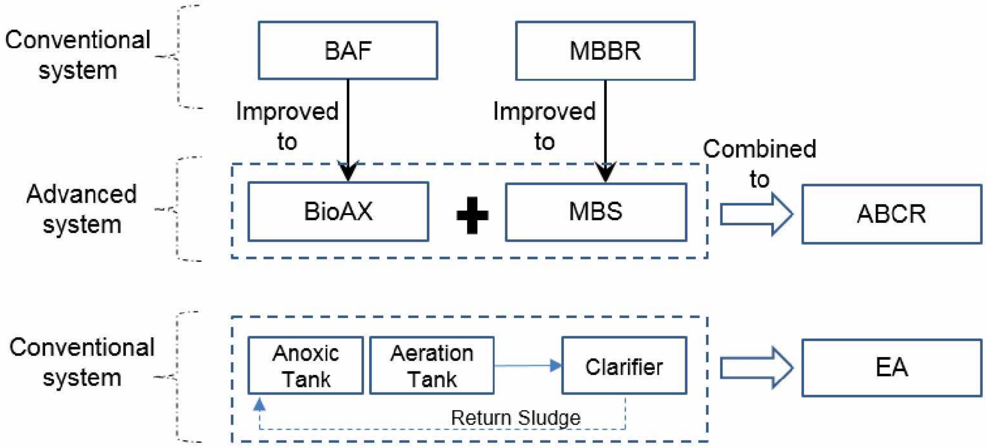

Figure 1.1 Graphical diagram comparing the advanced system (ABCR) and the conventional EA System

This study presents ABCR as a viable and advanced biofilm wastewater treatment technology to treat municipal sewage containing high organic content (e.g. $BOD_5 > 250$ mg/L) which is considered highly desirable to treat wastewater with a high density of population. This study compares the performance of ABCR to the conventional EA system that has been used in the existing STP. The EA system is currently the most widely-used mechanized processing system in Malaysia, especially for small and medium-sized STPs (Razik, 2007). The performance of ABCR was characterized according to the guideline issued by SPAN (SPAN, 2009), including the changes of monitoring parameters (such as COD, $BOD_5$, $NH_3$-N, and O&G) of influent and effluent and removal efficiency. The economic (electrical power and space saving) and environmental(sludge generation and GHG emissions) impact analyses were conducted to determine the feasibility of ABCR as compared to the EA system. The hypothesis and limitations of this research on ABCR system were also summarized.

This study investigated the application of a pilot-scale ABCR project to treat domestic wastewater under the tropical climate in Malaysia. ABCR is found to be superior for the removal of organic matter and $NH_3$-N. The performance of ABCR is evaluated by assessing the quality of the effluent, which was found to comply with the emission index Standard A set by SPAN under the Malaysian Sewerage Industry Guidelines (SPAN, 2009). The economic impact of ABCR in terms of energy consumption was evaluated to estimate the potential for reducing carbon emissions.

## 1.2 Problem Statement

Most of the STPs existing in Malaysia, such as the EA or the aerated lagoon (AL) system, are of low efficiency and occupy large areas. The rapid urbanization has caused land resources to be more valuable and scarcer, along with an increased expectation of better-living environment. The current STPs system in Malaysia can affect the living standards in several ways. Firstly, the conventional sewage treatment process gradually loses its advantage in space utilization, which could not catch up with the rapid urban expansion. Secondly, if the concentration of organic pollutant is high in wastewater, it needs to be more efficiently treated, especially when it involves a high level of $NH_3$-N. High $NH_3$-N in the wastewater can lead to severe water pollution and eutrophication, notably under heavy rain. The high $NH_3$-N in wastewater ($NH_3\text{-N} > 500$ mg/L) which are generated from food waste (Bong et al., 2018), and chemical fertilizer (Savci, 2012) are among the main sources of unpleasant smell. The existing open STPs in Malaysia are considered as one of the sources to pose a negative impact (e.g., odour) to the surrounding environment. It has been reported that wastewater with high ammonium concentration will lead to high emission of $NH_3$-N under high pH condition (Shao et al., 2017). It is necessary to introduce more advanced STPs with higher removal efficiency on the targeted pollutants to adapt to the increasingly intense urban land use. Treatment of high $NH_3$-N in wastewater remains a challenging task in the field of environmental engineering, as the choice of treatment method for $NH_3$-N relies on several factors, including standards of the treated water, chemical and physical properties of the wastewater and financial allocation (Tabassum et al., 2018a). Thirdly, in the case of rising global temperature, reducing GHG emissions has become the focus of attention.

There is also an increasing demand in energy conservation and emissions reduction for a greener operation of the STP. An efficient STP can reduce indirect GHG emissions in the construction process by reducing volume, or in the operation process by reducing energy consumption and sludge production. The design of STPs should be improved with technological innovation and to reduce GHG emissions. Despite being a sound and mature technology, the conventional removal of biological nitrogen technology has a few drawbacks such as long process, sludge bulking and difficulties in maintaining sufficient nitrifying biomass. The development of a more advanced biological method is required to effectively remove $NH_3$-N at a lower cost and with other co-benefits of space saving, shorter treatment duration and minimized energy consumption that leads to lower GHG emissions.

Most of the current sewage treatment facilities in Malaysia are implementing old systems with low efficiency, where the proportion of mechanized STPs is less than 45 %. Only about 15 % of STP effluent can meet Standard A, while the rest can only meet Standard B or lower standards as reported by IWK in its corporate sustainability report in 2007 (IWK, 2007). The more advanced technologies adopted in Malaysia, such as A-A-O process adopted in Pantai 2 STP and sequencing batch reactor (SBR) process adopted in Jelutong STP, have better effects on the quality of effluent. However, there are still some other disadvantages, such as the need for a large area and high sludge generation. Introduction of novel STPs based on attached growth (or hybrid growth) processes is disirable in Malaysian to eliminate or relieve the shortcomings of the existing STPs. This study introduces a novel sewage treatment plant (STP) system, named as ABCR as an improved STP which has been used to treat industrial wastewater by one of its single reactor or by two combined reactors in the temperate countries such as China and Japan.

The ABCR has not been used to treat the domestic wastewater and yet to be tested in tropical countries with heavy rainfall and potential dry season. The performance of ABCR in different climatic conditions needs to be verified. Before implementing a new sewage treatment system in Malaysia, confirmatory tests should be carried out according to government requirements. However, the scale of the laboratory cannot simulate the outdoor climate very well. In this study, the pilot-scale ABCR system was used for the experimental study. Previous studies have reported its application on some industrial wastewater treatment (Li et al., 2014). One of the reactors in ABCR, BioAX, has been used to treat centrifugal mother liquid with the removal rates of TL-1000 and TL-800 (two kinds of polyvinyl chloride products with different polymerization degree) at 90 to 95 % and 80 to 90 % in lab-scale experiments (Tabassum et al., 2018b). The MBS reactor also showed its high efficiency in removing $NH_3$-N (95 %) and total nitrogen (TN) (90 %) (Tabassum et al., 2018a). The ABCR system, combining BioAX and MBS reactors, was used in this research to treat domestic sewage in Malaysia.

## 1.3 Objectives of Study

The objectives of this study are:

1) To characterize the performance of ABCR, a novel bio-film wastewater treatment system, using advanced biological water purification product based on a combined BioAX and MBS reactor to treat the domestic sewage in Malaysia.

2) To evaluate the economic (power and space saving) and environmental impacts (sludge generation and GHG emissions) of ABCR to treat the domestic sewage in Malaysia.

## 1.4 Scope of Study

Several scopes are outlined to achieve the objectives as follow:

1) To review the characteristics of the mainstream sewage treatment processes.
2) To characterize the quality of the sewage treated using ABCR as compared to the conventional STP based on the EA system.
3) To collect data under four different flow rates and further data collection under selected hydraulic retention time (HRT) for ABCR system.
4) To compare the process efficiency in terms of energy usage, sludge generation rate, and footprint of space saving between ABCR and the EA.
5) To evaluate the potential mitigation of GHG emissions of using ABCR as compared to the conventional EA.

## 1.5 Significant of Study

This research is expected to contribute significantly in introducing an efficient sewage treatment system to treat the sewage of urban areas in Malaysia in a shorter time. Compared with the local conventional EA process, the ABCR system has shown some apparent advantages in terms of effluent quality and space saving. This study also evaluated the economic and environmental impacts of the novel ABCR system to treat the domestic wastewater in a tropical climate condition such as Malaysia. The impact analyses showed that ABCR is viable for implementation in Malaysia.

This study provides evidence on land and power savings from the novel sewage treatment system. The findings from this study are useful for further promotion to the local authorities and developers to shift to a more efficient technology in treating domestic sewage, especially in the high-rise area where land resources are scarce. The outcomes of the present study could serve as a baseline study to explore further the potential of treating polluted industrial wastewater with a high level of organic pollutants.

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# LIST OF PUBLICATIONS

## Indexed Journal

1. **Zhang, H**., Liu, C., Lee, C.T., and Zhang, Z. (2019). A Novel Bio-film Wastewater Treatment System using Encapsulated Microbes. *Chemical Engineering Transactions*. 72, 181–186. https://doi.org/10.3303/CET1972031. **(Indexed by SCOPUS)**
2. **Liu, C**., Lee, C.T. and Zhang, H. (2019). Design of Sewage Treatment Plants for High-Density Urban Reclamation Land. *Chemical Engineering Transactions*. 72, 187–192. https://doi.org/10.3303/CET1972032. **(Indexed by SCOPUS)**