
**UNIVERSITI PUTRA MALAYSIA**

# *ANAEROBIC DIGESTION FOR CATTLE MANURE TREATMENT AND ITS KINETIC MODELLING IN AN OSCILLATORY FLOW BIOGAS REACTOR*

**ISMAIL MUHAMMAD NASIR**

**FK 2016 159**

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**By**

**ISMAIL MUHAMMAD NASIR**

**Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy**

**November 2016**

**DEDICATION**

This thesis is dedicated to my beloved parents for your great support and continuous care.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in partial fulfillment of the requirement for the degree of Doctor of Philosophy

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**November 2016**

**Chairman : Assoc. Prof. Tinia Idaty Mohd. Ghazi, PhD**
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Anaerobic digestion of animal manure is gradually becoming essential as a means of protecting the environment and recycling materials efficiently into the farming systems. Over the last few decades, efforts have been made for treating dairy cattle manure according to the growing 'waste to energy' recycle notion in engineered bioreactors, rather than collecting in lagoons or left to decompose in the open which cause a significant environmental hazard. There are quite a number of bioreactors operating at commercial animal manure facilities and allow for the recovery of clean energy 'biogas' from waste without methane emissions into the atmosphere, which cause adverse greenhouse effects. Majority of these projects generate electricity and or capture the waste heat for different in-house requirements.

Various reactor design configurations for the anaerobic treatment of cattle manure at the laboratory scale and full-scale have been applied and their performance evaluated. Recent developments in mixing technology has developed a new way of mixing substrates by introducing an oscillatory motion to replace the conventional mechanical agitation or an air bubble displacement. This mixing is referred to as oscillatory flow mixing (OFM), which relatively provides good mixing and a range of specific process enhancements, such as improved mass transfer, heat transfer, and narrow residence time distribution.

The main aim of this research was to evaluate the potential biogas and methane production in the anaerobic digestion of cattle manure using a novel reactor design. A novel oscillatory flow biogas reactor (OFBR) was used to assess the impact of various organic loading rate variation, as well as different HRT, on the OFBR operation. Experiments were conducted in both batch and semi-continuous mode using a 6 L bioreactor, under thermophilic condition (55°C). The process performance was assessed using various parameters such as: volatile solids (VS) and chemical oxygen demand (COD) removal, biogas and methane production and yields. Whereas, the

digestate quality was monitored with the following parameters: VS, pH, volatile fatty acids (VFA), and ammonia nitrogen ($NH_3$-N) concentration.

Initially, batch experiments were conducted in order to assess the first start-up of the cattle manure digestion. Moreover, they provided digestate for the succeeding semi-continuous studies, in addition to providing vital information regarding ultimate process efficiency in terms of biogas and methane yield and solids removal. Furthermore, rapid start-up batch experiments were used to determine the required HRT for semi-continuous studies. Optimum organic loading rate (OLR) was determined with the use of the OFBR semi-continuous process. The optimum OLR was found to be 2.4 g VS/L/day based on the operational conditions set for this study, at which maximum volumetric biogas production of 5.2 L per L reactor per day and methane production of 3.13 L per L reactor per day were achieved during the phase one of the semi-continuous study. According to the results obtained in the phase two of the semi-continuous study, the process performance observed at HRT of 12 days were similar to the first organic loading (1.3 g VS/L/day) in the phase one study at HRT of 18 days. This showed that the operational conditions in the phase two experiment might be more desirable economically than in the phase one in relation to reducing operational cost and bioreactor volume.

Finally, a steady-state mathematical model was developed; based on the Contois bacterial growth kinetics, describing the methane production rate of the semi-continuous operation of the OFBR utilising data produced and a novel kinetic approach. The best fit values for the maximum specific growth rate ($\mu_m$) and dimensionless kinetic parameter (K) were found as 0.2 $day^{-1}$ and 0.8, for phase one, and 0.22 $day^{-1}$ and 0.84, for phase two, respectively. In addition, under the studied experimental conditions, the sum of the residual error of the predictions of Chen and Hashimoto's model ($R^2$ =0.84) using their recommended kinetic parameters ($\mu_m$ = 0.326; K = 0.81) had a good correlation with the experimental results in phase 2 ($R^2$ =0.85). Therefore, the findings from this study recommend that each anaerobic digester for manure treatment should be evaluated and designed individually to effectively serve its purpose, rather than random application of the manure digestion models and their proposed kinetic parameters which may lead to significant error in the prediction of methane production rate. The overall performance of the OFBR proved that the design is suitable for the anaerobic digestion of the cattle manure by providing successful manure treatment, based on VFA, VS and COD removal, for all operational modes examined in this study.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

**PENGHADAMAN ANAEROBIK UNTUK NAJIS LEMBU DAN PEMODELAN DAN KINETIK DALAM REAKTOR BIOGAS ALIRAN OSCILATORY**

Oleh

**ISMAIL MUHAMMAD NASIR**

**November 2016**

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Pencernaan anaerobik bagi menghasilkan baja haiwan semakin menjadi penting sebagai satu cara untuk melindungi alam sekitar dan mengitar semula bahan dengan efisien dalam sistem penternakan. Sejak beberapa dekad yang lalu, usaha telah dilakukan untuk merawat najis lembu tenusu berdasarkan pertumbuhan tanggapan kitar semula sisa tenaga dalam bioreaktor tereka bentuk, daripada mengumpulnya dalam lagun atau meninggalkannya untuk reput secara terbuka yang menyebabkan bahaya alam sekitar yang ketara. Terdapat agak banyak bioreaktor yang beroperasi di sarana baja haiwan komersial dan dibiarkan untuk pemulihan tenaga bersih biogas daripada sisa tanpa pelepasan metana ke atmosfera, yang menyebabkan kesan buruk rumah hijau. Kebanyakan projek tersebut menjana tenaga elektrik dan atau menangkap haba buangan untuk keperluan dalaman yang berbeza.

Pelbagai konfigurasi reka bentuk reaktor untuk rawatan anaerobik najis lembu pada skala makmal dan besar-besaran telah digunakan dan prestasi mereka dinilai. Perkembangan terkini dalam teknologi pencampuran telah membentuk satu cara baru untuk pencampuran substrat dengan memperkenalkan gerakan berayun untuk menggantikan pergolakan mekanikal yang konvensional atau anjakan gelembung udara. Percampuran ini dikenali sebagai percampuran aliran berayun (OFM), yang secara relatifnya menyediakan percampuran yang baik dan pelbagai penambahbaikan proses tertentu, seperti memperbaiki pemindahan jisim, pemindahan haba, dan taburan masa mastautin yang singkat.

Tujuan utama kajian ini adalah untuk menilai potensi pengeluaran biogas dan metana dalam pencernaan anaerobik najis lembu menggunakan reka bentuk reaktor yang baru. Reaktor biogas aliran berayun baru (OFBR) telah digunakan untuk menilai kesan pelbagai variasi kadar punggah organik, serta masa tahanan hidraulik yang berbeza (HRT), ke atas operasi OFBR. Eksperimen telah dijalankan dalam kedua-dua mod iaitu kelompok dan separa berterusan menggunakan bioreaktor 6 L, di bawah keadaan

termofilik (55°C). Prestasi proses dinilai menggunakan pelbagai parameter seperti: pepejal meruap (VS) dan penyingkiran permintaan oksigen kimia (COD), pengeluaran serta hasil biogas dan metana Manakala, kualiti digestat dipantau dengan parameter berikut: VS, pH, asid lemak meruap (VFA) dan kepekatan nitrogen amonia ($NH_3$-N) .

Pada awalnya, eksperimen kelompok telah dijalankan untuk menilai permulaan pertama pencernaan najis lembu. Selain itu, eksperimen tersebut menyediakan digestat bagi kajian separa berterusan, selain menyediakan maklumat penting mengenai kecekapan proses muktamad dari segi hasil biogas dan metana serta penyingkiran pepejal. Selain itu, eksperimen kelompok permulaan yang pantas telah digunakan untuk menentukan HRT yang diperlukan bagi kajian separa berterusan. Kadar beban organik optimum (OLR) ditentukan dengan menggunakan proses separa berterusan OFBR. OLR optimum yang didapati ialah 2.4 g VS/L/hari berdasarkan keadaan operasi yang ditentukan bagi kajian ini, iaitu pengeluaran isipadu biogas maksimum sebanyak 5.2 L setiap L reaktor sehari telah dan penghasilan metana sebanyak 3.13 L setiap L reaktor sehari telah tercapai dalam fasa pertama kajian separa berterusan. Berdasarkan keputusan yang diperolehi dalam fasa kedua kajian separa berterusan, prestasi proses yang dihasilkan pada HRT 12 hari adalah menyamai dengan beban organik yang pertama (1.3 g VS/L/hari) dalam fasa satu kajian, iaitu HRT bagi 18 hari. Ini menunjukkan bahawa keadaan operasi dalam eksperimen fasa kedua mungkin lebih ekonomikal berbanding dengan fasa pertama dari segi pengurangan kos operasi dan isipadu bioreaktor.

Akhir sekali, model matematik keadaan tetap dibangunkan; berdasarkan kepada kinetik pertumbuhan bakteria Contois, bagi menerangkan kadar penghasilan metana dalam operasi separa berterusan OFBR yang menggunakan data yang telah dihasilkan dan pendekatan kinetik baru. Nilai patut yang terbaik untuk kadar pertumbuhan tertentu yang maksimum ($\mu_m$) dan parameter kinetik tiada berdimensi (K) ditemui sebagai 0.2 setiap hari dan 0.8, untuk fasa pertama, dan 0.22 setiap hari dan 0.84, bagi fasa kedua, masing-masing. Di samping itu, di bawah keadaan eksperimen yang dikaji, Jumlah ralat sisa ramalan model Chen dan Hashimoto ($R^2$ =0.84) yang menggunakan parameter yang disyorkan ($\mu_m$ = 0.326; K = 0.81) mempunyai hubungan yang baik dengan keputusan eksperimen dalam fasa kedua ($R^2$ =0.85). Oleh itu, hasil daripada kajian ini mengesyorkan supaya setiap bioreaktor anaerobik untuk rawatan najis perlu dikaji dan direka secara individu dengan tujuan yang berkesan, dan bukannya menggunakan model pencernaan secara rawak beserta parameter kinetik yang dicadangkan oleh model tersebut yang boleh membawa kepada kesilapan ketara dalam jangkaan untuk kadar pengeluaran metana. Prestasi keseluruhan OFBR yang membuktikan bahawa reka bentuknya adalah sesuai dan berjaya untuk pencernaan anaerobik untuk merawart najis lembu, berdasarkan kepada penyingkiran VFA, VS dan COD, bagi semua mod operasi yang dikaji dalam kajian ini.

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I certify that a Thesis Examination Committee has met on 3 November 2016 to conduct the final examination of Ismail Muhammad Nasir on his thesis entitled "Anaerobic Digestion for Cattle Manure Treatment and its Kinetic Modelling in an Oscillatory Flow Biogas Reactor" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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| | |
|---|---|
| AD | anaerobic digestion |
| ADF | acid detergent fiber |
| ADM1 | anaerobic digestion model no.1 |
| AF | anaerobic filter |
| AFB | anaerobic fluidized bed |
| ASBR | anaerobic sequencing batch reactor |
| BMP | biochemical methane potential |
| BOD | biochemical oxygen demand |
| C/N | carbon/nitrogen ratio |
| CM | cattle manure |
| COD | chemical oxygen demand |
| CSTR | continuous stirred tank reactor |
| FAME | fatty acid methyl esters |
| FID | flame ionization detector |
| GC | gas chromatograph |
| GHG | greenhouse gases |
| HRT | hydraulic retention time |
| IBR | induced bed reactor |
| LBR | leach bed reactors |
| $CH_4$ | methane |
| NaOH | sodium hydroxide |
| NDF | neutral detergent fibre |
| $NH_3$-N | ammonia nitrogen |
| NKEA | national key economic areas |
| OBR | oscillatory baffled reactor |
| OFBR | oscillatory flow biogas reactor |
| OFM | oscillatory flow mixing |
| OFR | oscillatory flow reactor |
| OLR | organic loading rate |
| PFR | plug flow reactor |
| POME | palm oil mill effluent |
| $R_{en}$ | net flow Reynolds number |
| $R_{eo}$ | oscillatory Reynolds number |

| | |
|---|---|
| St | Strouhal number |
| STP | standard temperature and pressure |
| SRT | solid retention time |
| STR | stirred tank reactor |
| TCD | thermal conductivity detector |
| TCOD | total chemical oxygen demand |
| TCL | treatment cycle length |
| TPAD | temperature phased anaerobic digester |
| TPU | Taman Pertanian Universiti |
| TS | total solids |
| TVFA | total volatile fatty acid |
| UASB | up-flow anaerobic sludge blanket |
| VFA | volatile fatty acid |
| VS | volatile solids |

# CHAPTER 1

# INTRODUCTION

## 1.1 Background of the study

Animal waste, predominantly manure, has been applied to maintain the soil fertility more than a century ago. But, in recent times, intensive animal production has led to the high concentration of animals in small areas, thereby producing great amounts of waste with inadequate nearby land for its application. In Malaysia, the livestock industry contributes 22% of the total agricultural sector, however, the non-ruminant accounted for the immense of production (Tapsir and Fadhilah, 2010). Presently, the production of beef cattle is gaining momentum in Malaysia, most of which are plantation integrators, semi intensive farming system, small and medium scale traditional farmers and commercial feedlot operators (Tapsir and Fadhilah, 2010). These operations produce 28% of the total annual domestic requirement for beef production, and imports 70% of its beef requirement including live cattle from Australia, India, New Zealand and the United States to meet the domestic consumption (Warr et al., 2008; Siwar et al., 2013).

But, under the $10^{th}$ Malaysian Plan, the government is aiming to reduce its imports and improve the beef self-sufficiency by expanding its feed lotting industry (Siwar et al., 2013). These goals will lead to spatial concentration of the cattle population; consequently, nutrient runoff from the crop fields due to higher production of cattle manure (CM) will pose environmental concerns. Other environmental effect may include: emission of unpleasant odors, harmful air pollutants and greenhouse gases (Cuéllar and Webber, 2008). It was reported by Steinfeld et al. (2007) that the animal production sector is in charge for 18% of the world wide greenhouse gas emissions, measured in $CO_2$ equivalent and for 37% of the anthropogenic methane, which has 23 times the global warming potential of $CO_2$. Moreover, 65% of anthropogenic nitrous oxide and 64% of anthropogenic ammonia emissions are produced from the worldwide animal production sector. As a result, the environmental legislators are aiming on the means to encourage the confined animal producers to operate in manner to protect the environment while sustaining profitability and competitiveness (Somda et al., 2003).

The anaerobic digestion (AD) of organic wastes represents a major research focus because of the global needs for waste recycling and renewable energy production. Over the last few decades, the ability of anaerobic microbial consortia to convert the organic matter from manure into useful renewable energy in the form of biogas has gained popular attention. AD is regarded as the most effective and popular animal manure stabilization process. AD is a complex biotechnological process that converts nearly all types of organic wastes into methane, carbon dioxide and stabilized digestate. In AD, hydrolysis stage is the vital first stage where the particulate organic matter is hydrolyzed to soluble substrates for the acidogenesis stage, and further

determines the availability of substrate for acetogenesis and methanogenesis stage (Vavilin, 1996). The AD of CM has several benefits over the conventional CM management which includes, (i) methane rich-biogas production, which is a renewable fuel that can be used to replace fossil fuels thereby mitigating greenhouse gas emissions (Cuéllar and Webber, 2008) (ii) enhancement of the fertilizer quality due to improved nutrient availability and greater flow characteristics (Ward et al., 2008); and (iii) reduction of pathogens and unpleasant odour emission (Holm-Nielsen et al., 2009). Furthermore, the digestate can be refined into concentrated fertilizers, fiber products and clean water, all appropriate for recycling (Holm-Nielsen et al., 2009). In AD, the utilization of the most suitable bioreactor technology for the treatment of animal manure is crucial while creating synergistic effect in the entire process and final biogas quality. The bioreactor is of such significance in the biological processes like the AD as the heart on a live body. A bioreactor is defined as a device where a biological reaction or changes take place, usually a fermentation or biotransformation, including the tank bioreactors, immobilised cell bioreactors, hollow fibre and membrane bioreactors and digesters (Reis, 2006). The design of biological reactors is an integral part of biotechnology (Van't Riet and Tramper, 1991).

Over the last decade, important developments have been achieved in understanding the anaerobic digestion with different groups of bioreactor designs (Nasir et al., 2012). A great number of novel reactor designs has been adapted and developed recently, allowing a considerable higher rate of reaction per unit volume of bioreactor (Nasir et al., 2012). One specific novel reactor that gained increasing interest in the last decade is the oscillatory flow reactor (OFR) based on oscillatory flow mixing (OFM), which has been shown to enhance the fluid mixing and to provide narrow residence time distribution (Mohd. Ghazi et al., 2008).

## 1.2 A general description on OFM

Tubular reactor designs are novel reactors that provide a near perfect plug flow even under variable throughput condition. However, they are generally dependent on turbulent flow and susceptible to changes in throughput, hence require longer residence time resulting in a larger tubes and high pressure drop along the length of the reactor (Mackley and Ni, 1991). Oscillatory flow mixing (OFM) is a new development in the mixing technology which has been explored over the last few decades. It has a quite number of similarities to other tubular mixing technologies, most especially pulsed and reciprocating plate columns, but it has shown greater advantageous properties when operated at laboratory scale (Reis, 2008). In particular, it allows for the systematic control of the oscillatory conditions and the reduction of axial dispersion when operating as a continuous process, thereby leading to the control of residence time distributions independent of the throughput rate (Smith and Mackley, 2006). OFM generally consists of orifice baffle plates arranged equally in a column in which fluid is oscillated in the range of 0.5-6 Hz, at amplitude of 1-100 mm (Ni et al. 2003). This fluid flow interact with the baffles thereby forming vortices which provide both axial and radial mixing in the column, resulting in an effective and even mixing in the regions between successive orifice baffles (Ni et al., 2003).

Therefore a device that employs this mixing strategy is referred to as oscillatory flow reactor (OFR). The ability of the OFR to generate mixing in the radial direction makes it exceptional when compared to the conventional tubular reactors mainly in the aspect of mixing intensity control, axial dispersion and heat transfer processes. It was demonstrated that OFM offers a highly effective, alternative means of external agitation for batch as well as continuous processes, and provides a range of specific process improvements (Boodhoo and Harvey, 2013). Efficient mixing is amongst the most important control parameters for the bioreactors used in biological treatment. Also, it maintains uniform solids content in the bioreactor. Efficient mixing of the contents of an anaerobic digester is essential for process stability, minimizing the scum and foam formation, and preventing solids deposition in the bioreactor (Massart et al., 2008). In spite of the importance of mixing in achieving effective substrate conversion, there is no information about the effects of oscillatory flow mixing (OFM) on the anaerobic digestion. Therefore, this study seeks to address this issue by examining the feasibility of the OFM for AD of cattle manure.

## 1.3 Cattle manure production and management in Malaysia

Increased production of animal manure accompanied with environmental problems facing the conventional means of disposal has resulted in tremendous effort to find an alternative means of disposal. In Malaysia, the 10th Malaysia plan (2011-2015) outlines the government's strategies that will make agriculture the third machine of economic growth (Hashim and Ho, 2011). To achieve this goal, different forms of support and schemes that will boost investments has been set up particularly assigned with the provision of capital facilities for interested investors and formulation of legislations (Hashim and Ho, 2011). In addition, the Malaysian government under the National Meat Policy, targets to increase cows and buffaloes from the current 1 million to 1.6 million in 2015 (Yusuf et al., 2011). This will possibly increase the Malaysia's self-reliance in meat products to 40% from the existing 25%. Similarly, there is a proposal to utilize around two million hectares of oil palm plantation for cattle rearing to optimize land use and increase breeding stock (MAHA, 2008). Therefore, if these policies succeed in achieving the target goals, it will contribute among other things to greenhouse gases (GHG) emission from cattle manure, water pollution and even health risk. However, proper manure management practices in minimizing the GHG's emission can be done to avert the various problems through anaerobic manure digestion and the capture of biogas. This is in line with the National Key Economic Areas (NKEA), which has been inspired by the Malaysian government in the 10th Malaysia Plan.

Generally, many of the manure management processes like the storage and spreading, composting, vermicomposting etc, are complementary to the anaerobic digestion (Flotats et al., 2012). Nevertheless, the anaerobic digestion for the biogas production is one of the essential manure management processes, having significant effects on GHG's emission reduction, the waste handling and the renewable energy production. Furthermore, the digestate can be used as replacement for mineral fertilizer because it contains rich nutrient substances.

## 1.4 Problem Statement

The animal production sector generates large amounts of manure which lead to a significant challenge in meeting the increasingly stringent environmental regulations in their disposal. This industry pose a serious environmental hazard because of the pollution caused by the manure discharge, such as the surface and groundwater contamination, unpleasant odour and the contribution of methane emissions to the global climate change. Anaerobic digestion (AD) of the animal manure is an environmental friendly way to combat these problems, and it has been used effectively to protect environmental pollution thereby generating the renewable energy.

The most common reactor design applied in AD is the continuous stirred tank reactor (CSTR), as it is simple to construct and operate and low cost of capital as compared to the other reactor designs. However, the simplicity of the CSTR incurs aggravating problems to operators, which include; operation at a prolonged hydraulic retention time (HRT) with long start-up period. Also, the mechanical mixing strategy of the CSTR and turbulence generation in the tubular reactors are prone to issues like pump blockages (ragging), solid deposits, dead spots, and scum or foam accumulation. For cost-effectiveness concern, they have inefficient heating and mixing mechanisms that are often needed in medium and large scale bioreactors, which result in low biogas production and serious mass transfer limitations. Various alternate concept of reactor design have, therefore, been developed to solve these problems by shortening the start-up time and retention time. The plug flow reactor (PFR) came into existence to overcome the problems related to poor retention time by the CSTR. By virtue of its ability to allow for reactant flow at high enough velocity to achieve turbulence; and retains material flow as a plug makes it an attractive process option. However, its limitation is that high velocity must be maintained, hence, this is a problem for long reactions as maintaining high velocity for longer period results in long and narrow bioreactors causing problems such as poor temperature control, high maintenance cost, etc.

Then, an emerging novel approach mixing technology that can effectively intensify many multiphase chemical and biological processes; is believed to provide a design capable of overcoming those conventional digesters shortcomings while still keeping their benefit in terms of simplicity. This advanced novel design that is the oscillatory flow biogas reactor (OFBR) fixes a series of intrinsic problems in terms of long HRT, uniform heating, mixing, clogging, and deposits formations that have hampered the conventional digesters application. In OFBR, the eddy mixing achieved with small fluid pulsations and periodic restricting baffles, dispersed in an elongated column, results in the creation of strong radial mixing within the compartments defined by successive baffles. Each baffle is regarded to act as small CSTRs, which might result in a short HRT due to having many tanks in series. Therefore, the shortening of the HRT and the start-up time and possible higher biogas yield bear practical importance as it can boost the attractiveness of OFBR application in the biogas production.

Recent research in our laboratory on the batch anaerobic thermophillic treatment of cattle manure in a novel OFBR found an improved solids reduction (22%) and higher biogas yield (27%) compared to the conventional CSTRs. For this reason, the novel oscillatory flow mixing (OFM) have gained interest in recent years. Hence, this study is essentially to assess the performance of this novel OFBR approach in treating the cattle manure for enhanced biogas methane production. Generally, there has been very little research conducted into the applicability of OFBR in the AD for the biogas production. Also, none of these researches found in the literature so far that evaluate the effect of OFM on the anaerobic digestion of cattle manure using the novel OFBR.

## 1.5 Objectives

The overall research aim is to optimize and the evaluate the biogas production from the anaerobic digestion of cattle manure in an oscillatory flow biogas reactor (OFBR). The objectives of this study were:

1. To investigate the start-up of anaerobic digestion (AD) of the cattle manure (CM) and to evaluate the impact of oscillatory flow mixing (OFM) to accelerate the batch process.
2. To evaluate the effect of process organic loading rate (OLR) variation during the semi-continuous AD of CM at fixed and variable hydraulic retention time (HRT).
3. To determine the optimum experimental OLR in terms of volumetric methane production and process conversion efficiencies (methane yield, VS and COD reductions).
4. To develop a mathematical model for the semi-continuous OFBR, and further calculate the kinetic constant using the model for the methane production rate of an OFBR involving Contois kinetics.

## 1.6 Scope

To achieve the above objectives, scopes of the study are given as follows:

1. The start-up and the effect of OFM and OLR studies were conducted in a laboratory scale novel OFBR set up.
2. The novel OFBR is feasible at substrate oscillation frequencies between 0 and 50 Hz, and amplitude between 0 and 50 mm.
3. The selected center to peak amplitude and frequency for the OFBR was 20 mm and 2 Hz, respectively (based on preliminary studies and previous experiment).
4. Cattle manure was collected from a dairy farm in Taman Pertanian Universiti (TPU) situated in the university campus.
5. Inoculum used for the biochemical methane potential (BMP) test and for the digestion consisted of palm oil mill effluent from a palm oil mill in Dengkil, Selangor.

6. The characterization of manure and digestate and the analyses of the operational parameters of AD were performed in the Green Technology laboratory, UPM.
7. The semi-continuous study was performed to achieve the following:

    i) the system performance in terms of the biogas and methane production rate, and specific biogas and methane yield;
    ii) the process stability in terms of pH, volatile fatty acid (VFA), and ammonia nitrogen ($NH_3$-N) concentration;
    iii) the process efficiencies in terms of volatile solids (VS) and chemical oxygen demand (COD) reductions;
    iv) the quality of the final digestate.
8. The methane content in the biogas was analysed with the gas chromatography in the analytical laboratory, UPM.

## 1.7 Organization of Chapters

This thesis is divided into five chapters with the appendices at the end. Chapter 1 consists of the brief introduction, also, the main objectives and research scope are presented.

Chapter 2 gives a detailed literature review on the previous research on the anaerobic digestion of animal manure and various bioreactors employed for anaerobic treatment of manure. Also, a detailed assessment of the information available on OFR and the influence of oscillatory flow mixing were presented.

Chapter 3 details the methods employed to investigate the start-up and performance of the batch process, the effect of oscillatory flow mixing and loading rate on the anaerobic digestion.

Chapter 4 presents the effect of chemical pretreatment of cattle manure on the anaerobic digestion and biogas production. Also, it presents the impact of varying the oscillatory flow mixing under three different frequencies in the batch digestion, and further, the impact of different OLR in semi-continuous digestion was determined and presented. Finally, the development of the anaerobic digestion model that is comparatively to a plug flow reactor was presented, and the kinetic parameters were fitted to the semi-continuous experimental results.

Chapter 5 summarizes the key conclusions of this research and provides recommendations for future research directions based on the findings of this study.

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