# การบูรณาการถังหมักแบบไร้อากาศร่วมกับระบบถังปฏิกรณ์ชีวภาพเมมเบรนแบบคลองวนเวียนในการลดขยะอินทรีย์ให้เหลือศูนย์สำหรับอาคาร

นางสาวอาภาพรรณ สัตยาวิบูล

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรดุษฎีบัณฑิต
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# INTEGRATION OF ANAEROBIC DIGESTER WITH OXIDATION DITCH-MEMBRANE BIOREACTOR AS A ZERO ORGANIC WASTE SYSTEM FOR BUILDING APPLICATION

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A Dissertation Submitted in Partial Fulfillment of the Requirements
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| Thesis Title | INTEGRATION OF ANAEROBIC DIGESTER WITH OXIDATION DITCH-MEMBRANE BIOREACTOR AS A ZERO ORGANIC WASTE SYSTEM FOR BUILDING APPLICATION |
| By | Miss Arpapan Satayavibul |
| Field of Study | Environmental Science |
| Thesis Advisor | Associate Professor Chavalit Ratanatamskul, Ph.D. |

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อาภาพรรณ สัตยาวิบูล : การบูรณาการถังหมักแบบไร้อากาศร่วมกับระบบถังปฏิกรณ์ชีวภาพเมมเบรนแบบคลองวนเวียนในการลดขยะอินทรีย์ให้เหลือศูนย์สำหรับอาคาร (INTEGRATION OF ANAEROBIC DIGESTER WITH OXIDATION DITCH-MEMBRANE BIOREACTOR AS A ZERO ORGANIC WASTE SYSTEM FOR BUILDING APPLICATION) อ.ที่ปรึกษาวิทยานิพนธ์หลัก: รศ. ดร. ชวลิต รัตนธรรมสกุล, 99 หน้า.

การศึกษาครั้งนี้มีวัตถุประสงค์เพื่อศึกษาประสิทธิภาพการกำจัดสารอินทรีย์ของระบบถังหมักแบบไร้อากาศ (AD) ร่วมกับถังปฏิกรณ์ชีวภาพเมมเบรนแบบคลองวนเวียน (OD-MBR) ในการจัดการตะกอนเหลวจากถังหมักและตะกอนน้ำเสียเพื่อลดขยะอินทรีย์ให้เหลือศูนย์ โดยนำเศษอาหารจากโรงอาหารมาหมักร่วมกับตะกอนน้ำเสียจากระบบถังปฏิกรณ์ชีวภาพเมมเบรนแบบคลองวนเวียนที่อัตราส่วน 10:1 โดยน้ำหนัก และตะกอนเหลวจากกระบวนการหมักจะนำมาบำบัดต่อด้วยระบบ OD-MBR เพื่อศึกษาผลผลิตก๊าซมีเทนและร้อยละประสิทธิภาพในการกำจัดของเสียทั้งหมด การวิจัยนี้เป็นการทดลองแบบกึ่งต่อเนื่อง ปรับสภาวะที่เหมาะสมเป็น 6 รูปแบบการศึกษา ดังนี้ ที่ระยะเวลากักพักน้ำ 24, 18 และ 12 ชม. ความเร็วของน้ำเท่ากับ 0.3 และ 0.6 เมตรต่อวินาที รูปแบบละ 28 วัน ผลการศึกษาพบว่า การเดินระบบร่วม AD และ OD-MBR มีการผลิตก๊าซชีวภาพทั้งหมดเท่ากับ 167.63 Nm$^3$ ตลอดช่วงการทดลอง โดยการทดลองที่ระยะเวลากักพักน้ำ 24 ชั่วโมง และความเร็วของน้ำเท่ากับ 0.3 เมตรต่อวินาที (SC1) มีปริมาณก๊าซชีวภาพสูงสุด เท่ากับ 34.92 Nm$^3$ และให้ผลผลิตก๊าซมีเทน เท่ากับ 1.12 m$^3$CH$_4$/kg VS removed ส่วนประสิทธิภาพในการบำบัดของเสีย พบว่าระบบร่วมมีประสิทธิภาพในการบำบัด COD ได้ร้อยละ 85.44-93.77 TKN ร้อยละ 64.31-85.57 ไนเตรทร้อยละ 40.82-54.17 และฟอสฟอรัส ร้อยละ 44-51.17 สำหรับการประเมินสมดุลพลังงานสุทธิ พบว่า ค่าพลังงานสุทธิของระบบร่วมมีค่าเป็นลบในทุกการทดลอง แต่เมื่อพิจารณาถึงการประหยัดพลังงานของระบบร่วม สามารถประหยัดค่าก๊าซหุงต้มสูงที่สุดในการทดลองที่ 1 (SC1) คิดเป็นเงิน 4,428 บาท/ปี การประเมินวัฏจักรชีวิตโดยใช้โปรแกรม SimaPro 8 สำหรับการประเมินผลกระทบทางสิ่งแวดล้อมของระบบร่วมในด้านศักยภาพในการก่อให้เกิดโลกร้อน ศักยภาพการก่อให้เกิดภาวะกรด และศักยภาพการเพิ่มธาตุอาหารในแหล่งน้ำ ผลการศึกษาพบว่า ระบบร่วมมีศักยภาพในการก่อให้เกิดโลกร้อนเท่ากับ 1.29 kg CO$_2$ eq. per FU ศักยภาพก่อให้เกิดภาวะกรด เท่ากับ 0.0128 kg SO$_2$ eq per FU และ ศักยภาพในการเพิ่มธาตุอาหารในแหล่งน้ำ เท่ากับ 4.659 kg PO$_4$ eq per FU

สาขาวิชา วิทยาศาสตร์สิ่งแวดล้อม ลายมือชื่อนิสิต ........................................
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KEYWORDS: ANAEROBIC DIGESTION / DIGESTATE / OXIDATION DITCH MEMBRANE BIOREACTOR / LIFE CYCLE ASSESSMENT / ENERGY BALANCE

ARPAPAN SATAYAVIBUL: INTEGRATION OF ANAEROBIC DIGESTER WITH OXIDATION DITCH-MEMBRANE BIOREACTOR AS A ZERO ORGANIC WASTE SYSTEM FOR BUILDING APPLICATION. ADVISOR: ASSOC. PROF. CHAVALIT RATANATAMSKUL, Ph.D., 99 pp.

The objective of this study is to study the efficiency of organic substance removing in anaerobic digestion system and oxidation ditch membrane bioreactor (OD-MBR) for managing liquid digestate and wastewater sludge to completely zero organic waste. The process can be done by digesting food waste from the canteen with sludge from OD-MBR with the proportion of 10:1 by weight and liquid digestate from anaerobic digestion process will be further treated by OD-MBR to study the productivity of methane and efficiency of waste treatment. This study is a semi-continuous experiment by adjusting the experimental conditions for six conditions, as follows; HRT of 24, 18, and 12 hours at the water velocity of 0.3 and 0.6 m/s with 28 days per condition. The result shows that the combined system has high efficiency of waste treatment and the total amount of produced biogas is 167.63 Nm$^3$ along the experiment. The highest amount of biogas of 34.92 Nm$^3$ is from the experiment using a HRT 24 hours and water velocity 0.3 m/s (SC1). The highest specific methane yield of 1.12 m$^3$CH$_4$/kg VS removed. For the efficiency of waste treatment, the range which COD can be treated is 85.44-93.77%. TKN is 64.31-85.57%, Nitrate is 40.82-54.17%, and phosphorus is 44-51.17%. In the term of net energy balance the result show that net energy balance is negative in every experiment. However, when considering the energy saving, for combined system Experiment 1, (SC1) can save LPG the most or 4,428 THB/year. The evaluation by LCA with SimaPro 8 software for global warming potential (GWP), acidification potential (AP), and eutrophication potential (EP) shows that the combined system between AD and OD-MBR has the GWP of 1.29 kg CO$_2$ eq. per FU, AP of 0.0128 kg SO$_2$ eq per FU, and EP of 4.659 kg PO$_4$ eq per FU.

Field of Study: Environmental Science Student's Signature ..............................

Academic Year: 2017 Advisor's Signature ..............................

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# CHAPTER 1

# INTRODUCTION

## 1.1 Background

Organic waste is the largest component of MSW which is produced from household or residential areas, commercial area such as restaurants, cafeterias, and market. The main forms of organic waste are household food waste including food scraps and food preparation, garden waste, agricultural waste, livestock manure and sewage sludge. In Thailand, 24.73 million tons of municipal solid waste (MSW) was generated in 2012 or around 67,577 tons/day. The amount of organic waste utilization (composting and produce the biogas) was reported as 1.14 million tons/year (Pollution Control Department, 2014). Organic wastes become one of the major problems of solid waste management in Thailand. Most of organic wastes are placed in landfill sites leading to the leachate generation and also the production of methane gas that can cause landfill fires. However, incineration may not be suitable for organic waste because of low calorific value due to its high moisture content. In recent years there has been increased interest in diverting the organic fraction of MSW to produce biogas, an energy source and a soil amendment, due to the high decomposition potential.

Anaerobic digestion (AD) is a widely use method for treating various type of organic waste to produce energy and resource recovery. AD can convert the organic biodegradable fraction by anaerobic microorganisms into high methane content biogas and the residue can be used as a fertilizer or soil improver. AD can minimize the release of greenhouse gases (GHG) to the atmosphere, because gases will be captured in the gas tank for energy generation purpose. Chulalongkorn University recently has developed a prototype combined AD with the water reuse system, OD-MBR (oxidation ditch–membrane bioreactor) as a novel technology by using this integrated method for zero organic-waste system that can be applied for building application. The AD has also been considered a good treatment for organic waste fraction to produce biogas, soil conditioner and fertilizer. The final output from anaerobic digestion systems is liquid digestate, which originates both from the moisture content of the original waste that was treated and water produced during the microbial reactions in the digestion systems. This liquid digestate may be released from the dewatering of the digestate or separated from the digestate. The wastewater exiting the anaerobic digestion facility will typically have elevated levels of biochemical oxygen demand (BOD) and chemical oxygen demand (COD). These measures of the reactivity of the effluent indicate an ability to pollute water resources. If this effluent is discharged directly into water environment, it can cause eutrophication problem. So, further treatment of the wastewater is often required. Oxidation ditch-membrane bioreactor (OD-MBR) is a circular basin through which the wastewater flows. Activated sludge is added to the oxidation ditch so that the microorganisms will digest the BOD, COD in the water. After that the water output can be reusable in garden and sludge from OD-MBR is returned to the AD to produce biogas. Life cycle assessment (LCA) is an effective environmental tool for evaluating the environmental impact from product or activity. The environmental impacts obtained from LCA are described as potential impacts. In many studies has been used to applying LCA to waste management system, however, have not been evaluated for food waste-to-energy technology.

This study aims to develop the prototype integrated AD and OD-MBR system as a zero organic-waste system that can be applied for Thai society. The current situation of organic waste management problems, possibilities for improvement the anaerobic digestion and the feasibility application of the combined system will be analyzed in this study. The analysis of selected approach will be done, using the Life Cycle Assessment (LCA) and net energy balance analysis. The clear representation of various processes and flows of organic waste gives an account of which particular sub-processes to be focused in terms of making a management decision to improve overall organic waste management for local need.

## 1.2 Objectives

1.2.1 To develop a prototype combined system of AD with OD-MBR as a zero organic-waste system for building application.

1.2.2 To optimize the operating conditions for AD and OD-MBR system in term of system performance.

1.2.3 To evaluate Life Cycle Assessment (LCA) for the developed zero organic-waste system

1.2.4 To analyze the net energy balance of the prototype system for building application

## 1.3 Scope of Study

This study focuses on organic waste treatment at Chulachakrabongse building, which located in Chulalongkorn University. Food waste is obtained from canteen at Chulachakrabongse building, Chulalongkorn campus. The food waste is disposed and manual sorted by housekeeper. The sludge is collected from the oxidation ditch-membrane bioreactor. This prototype system is to combine anaerobic digestion (AD) and oxidation ditch-membrane bioreactor (OD-MBR) as a zero organic-waste system for building application. The efficiency of combined system will be tested by analyzing water effluent compared to water quality standard. The water quality will be analyzed for pH, DO, TKN, $NO_3$-N, $NO_2$-N, COD and TP. A life cycle assessment (LCA) was conducted to analyze the different alternatives in terms of global warming potential (GWP), acidification, eutrophication and energy use.

## 1.4 Expected Benefits

Develop the prototype of AD with OD-MBR as a zero organic-waste system for building application in tropical region. Also, more information on LCA and net-energy balance analysis can be used for practical system operation.

# CHAPTER 2
# LITERATURE REVIEW

## 2.1 Overview on MSW in Thailand

Municipal solid waste (MSW) is a term usually applied to a heterogeneous collection of waste produced in urban areas, the nature of which varies from region to region. The characteristics and quality of the solid waste generated in a region is not only a fraction of the living standard and lifestyle of the region inhabitants, but also of the abundance and type of the region's natural resources. Urban wastes can be subdivided into two major components such as organic and inorganic (Rewlutthum, 2013)

Thailand is a one of developing countries in Southeast Asia with a total population about 66 million, that cause an accumulating problem on solid waste management and disposal. The quantity of generated solid waste mainly depends on population, economic growth and the efficiency of reuse and recycling system (Chiemchaisri, Juanga, & Visvanathan, 2007). The total MSW generation in Thailand increased from 14.3 million tons in 2002 to 16 million tons in 2012 (Pollution Control Department, 2015).

In 2013, PCD reported a total municipal solid waste (MSW) generation of 26.774 million tons or about 73,355 tons a day, slightly increased from 2012 around 8 percent. This number is based on a national correspondence survey of the responsible local administrations carried out by the PCD in 2013. The volume can be divided into the solid waste generated in BMA at about 4.137 million tons (16%), the solid waste generated in municipalities and Pattaya City generated about 10.241 million tons (38%), and the solid waste generated in SAO at about 12.396 million tons (46%). The national average waste generated per person was 1.15 kg/day as show in Table 2.1 and Fig 2.1

**Table 2.1** The volume of solid waste generated in Thailand

| Local Administrative Organizations | The volume of MSW | |
|---|---|---|
| | million tons | percentage (%) |
| Bangkok Metropolitan Administration (BMA) | 4.137 | 16% |
| Municipalities and Pattaya City | 10.241 | 38% |
| Subdistrict Administrative Organizations (SAO) | 12.396 | 46% |
| Total | 26.774 | 100% |

**Source**: Pollution Control Department (2014)

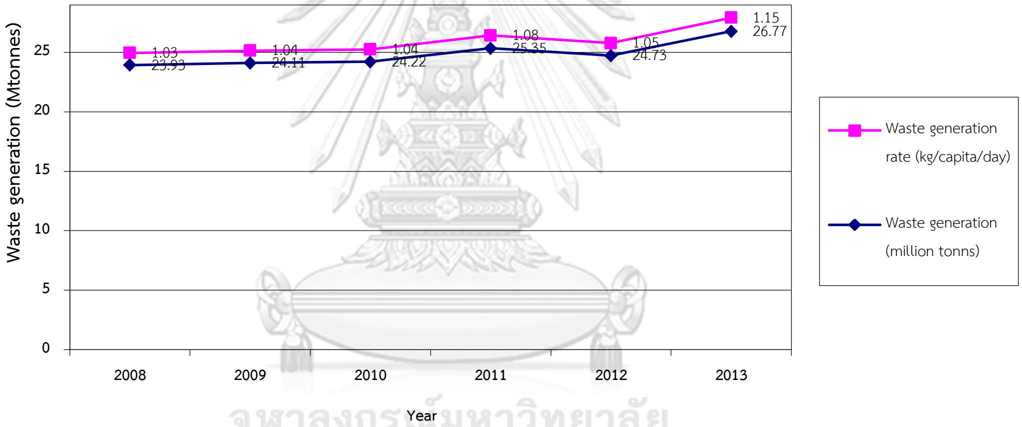


**Figure 2.1** Total waste generation in Thailand during 2008-2013

**Source**: Pollution Control Department (2014)

Out of 7,782 local administration organizations, 4,179 (54%) of them provided waste transport and disposal services. About 7.421 million tons or 20,332 tons a day, equal to 52% of the total volume of the collected waste is delivered to suitable waste management facilities. On the other hand, 6.938 million tons, or 19,008 tons a day, equal to 48% of the total volume of the collected waste, especially in small SAOs, were unsuitably disposed of by open burning or open dumping into old abandoned pits or undeveloped areas (Pollution Control Department, 2014).

The volume of 14.359 million tons of the collected solid waste was disposed of at one of the 2,490 waste management facilities scattered throughout the country. The waste management facilities can be divided into suitable disposal facilities and unsuitable facilities. Suitable waste disposal sites refer to 446 sanitary landfills, engineered landfills, control dumps with the capacity of less than 50 tons/day, incinerators with air pollution control systems, Waste to Energy Technology (WTE), composting, and mechanical biological treatment systems (Table 2.2). On the other hand, unsuitable waste disposal sites refer to 2,024 open dumps, control dumps with the capacity of at least 50 tons/day, open burning sites, and incinerators without air pollution control systems (Pollution Control Department, 2014).

**Table 2.2** Suitable waste disposal sites

| Public sites | | Private sites | |
|---|---|---|---|
| Type | Amount | Type | Amount |
| Sanitary landfills/ engineered landfills | 64 | Sanitary landfills/ engineered landfills | 9 |
| Control dumps with the capacity of less than 50 tons/day | 341 | Control dumps with the capacity of less than 50 tons/day | 26 |
| Incinerators with air pollution control system | 1 | Incinerators with air pollution control system | 1 |
| Incinerators with the capacity of less than 10 tons/day and have an emission control system (cyclones) | 8 | Waste to Energy Technology | 1 |
| Integrated system | 12 | | |
| Mechanical biological treatment system | 1 | Mechanical biological treatment system | 2 |
| Total (public sites) | 427 | Total (private sites) | 39 |

**Source:** Pollution Control Department (2014)

### 2.1.1 Municipal Solid Waste Characteristics

From Table 2.3 below shows that the largest portion of MSW component in Thailand is organic waste (64%). Follow by plastic and paper about 17% and 8%. So the important to reduce the quantity of organic components by appropriate organic waste treatment technology is the way that waste components are utilized and reduce amount of organic waste to landfill.

**Table 2.3** Municipal solid wastes composition in Thailand

| Component | Percentage (%) |
|---|---|
| Organics | 64 |
| Plastic | 17 |
| Paper | 8 |
| Glass | 3 |
| Metal | 2 |
| Wood | 1 |
| Rubber and Leather | 1 |
| Textile | 1 |
| Other waste | 3 |
| Total | 100 |

**Source:** (Pollution Control Department, 2014)

Fig 2.2 shows the overview of MSW flow in 2013 in Thailand. Out of the volume of 26.774 million tons/year of municipal solid waste generated in 2013, Properly management is approximately 5.152 million tons, or 19% of the volume was utilized and sanitary disposed about 7.421 million tons. The remaining MSW is over 14 million tons was improper disposed such as open burning, open dump. The methods of waste utilization can be divided into 3 methods as following:

1) Recycling method is processed by the separation and recovery of recyclable waste including glass, paper, plastic, steel, and aluminums from junk shops, community recycling centers, waste banks, packaging buyback/return systems, and product inventions from waste. The volume of waste collected for recycling purpose was around 3.935 million tons, or 76%, of the total volume of the utilized waste.

2) Organic waste utilization is processed by sorting organic waste including food scraps, vegetables, and fruits in order to make compost and enzyme ionic plasma used as fertilizer, and to make biogas used as an alternative energy source. The volume of organic waste collected for this purpose was around 1.114 million tons, or 22%, of the total volume of the utilized waste.

3) Waste-to-Energy method is processed by putting solid waste in the processing procedure to generate energy in the form of electricity or an alternative energy source of refuse derived fuel (RDF). The volume of waste collected for this purpose was about 0.103 million tons, or 2%, of the total volume of the utilized waste

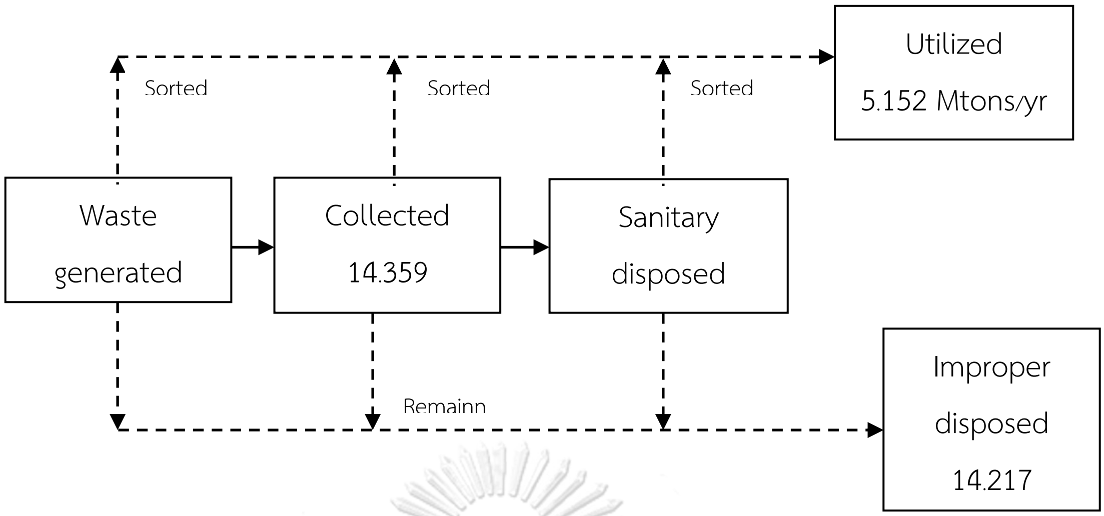


**Figure 2.2** Mass Flow of municipal solid waste in Thailand 2013

**Source:** (Pollution Control Department, 2014)

At present, the PCD ran the Reduce, Reuse and Recycle (3Rs) strategy to reduce, reuse and recycle waste. Waste was controlled for production, distribution, consumption, treatment and disposal with cooperation of all parties such as Local Administrative Organizations, private companies, operators and people. The strategy consists of four strategies: 1) resource efficiency; 2) sustainable consumption; 3) increasing the efficiency of waste recovery and utilization; and 4) proper waste treatment and disposal.

## 2.2 Integrated Solid Waste Management System

Integrated solid waste management (ISWM) can be defined as the selection and application of suitable techniques, technologies, and management programs to achieve specific waste management objectives and goals. A hierarchy (arrangement in order of rank) in waste management can be used to rank actions to implement programs within the community. The ISWM hierarchy is composed of the following elements: source reduction, recycling, waste transformation, and landfilling (Tchobanohlous, 1993). The concept of ISWM strives to strike a balance between three dimensions of waste management: environmental effectiveness, social acceptability and economic affordability. ISWM also focuses on to reduce environmental impact and drive cost down, a system should be integrated in waste materials, resource of waste and treatment method, market oriented i.e. energy and materials have end uses (Marshall & Farahbakhsh, 2013). The ISWM has developed by EPA into four hierarchy that consist of source reduction and reuse, recycling/composting, energy recovery and treatment and disposal (Environmental Protection Agency [EPA], 2014).

**Figure 2.3** Integrated solid waste management hierarchy

**Source:** (Environmental Protection Agency [EPA], 2014)

### 2.2.1 Source reduction and reuse

The highest rank of the ISWM hierarchy, source reduction, involves reducing the mount and/or toxicity of the wastes that are now generated. Source reduction is first in the hierarchy because it is the most effective way to reduce the quantity of waste, the cost associated with its handling, and its environmental impacts. Waste reduction may occur through the design, manufacture, and packaging of products with minimum toxic content, minimum volume of material, or a longer useful life. Waste reduction may also occur at the household commercial or industrial facility through selective buying patterns and the reuse of products and materials (Tchobanohlous, 1993).

### 2.2.2 Recycling/composting

Recycling is an important factor in helping to reduce the demand on resources and the amount of waste requiring disposal by landfilling (Tchobanohlous, 1993). Recycling also include digesting of food wastes, green wastes, and other organic materials.

### 2.2.3 Energy recovery

Energy recovery from waste is the conversion of non-recyclable waste materials into useable heat, electricity, or fuel through a variety of processes, including combustion, gasification, pyrolysis, anaerobic digestion, and landfill gas (LFG) recovery. This process is often called waste-to-energy (WTE). The results of this process are to reduced use of landfill capacity and reduction in waste volume through combustion.

### 2.2.4 Treatment and disposal

Ultimately, something must be done with (1) the solid wastes that cannot be recycled and are of no further use; (2) the have been residual matter remaining after solid wastes have been separated at a materials recovery facility; and (3) the residual matter remaining after the recovery of conversion products or energy. There are only two alternatives available for the long term handling of the ocean. Landfilling, the fourth rank of the ISWM hierarchy, involves the controlled disposal of wastes on or in the earth’s mantle, and it is by far the most common method of ultimate disposal of wastes on or in the earth’s mantle, and it is by far the most common method of ultimate disposal for waste residuals. Landfilling is the lowest rank in the ISWM hierarchy because it represents the least desirable means of dealing with society’s wastes (Tchobanohlous, 1993).

## 2.3 Overview of Organic Waste

Municipal solid waste can be divided into two parts: organic or biodegradable waste and non-organic or non-biodegradable waste. Organic waste includes kitchen waste, food waste, fruit and vegetables pilling, leaves and garden trimmings, crop residues.

### 2.3.1 Organic Waste Management in Thailand

#### 2.3.1.1 Composting

The composting process uses biological microorganisms to decompose organic MSW under controlled aerobic conditions. The product, compost, can be used on land as soil conditioner or to be upgraded to fertilizer with chemical amendments. The composting process can be divided into three phases. The first stage is preprocessing whereby the oversized, contaminated materials are removed either manually or mechanically using sorting equipment. Size reduction and mixing using a shredder or rotary drum are optional for this homogenization purpose. To reduce the degree of contaminant, the commingled waste requires a greater degree of sorting upstream of the biological stage. In the second stage, microbiology decomposes the MSW into simple compounds and generates heat.

The characteristics of MSW in Thailand, composting trends to be the most appropriate technology for waste disposal and treatment. Composting also generates valuable fertilizer or soil conditioners that can be used for agricultural and horticulture areas (Sharp & Sang-Arun, 2012). The scale of composting in Thailand can range from large scale to household composting.

#### 2.3.1.2 Anaerobic digestion

Anaerobic digestion (AD) is a biological process in which bacteria break down organic matter producing biogas as the end product. AD is a sequence of chemical reactions during which organic matter is decomposed through the metabolic pathways of naturally occurring microorganisms in an oxygen depleted environment. AD is a promising technology which could effectively address the problem of waste disposal yielding valuable outputs like biogas and fertilizer. AD without any pretreatment but with energy recovery is the most attractive method for treating solid wastes (Prabhudessai, Ganguly, & Mutnuri, 2013).

The process of anaerobic digestion (AD) organic materials are convert to biogas, a mixture of carbon dioxide and methane with trace of other constituents, by a consortium of bacteria which are sensitive to or inhibited by oxygen. Using AD it is possible to convert rather plant residues, agricultural wastes, manure, effluents from the food and beverage, paper and pulping and some chemical industry wastes into useful by-products. The organic fraction of municipal solid waste (MSW) can be digested to give a potentially useful fuel which may be variously used to provide heat, electrical power or transport (Wheatley, 1990).

The bioconversion of organic materials to methane is accomplished by chemoheterotrophic, non-methanogenic and methanogenic bacteria, which larger, polymeric compounds first hydrolyzed to free sugars, alcohols, volatile fatty acids, hydrogen and carbon dioxide. This mixture is oxidized to acetic acid, carbon dioxide and hydrogen which are then converted to methane. Lignin is not degraded by most AD system; the rate of cellulose breakdown is slow (weeks), hemicellulose and protein somewhat faster (days) and small molecules such as sugar, fatty acids and alcohols fast (hours). Variation in feed composition or temperature can cause an imbalance in microbial activity resulting in changes in pH, gas composition and efficiency of COD removal. Stability is a major composition in commercial systems and maybe controlled by addition of alkali as well as control of feedstock composition and feeding rate (Wheatley, 1990).

Digestion technology can be divided into wet and dry processes. The wet method is typically performed with a water content of 10-15% TS. To increase water content in MSW, the co-digestion with liquid substrate i.e. manure, sewage sludge can be executed. The dry concept operated with 25-40% TS is able to use MSW as a main feedstock of digestion process. The single or double stage reactors are used for both digesting technologies. Despite higher gas yield and lower hydraulic retention time (HRT) in double stage, the capital cost for the additional step increases enormously. In addition, the digestion process is accomplished either by thermophilic or mesophilic conditions. Owing to the advantage in faster degradation, destruction of pathogens and a higher biogas yield, thermophilic decomposition has become a more common used (Chanchampee, 2010)

Products and uses

The value of an AD system can be evaluated either in terms of the cost of disposal of organic wastes, or in term of the value of products. The main product in many case is biogas. Hence, the success of many projects depends on the net fuel value of the gas produced in a given time, which in turn reflects composition and volume as well as the value of other fuels for which it can be substituted on the one hand and the capital investment and annual running costs on the other (Wheatley, 1990)

From the Table 2.4 the properties and the volume of biogas produced are depending on many factors such as, microbial cells, temperature, type of feedstock and engineering (Wheatley, 1990).

**Table 2.4** Constituents of biogas derived from different sources

| Constituent gas | Agricultural wastes | Sewage sludge | Industrial wastes | Landfill gas |
|---|---|---|---|---|
| Methane | 50-80% | 50-80% | 50-70% | 45-65% |
| Carbondioxide | 30-50% | 20-50% | 30-50% | 34-55% |
| Hydrogen | 0-2% | 0-5% | 0-2% | 0-1% |
| Hydrogen sulfide | 500 ppm | 100 ppm | - | 0.5-100 ppm |
| Nitrogen | 0-1% | 0-3% | 0-1% | 0-20% |
| Oxygen | 0-1% | 0-1% | 0-1% | 0-5% |

**Source:** (Wheatley, 1990)

## 2.4. Oxidation Ditch Membrane Bioreactor

A typical process of an oxidation ditch influent passing through a bar screen flows straight into an oxidation ditch. Oxygen is added to the mixed liquor in the oxidation ditch using brush aerator which increases the surface area of the wastewater and creates waves and movement within the ditch. The aeration in oxidation ditch sharply increases the dissolved oxygen (DO) concentration but the DO decreases as the biomass uptake the oxygen when the mixed liquor travels through the ditch. After biodegradable organics or BOD is removed, mixed liquor will flow out of the oxidation ditch and sludge will usually be settled and removed in the secondary clarifier. Tertiary filtration after clarification may be necessary, depending on the effluent requirements. The specific advantages of oxidation ditches include the following: long hydraulic retention time and complete mixing minimize the impact of a shock load, produces less sludge than the other biological treatment processes, energy efficient operations result in reduced energy costs compared to other biological treatment processes. On the other hand, oxidation ditch has some disadvantages such as high effluent suspended solids concentrations and requires large land area.

However, the quality of effluent from oxidation ditch is not sufficient enough for higher standards that are required for unlimited irrigation and reuse of the water. Membrane bioreactor (MBR) technology has been applied to provide high quality effluent by constructing a membrane system into the existing clarifier. Membrane bioreactor is a process that combination of biological wastewater treatment with membrane filtration. For high quality of water effluent such as organic and suspended solid removal. The benefits of using the MBR technology are no extra land requirement, produce high quality effluent for reuse, no odor, and allows treatment of much higher capacity of wastewater.

### 2.4.1 Membrane Process

This is a physical process, where separated components remain chemically unchanged. Components that pass through membrane pores are called permeate, while rejected ones form concentrate or retentate.

#### 2.4.1.1 Membrane classification

1) Microfiltration working at low pressure, size exclusion, pathogenic bacteria and some viruses.

2) Ultrafiltration working at low pressure at 100 psi, size exclusion

3) Nanofiltration

4) Reverse Osmosis

There are four types of membrane configuration which are currently in operation:

1) Tubular form

2) Plate and frame module

3) Spiral wound module

4) Hollow fiber module

### 2.4.2 Fouling mechanisms

Fouling occurs as a consequence of interactions between the membrane and the mixed liquor, and is one of the principal limitations of the MBR process. Fouling of membranes in MBRs is a very complex phenomenon with diverse interlinkages among its causes, and it is very difficult to localise and define membrane fouling clearly. The main causes of membrane fouling are:

Adsorption of macromolecular
Growth of biofilms on the membrane surface
Precipitation of inorganic matter
Aging of the membrane

## 2.5 Life Cycle Assessment (LCA)

LCA (life cycle assessment) is a process to assess the potential environmental burdens associated with a product, a process or an activity. Characteristic parts in an LCA are identifying and quantifying energy and material flows, and evaluating the environmental impacts associated with these flows. The assessment should encompass the entire life cycle of the studied system (the studied system can be a product, a process or an activity), including material and energy raw ware acquisition, manufacturing, usage and waste treatment (Lens, Hamelers, Hoitink, & Bidlingmaier, 2004).

### 2.5.1 The LCA framework

The framework outlined is based on the ISO Standard 14040: 2006. According to the standard references a complete LCA consists of the following interrelated components:

(1) Definition of the goal and scope

(2) Life cycle inventory analysis (LCI)

(3) Life cycle impact assessment (LCIA)

(3.1) Classification
(3.2) Characterization
(3.3) Valuation or weighting
(4) Interpretation

In the goal definition and scoping, the purpose of and the range covered by the study should be defined. This includes definition of system boundaries, data requirements, assumption and limitations.

In the inventory analysis, the inputs and outputs of the system under study are analyzed. The system is usually a product through its lifetime. The inputs to the system are, e.g. energy and raw materials. The outputs from the system are, e.g. emissions from processes during raw material acquisition, manufacturing, transportation, usage and waste management. The inventory analysis results in tables of inputs and outputs of the system or systems under study.

Impact assessment is a process to characterize and evaluate the influence of the inputs and outputs identified in the inventory analysis. The impact assessment of an environmental LCA should consider the following major categories:

- Resource depletion
- Impacts on human health
- Ecological impacts.

Each of these major categories is further divided into several impact subcategories.

The impact assessment is divided into three steps: classification, characterization and valuation. In the classification, the different inputs and outputs are assigned to different impact categories. An analysis and quantification of each impact category is made in the characterization step. Valuation or weighting is the step in which the data of the different specific impact categories are weighted so that they can be compared.

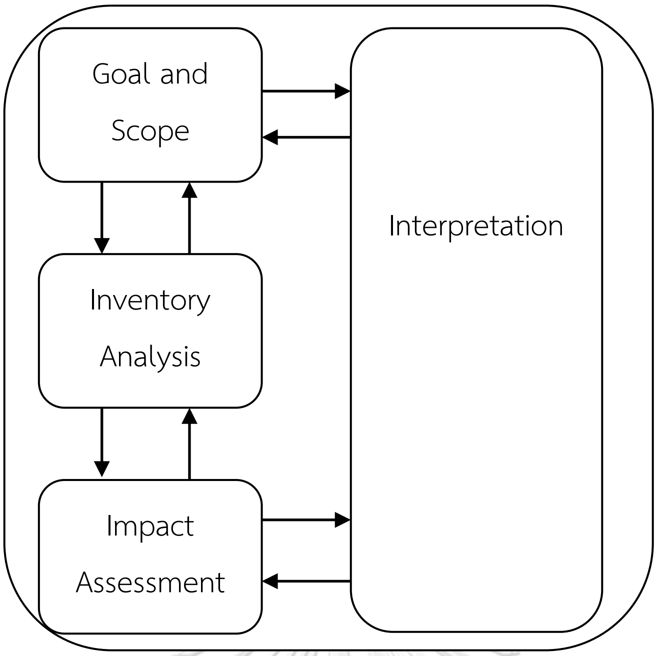


**Figure 2.4** Life Cycle Assessment Framework

**Source:** (Standardization, 1997)

### 2.5.2 Some important terms and methods used in LCA

#### 1) Functional unit

The functional unit is the basis for the calculations in a quantitative LCA. It is a product, a material or a service for which the environmental loading are quantified. In an absolute LCA the whole life cycle of a specific product, material or service is studied, and the different parts of the life cycle are compared with each other. In this case the functional unit should be, e.g. one item of the studied product.

On the other hand, in a comparative LCA different products are compared with each other. In that case it is not always relevant to compare the direct products, but more to compare the function of the products. For example, crushed tomatoes can be bought in either Tetra Brik packages (a composite package based on cardboard covered with aluminium foil and polyethylene foil) with a volume of 0.51, or in tin cans with a volume of 0.41. It is not relevant to compare one piece of Tetra Brik package with one piece of tin can, instead the comparative LCA should be based on, e.g. 21 of each – i.e. four pieces of the Tetra Brik and five pieces of the tin can. The functional unit in this example is 21 of package volume.

The choice of appropriate functional units is of great importance for the LCA. A relevant choice of the functional units is needed for relevant results. For waste management systems it is often preferable to work with several functional units each one representing an essential utility that is produced from waste. For example organic degradable waste can be incinerated, anaerobic digested or composted. When incinerated, the product (in Sweden) will be district heating. When anaerobically digested, the products can be district heating, biogas for vehicle or for electricity depending on how the biogas is used. When aerobically digested or composted we also produce a fertilizer. When assessing management of organic waste several functional units must be used:

- Treatment of a specific amount of waste,
- Production of a specific amount of district heating energy,
- Production of a specific amount of electricity,
- Production of a specific amount of nitrogen (N) and phosphorus (P) fertilizer (eventually also K fertilizer),
- Production of a specific amount of vehicle fuel (e.g. the amount necessary to drive a bus or a car X km).

In all scenarios and cases the same functional units must be used. If the functional unit is not produced from waste, it has to be produced from another source

2) Emission factor

In an LCA the used data is often presented as emission factors and energy factors. Information in databases is often expressed as emission factors. The emission factors gives the emission for a process or sub-process in the life cycle, in relation to an input or output parameter, e.g. per weight of product, per weight of a certain element in the product, or related to the energy content of the product. For example, emission of HCl from waste incineration may be expressed as kg HCl emitted per kg Cl in the input to the incinerator. Energy consumption for transport can be presented as MJ fuel (or liters of diesel oil) per kg of transported product and per km transport distance.

3) System boundaries

The system boundaries define the system that is studied. An LCA is based on the material flows and energy flows oven the system boundaries. It is of absolute necessity to have well-defined system boundaries, in order to obtain unambiguous results. Usually the system boundaries can be:

- Geographical boundaries: e.g. disposal of waste generated within a municipality
- Time boundaries: e.g. the waste generated during 1 year
- Functional boundaries: e.g. wastes that can be used for biological treatment.

4) Allocation

A traditional problem in LCA is how to deal with processes or groups of processes with more than one input and/or output. Some examples are processes or productions with co-products of economic value (multi-output processes), and waste treatment where several different waste components are treated in the same process with common consumption of raw material and common formation of emission (multi-input processes). In LCA allocation can be defined as the act of partitioning in some proportionate shares the responsibility for environmental impacts caused by processes in a life cycle.

## 2.6 Related study

Annachhatre (2012) studied the performance of pilot-scale thermophilic dry anaerobic reactor for biogas production and to analyze the digestate management options. The first experiment was to study the different C/N ratio 27 and C/N ratio 32 of substrates. The results showed that the simulation with C/N ratio 32 had about 30% less ammonia-N in digestate as compared to that with C/N ratio 27. The system performed well at OLR and RT of 6.40 kg VS/$m^3$d and 24 days respectively, however, purpose of treatment also determines the optimum operating conditions. However, purpose of treatment also determines the optimum operating conditions. Digestate from the reactor was characterized and its C/N ratio and GHG emission potential was calculated. It was found that the C/N ratio of digestate was 15-20 for most of the study period, which is safe range for its application to agricultural land without further treatment. The GHG potential calculation shows that storage of the digestate for 2 months decreased its GHG potential by 10%, hence, storage was found to be a source of GHG emission. Moreover, application of digestate directly to land has minimum net GHG emission (i.e. 11 g$CO_2$-eq/kg digestate). Therefore, digestate should be applied to land immediately after digestion to minimize GHG emission from the storage system.

Andersen, Boldrin, Christensen, and Scheutz (2011) studied mass balance and life cycle inventory of six units home composting. The results showed that the loss of carbon (C) during composting was 63-77% in the six composting units. The carbon dioxide ($CO_2$) and methane ($CH_4$) emission made up 51-95% and 0.3-3.9% respectively of the lost C. The total loss of nitrogen (N) during composting was 51-68% and the nitrous oxide ($N_2O$) made up 2.8-6.3% of this loss. The $NH_3$ losses were very uncertain but small. The amount of leachate was 130 L/mg wet waste (ww). The loss of heavy metals via leachate was negligible and the loss of C and N via leachate was very low (0.3-0.6% of total loss of C and 1.3-3.0% of total emitted N).

H. Zhang and Matsuto (2011) study mass balance of composting facility in different type of organic waste. Groups of composting facilities were divided into 6 types of organic waste there are (1)food waste only, (2) food waste 50% and others, (3) livestock manure 60% and others, (4) septic tank sludge 80% and others, (5) food waste livestock manure sewage sludge and (6) tree branches only. The results show that the decomposition rate of food waste were 70%, 30-40% for livestock manure and tree branches has lowest 5-20%. The highest N content occurred in food waste whereas, phosphorous and potassium highest in livestock manure.

Khoo, Lim, and Tan (2010) was to investigate environmental performance of food waste conversion based on LCA approach. The food waste conversion methods include incineration, recycling via AD combined with composting of digestate and aerobic composting plant. The category indicators are global warming potential, acidification, eutrophication, photochemical oxidation and energy use. The result showed that GWP for the proposed aerobic composting is relatively higher than the incinerators.  Composting generated high emissions of ammonia.

Liamsanguan and Gheewala (2008) compared two methods between landfill without energy recovery and incineration with energy recovery that current used for MSW management in Phuket, Thailand by using LCA. The results indicated that energy consumption of the incineration is preferred method over the landfilling. The greenhouse gas emissions of landfilling produces GHG emission 1311 kg $CO_2$ eq./ton MSW treated. For incineration, the GHG contributing 736 kg $CO_2$ eq./ton MSW treated. Incineration performs better than landfilling for both MSW management methods.

Chiemchaisri et al. (2007) studied MSW management and disposal emission inventory in Thailand. The result show that there were 95 landfills sites and 330 open dumps sites the total disposal sites are 425 in Thailand 2004. Methane emission from MSW disposal was carried out by using LandGEM (Landfill Gas Model). The current methane emission from disposal sites are 115.4 Gg/year if the open dump sites upgraded to sanitary landfill methane emission will rise to 118.5 Gg/year; and it will increase to 193.5 Gg/year if existing sanitary landfill upgraded to integrated waste management facilities. Bangkok Metropolitan has the highest methane emission 54.83 Gg/year among all regions in Thailand. Predicted the methane generation in 2020 about 339 Gg/year. This would provide an opportunity to implement Cleaner Development Mechanism (CDM) strategy by utilizing landfill gas for energy use.

Melin et al. (2006) studied status and application of membrane bioreactor (MBR) for wastewater and reuse. The results show that removal efficiency of TSS >99%, COD 89-98%, BOD >97%, $NH_3$-N 80-90%, total N 36-80% and total P 62-97%. MBR for municipal wastewater treatment are advantage compares to conventional AS in terms of effluent quality.

Consonni, Giugliano, and Grosso (2005) examined the mass and energy balance for energy recovery from materials recovery (MR) residues in four alternative strategies. In strategy 1, the MR residue is feed directly to a grate combustor. In strategy 2, the MR residue is first subjected to light mechanical treatment. In strategy 3 and 4, the MR residue is converted into RDF, which is combusted in a fluidized bed combustor. Results show that pre-treating the MR residue and increasing the heating value of the feedstock fed to the WTE plant has effects on the energy efficiency of WTE plant. The largest energy saving are achieved by combusting the MR residue “as is” in large scale plants; with cogeneration, primary energy savings can reach 2.5% of total social energy use.

# CHAPTER 3

# METHODOLOGY

## 3.1 Scope of Study

In order to evaluate zero organic waste system for building application according to the goal and objectives, LCA was selected as support tools to assess the environmental impact. The prototype system of organic waste treatment will be developed by the combination of anaerobic digestion process with oxidation-ditch membrane bioreactor at optimal condition. The LCA quantifies environmental impact following the cradle to grave approach. Whereas financial cost analysis is to quantify costs of investment, system operating and maintenance costs, while net energy balance is the tool that uses on waste management methods. This study was divided into three steps. In the first step was to study the optimal condition for each system, the second step was to operate the developed AD (organic digestion) combined with OD-MBR (wastewater reuse) for zero organic-waste system and finally the LCA to quantify environmental impact in accordance with the cradle to grave approach, the net energy balance analysis is the tool for analysis of energy balance of waste management methods. The conceptual framework and the process flows and parameters in each system are presented in Fig 3.1 and 3.2

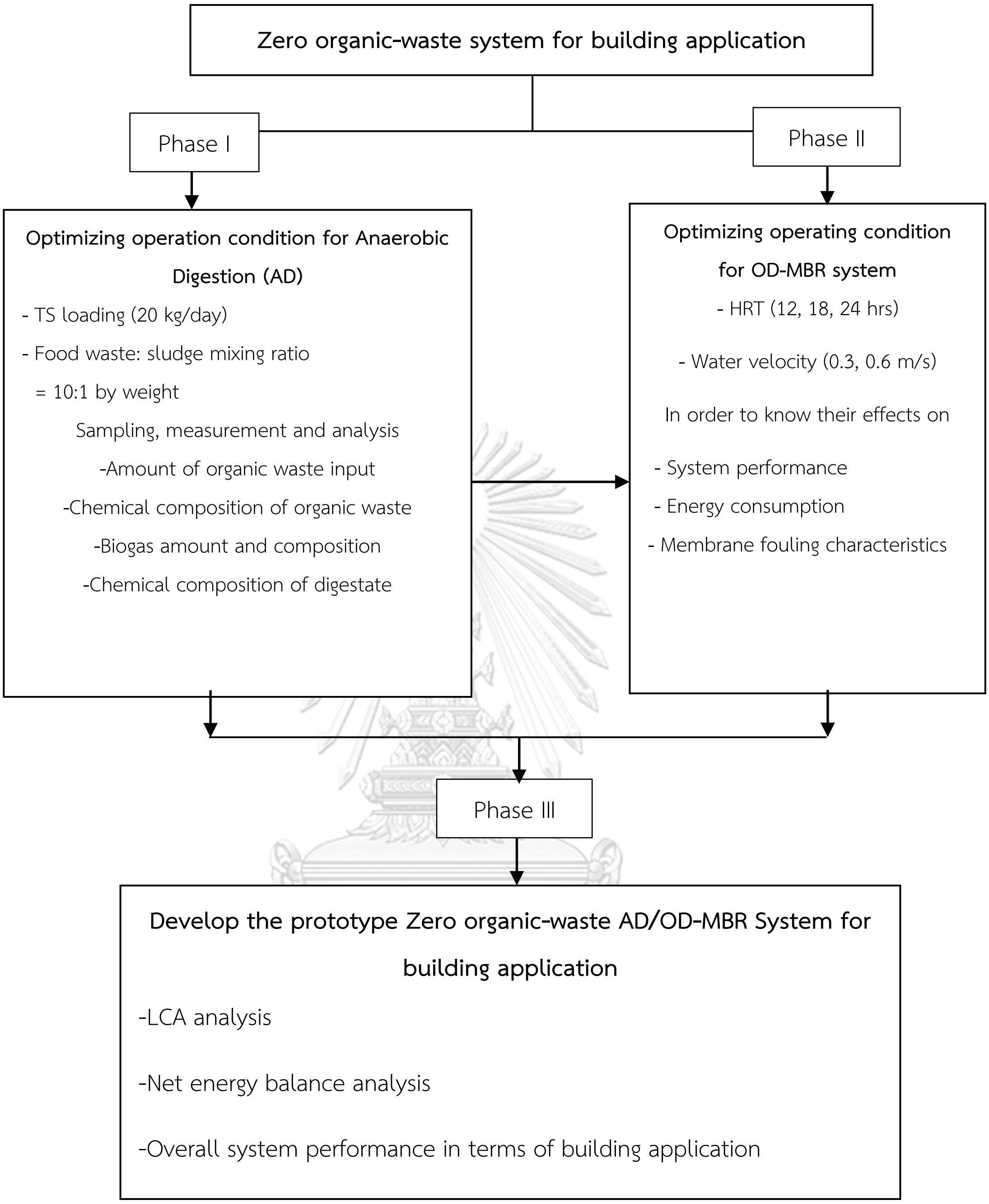


**Figure 3.1** Conceptual framework

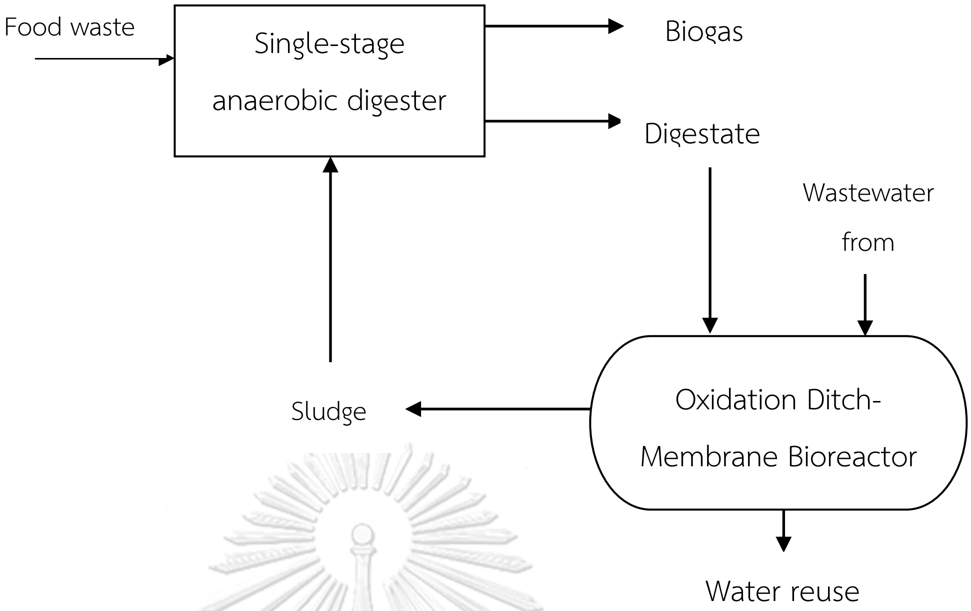


**Figure 3.2** Process flow diagram of the proposed zero organic-waste system

## 3.2 Study Area

The prototype single-stage anaerobic digester of food waste and oxidation ditch-membrane bioreactor (OD-MBR) for wastewater treatment was constructed at Chulachakrabongse Building in Chulalongkorn University campus. A single-stage AD has been receiving organic waste from canteen after manual sorting. An OD-MBR was fed with wastewater from AD process and operated at optimize condition. After that sludge from OD-MBR was return to AD treatment to produce the biogas.

## 3.3 Prototype of Single-stage Anaerobic Digester

The anaerobic digester units in this study are small-scale single-stage anaerobic digestion in Thailand. The anaerobic digester unit at Chulachakrabongse Building in Chulalongkorn University, Bangkok is a single stage anaerobic digester, which made from polyethylene (PE) and Polypropylene (PP). The volume of reactor was 2500 L with a working volume 1975 L. The feeding substrate was prepared by mixing food waste and shredding into small size. Then adding the substrate into the single stage anaerobic digester by the screw conveyor. The biogas generated from anaerobic digestion process was stored in the biogas holding tank and sent to the gas pipeline for using in canteen. The schematic diagram of a prototype single stage anaerobic digester as shown in Fig. 3.3 and 3.4

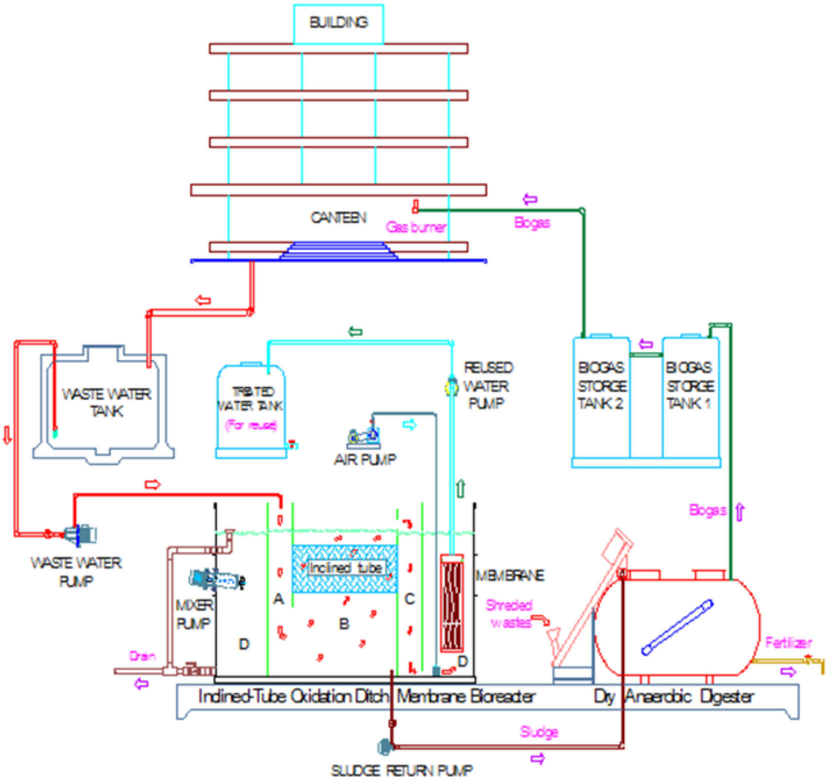


**Figure 3.3** Schematic diagram of a prototype single stage AD combine with OD-MBR

### 3.4 The OD-MBR system

The OD-MBR system has a total tank size of 1.0 x 2.1 x 1.8 m. with a total working volume of 3.15 cubic meters. The height of inclined tubes installed inside the inner compartment was set to be 0.5 m. as pre-treatment system for suspended solid in wastewater. A PVDF hollow fiber microfiltration membrane module having surface area of 6 m2 and pore size of 0.4 µm. is installed inside the aerobic compartment. The MBR unit has a maximum water production capacity of 4 $m^3$/day. With regard to the position of feed inlet, the wastewater is fed at the inclined tube compartment, and then treated water is moved to the outer-loop aerobic MBR compartment

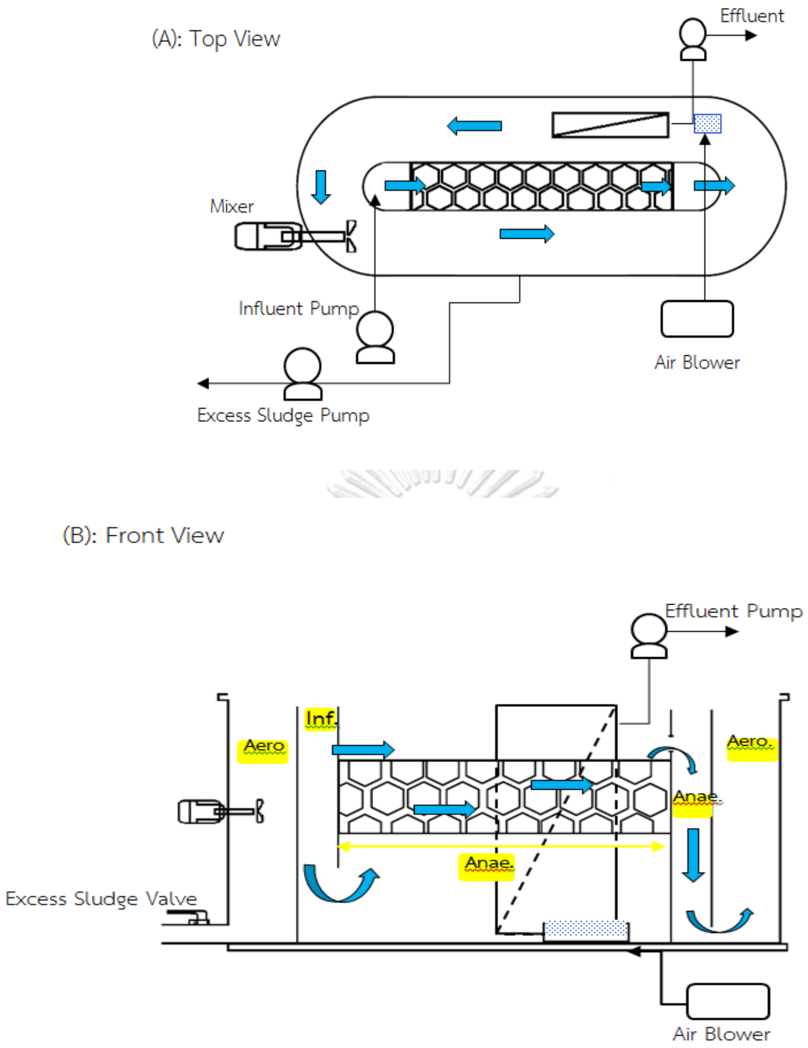


**Figure 3.4** Schematic diagram of oxidation ditch membrane bioreactor

Note: Aero.: Aerobic Zone

Anae.: Anaerobic Zone

Inf.: Influent

eff.: Effluent

⧄ : Microfiltration Membrane (MF)

▨ : Tube Diffuser

## 3.5 Sampling, Measurement and Analysis

### 3.5.1 Quantification of input organic waste and other material

Food waste will be collected from canteen at Chulachakrabongse building, Chulalongkorn University. The food waste will be weighted and then shredded into 5-10 mm by food grinder. Sludge will be collected from the OD MBR system. Total solid loading will be kept at 20 kg/day.

In addition to compositional characterization of the organic wastes, selected samples from studied areas were analyzed the characterization following parameters: pH, total solids (TS), volatile solids (VS), chemical oxygen demand (COD), total Kjeldahl nitrogen (TKN), total phosphorus (TP) and elemental composition (CHN). The analytical method of the samples presented in Table 3.1.

**Table 3.1** summarizes the analytical method for the characterization of the samples.

| Parameter | Analytical method |
|---|---|
| Total solid (TS) | Sample dried at 105±2°C (APHA, 2005) |
| Volatile solid (VS) | Sample ashed at 550±25°C (APHA, 2005) |
| Elemental composition | CHON Analyzer |
| Total phosphorous | Standard method AWWA, 2012 (4500) |
| TKN | Standard method AWWA, 2012 (4500-$N_{org}$B) |
| COD | Standard method AWWA, 2012 (5220C) |

### 3.5.2 Determination of gaseous emission

Gaseous emission from the process is considered in methane, nitrous oxide and carbon dioxide. The amount of biogas was measured by gas meter. The composition of biogas was collected in gas bag and then analyzed for gas composition by using Gas Chromatography (GC). Biogas production was adjusted to standard temperature (0°C) and Pressure (STP) (1 atm). The biogas composition was analyzed once a week.

### 3.5.3 Water quality analysis for OD-MBR system

DO concentration in the reactor is measured using a DO meter (InPro 6820, Mettler –Toledo) and pH is monitored using a pH-electrode (InPro 3030, Mettler-Toledo). Chemical oxygen demand (COD) is determined according to Standard Method 5220. Samples will be filtered using cellulose acetate syringe filters with pore size of 0.45 μm before the measurements of effluent TKN, nitrate and nitrite in the supernatant. Total phosphorous is determined according to Standard Method 4500. These measurements were performed once a week to interpret the process performance. For membrane fouling characteristics, as well as foulant characteristics will be determined by Fluorescent EEM spectra and FTIR analyses. The analytical method of the water quality presented in Table 3.2.

**Table 3.2** Summarizes the analytical method for water from OD-MBR

| Parameter | Analytical method |
|---|---|
| pH | pH-Meter |
| Dissolved Oxygen (DO) | DO-Meter |
| TKN | Standard method AWWA, 2012 (4500-$N_{org}$B) |
| Nitrate | Standard method AWWA, 2012 (4500-$NO_3^-$B) |
| Nitrite | Standard method AWWA, 2012 (4500-NorgB) |
| COD | Standard method AWWA, 2012 (5220C) |
| Total phosphorous | Standard method AWWA, 2012 (4500) |

## 3.6 Experimental Design

### 3.6.1 Experimental conditions for AD system

1) Single-stage AD

The AD was initially loaded with the 20 kg of food wastes, which collected from canteen after manual sorting at Chulachakrabongse building. Then shredding into small size and feed to anaerobic digester. The system was operated in a batch mode, without loading any additional feedstock, for first 14 days and denoted as start-up phase. The AD was operated in a continuous mode by loading with the designed feedstocks amount 20 kg of 1 time per day, specified amount of digestate was removed from the digester. Feeding and digestate withdrawal was done once a day.

2) Food waste and sludge mixing ratio

For the zero organic waste system, sludge was collected form OD-MBR system the volume of sludge was mix with food waste from canteen 10:1 by weight. During this period, the system was continuously monitored for the fluctuations in process parameters such as biogas amount and methane.

3.6.2 Experimental conditions for OD-MBR system

1) HRT

In this experiment, optimization of OD-MBR system by testing the effect of different HRT was studied. The OD-MBR was initially loaded with the 20 L of digestate from AD and wastewater from Chulachakrabongse building. The OD-MBR was operated in a continuous mode by loading with the digestate and wastewater under different HRT (12, 18 and 24 hrs) for determines the optimum condition of HRT.

2) Water velocity

HRT which performed well in previous experiment and was found optimum in terms of water quality. The OD-MBR was operated in a continuous mode by loading with the digestate and wastewater under different water velocity (0.3 and 0.6 m/s) for determines the optimum condition of water velocity.

## 3.7 Life Cycle Assessment (LCA)

For LCA calculation the overall scope of the LCA study is shown. The system boundary implies the margin of inflow and outflow. Brief information on LCI and LCIA are also presented. Methodological choices made in this study are described according to software procedures.

LCA consists of the system boundary and life cycle inventory by using the SimaPro 8 Software.

### 3.7.1 Goal and functional unit

The goal of this part of study is to evaluate zero organic waste management systems from perspective of GHG emissions. The functional unit (FU) is the definition of the functional outputs of the product system. The function for this study is defined as the resource recovery from wastes. The functional unit is defined as the by-products from anaerobic digestion of 1 kg of sludge. For data calculation, the reference flow is defined as the 1 kg of sludge.

### 3.7.2 System boundary

In terms of system boundaries, the food waste generation depicts only waste that is disposed in canteen at Chulachakrabongse building, Chulalongkorn campus and manual sorting by housekeeper. Wastewater comes from Chulachakrabongse Building and sludge is generated from OD-MBR system. The collection and transportation steps are excluded from the system boundary, and the burdens from consumption of water and chemicals as well as processes of construction and demolition of facilities are ignore. Chemical treatment, water consumption and electricity in operation process are collected to estimation life cycle inventory. All energy generated from waste and biogas can be utilized for cooking in canteen replaces commercial LPG gas. Water effluent from system also collected and estimated as life cycle inventory. The system boundary was show in Fig 3.5

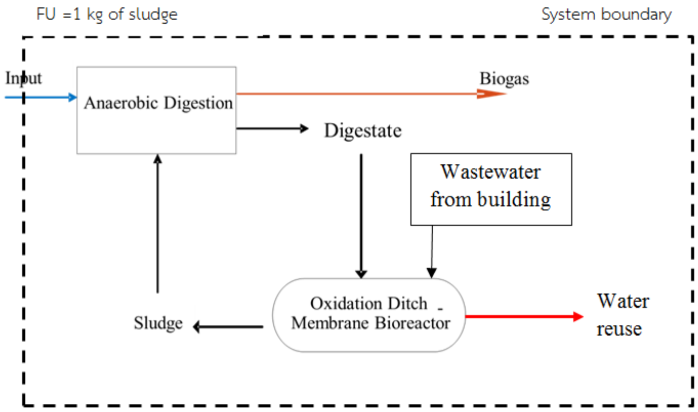


**Figure 3.5** System boundary

### 3.7.3 Inventory Data

The environment and resource aspect from different options of zero organic waste management were analyzed based on the LCA software, SimaPro version 8. The waste flows resulting from material balance analysis is necessary for generating data on emissions from the system examined. The analysis of LCA in this study was performed according to the operation process inventory from current organic waste management (Table 3.3). The operational information was obtained from literature previous study, laboratory analysis and my own calculations.

**Table 3.3** Data input to LCA for the operation phase

| | | Materials | Unit |
|---|---|---|---|
| Input | Material | Food waste<br>Sludge | kg<br>kg |
| | Energy | Electricity (process) | kWh |
| | Water | Wastewater<br>Digestate | kg<br>kg |
| | Chemical | Chemical use in process and back wash from membrane cleaning. | kg |
| Output | Product | Water reuse/Biogas produce | kg |
| | Waste | Wastewater/sludge/digestate | kg |

### 3.7.2 Life Cycle Impact Assessment

The environmental indicator and all predicted environmental impact category considered for this study are classified and characterized into global warming potential (GWP), acidification, eutrophication and energy use. These are chosen on the basis that they are most relevant to the system.

The zero organic waste management was proposed to find the possible organic waste management options. Compared with the baseline study and the zero organic waste system. In the baseline study, current situation will be not change. Organic waste come from Chulachakrabongse building not set as zero organic waste. And the zero organic waste system focused on the digestate management. The food waste come from Chulachakrabongse building and treated by anaerobic digestion and utilization of digestate as a water reuse.

# CHAPTER 4

# RESULTS

This study evaluated the performance, examined the power consumption, as well as assessed the environmental impact of a combined system between an anaerobic digester (AD) and oxidation-ditch membrane bioreactor (OD-MBR) purposely to achieve zero organic waste at Chulachakrabongse Building, Chulalongkorn University. The process involved fermenting food waste collected from the cafeteria using an anaerobic digester tank. The process yielded biogas and liquid digestate. The derived biogas was utilized through cooking at the cafeteria while the liquid digestate was treated at the oxidation-ditch membrane bioreactor where the treated water could be reused via plant watering. On the other hand, the derived sludge left from the OD-MBR treatment system was taken back to the food waste where everything was further fermented together.

## 4.1 Food waste characterization

The physical and chemical of food waste characteristic are mainly significant for anaerobic digestion process because food waste not only contains organic matter but also contain various trace elements (Mir, Hussain, & Verma, 2016). The organic matter in food waste is suitable for anaerobic bacteria growth. During the anaerobic digestion process microorganism can converted into biogas. Food waste samples were collected from canteen at Chulachakrabongse Building in Chulalongkorn University and analyzed their physical and chemical properties by using ASTM standard method. The food waste were analyzed the characterization following parameters: total solids (TS), total volatile solids (TVS), chemical oxygen demand (COD), total Kjeldahl nitrogen (TKN), total phosphorus (TP) and elemental composition (CHN). The results presented in Table 4.1.

**Table 4.1** The initial food waste characterizations

| Components | Unit | Average |
|---|---|---|
| Moisture content | % (d.b.) | 68.28 |
| TS | % (d.b.) | 31.72 |
| TVS | % (d.b.) | 91.63 |
| COD | mg/l (w.b.) | 159,273±20,124 |
| TKN | mg/l (w.b.) | 2,492±34.67 |
| TP | mg/l (w.b.) | 113±8.21 |
| C/N ratio | % (d.b.) | 21.55 |
| Sulfur | % (d.b.) | 0.04 |
| Oxygen | % (d.b.) | 38.63 |

The result showed that the physical and chemical properties of food waste from canteen at Chulachakrabongse Building had contained 68.28% of moisture content, 31.72% of total solid and 91.63% of total volatile solid to total solid (VS/TS). The chemical element component (C/N) was 21.55. This is consistent with research Gidarakos, Havas, and Ntzamilis (2006) found that moisture content is the main component of organic waste was 66.99%, the amount of carbon, hydrogen and nitrogen were 45.56%, 6.24% and 2.29% respectively. Similar to R. Zhang et al. (2007) found that moisture content is the main component of organic waste was 74%, the amount of carbon, and nitrogen was 46.78% and 3.16% respectively. The COD concentration of the food waste about 159,273±20,124 mg/l. The results show that the food wastes have high in moisture content indicated that high biodegradability and organic content more than 90% which were suitable for microbial growth (H. Zhang & Matsuto, 2011).

The ratio of carbon to nitrogen (C/N) is a important role in anaerobic digestion process. The carbon conducts as energy source and nitrogen helps to enhance the microbial growth. These two nutrients often act as limiting factor. The optimum ratio is between 20 and 30 (Lissens, Vandevivere, De Baere, Biey, & Verstraete, 2001). The high C/N ratio means nitrogen consumption is rapidly so biogas production is low. On the other hand, low C/N ratio causes ammonia accumulation. pH value exceeds 8.5 that is toxic to methanogenesis. Optimum C/N ratio can be achieved by mixing substrate of low and high C/N ratio (Khalid, Arshad, Anjum, Mahmood, & Dawson, 2011). It has been found that conversion of carbon to nitrogen in digestion process is 30–35 times faster, so ratio of C/N should be 30:1 in raw substrate. Nitrogen is considered as limiting factor and nitrogen sources like urea, bio-solids, and manure could be used as supplements' (COMPOSTING & SERIES). C/N ratio between 20 and 30 provide sufficient nitrogen for anaerobic process (Weiland, 2006). C/N between 22 and 25 is best for anaerobic digestion of fruit and vegetable wastes (Ghosh & Pohland, 1974).

### 4.2 Anaerobic digestion and combined system experiment

The initial substrate used in anaerobic digestion and combined experiments are shown in table 4.2, which the data calculated as the average of triplicates.

**Table 4.2** The initial substrate used in anaerobic digestion and combined experiments

| Conditions | pH | VS (mg/kg) | SS (mg/kg) |
|---|---|---|---|
| Single-stage | 7.29 ±0.10 | 254,335±14,381.11 | 22,116±932 |
| SC1 | 7.37±0.13 | 253,661±13,587.86 | 25,131±1,141 |
| SC2 | 7.56±0.15 | 255,407±9,010.26 | 25,868±439 |
| SC3 | 7.45±0.05 | 259,272±8,621.84 | 26,831±619 |
| SC4 | 7.20±0.11 | 270,863±5,091.72 | 21,439±1,181 |
| SC5 | 7.15±0.10 | 268,909±6,812.73 | 24,485±573 |
| SC6 | 7.10±0.10 | 275,454±7,348.09 | 23,630±538 |

Note: SC1 FW+sludge from OD-MBR under condition HRT 24 hr and water velocity = 0.3 m/s
SC2 FW+sludge from OD-MBR under condition HRT 24 hr and water velocity = 0.6 m/s
SC3 FW+sludge from OD-MBR under condition HRT 18 hr and water velocity = 0.3 m/s
SC4 FW+sludge from OD-MBR under condition HRT 18 hr and water velocity = 0.6 m/s
SC5 FW+sludge from OD-MBR under condition HRT 12 hr and water velocity = 0.3 m/s
SC6 FW+sludge from OD-MBR under condition HRT 12 hr and water velocity = 0.6 m/s

### 4.2.1 Biogas production

The daily biogas production during the digestion process of food waste (single-stage) and food waste (FW) mixed with sludge from OD-MBR (SL) with ratio 10:1 (combined system SC1-SC6) is shown in Table 4.3 and Fig 4.1. Biogas production was calculated by conversion of the biogas volume to Normal conditions (at $0^{\circ}C$ 1 atm). Variation of temperature and pressure at the time of measurement can contribute to errors in gas volume calculations. Therefore, the record of pressure and temperature is important to corrections.

The daily biogas production in combined system SC1 has higher biogas production than that of the single stage and combined system SC2-SC6 at maximum biogas of 6.3076 $Nm^3$. The average biogas production was 1.1137 $Nm^3$ in the single-stage system and 1.2471 $Nm^3$ in SC1 combined system.

**Table 4.3** Biogas production rate in single-stage system and combined system

| Biogas production (Nm$^3$) | Single-stage | Combined system | | | | | |
|---|---|---|---|---|---|---|---|
| | | SC1 | SC2 | SC3 | SC4 | SC5 | SC6 |
| Biogas production (Average) | 31.1842<br>(1.1137) | 34.9185<br>(1.2471) | 30.2898<br>(1.0818) | 26.1624<br>(0.9344) | 27.7597<br>(0.9914) | 24.4165<br>(0.8720) | 24.1363<br>(0.8620) |

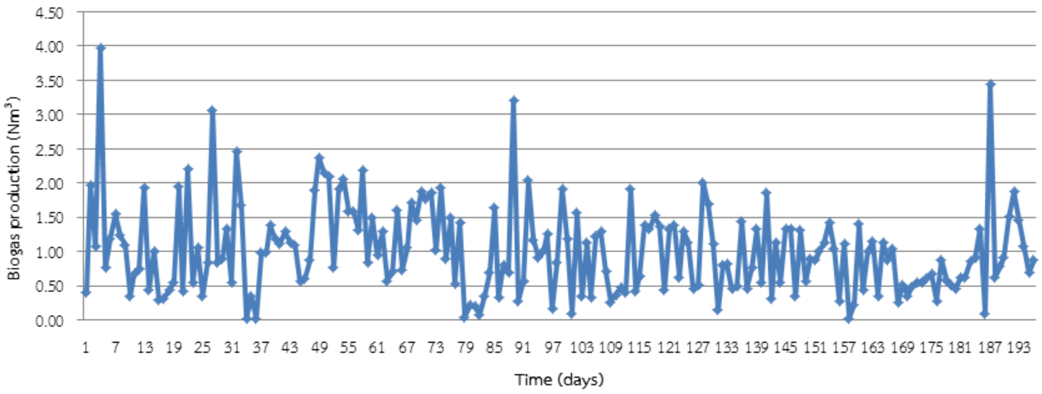


**Figure 4.1** Biogas production rate of single-stage and combined system

4.2.1.1 Accumulative biogas production

The accumulation of biogas production was plot in straight trend line with equation y = 1.0055x + 7.9879 as Fig 4.2

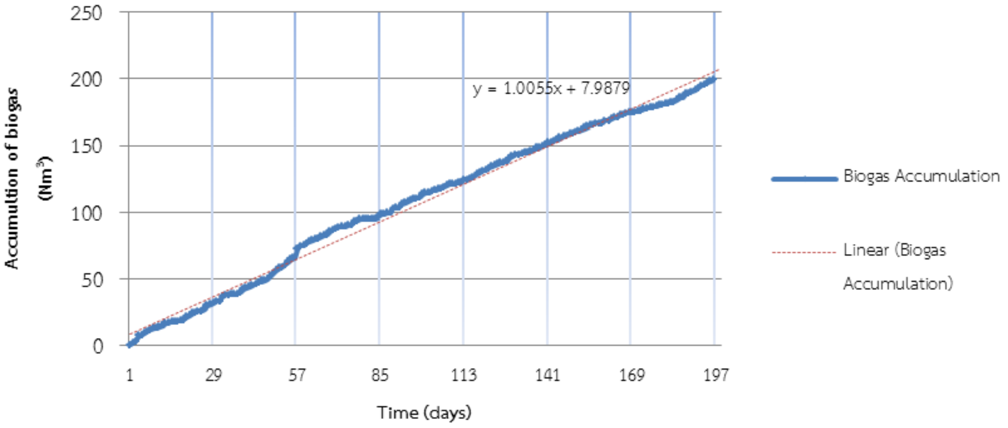


**Figure 4.2** Accumulation of biogas production in single-stage anaerobic digestion and combined with oxidation ditch membrane bioreactor

#### 4.2.1.2 Comparison of biogas production in different conditions

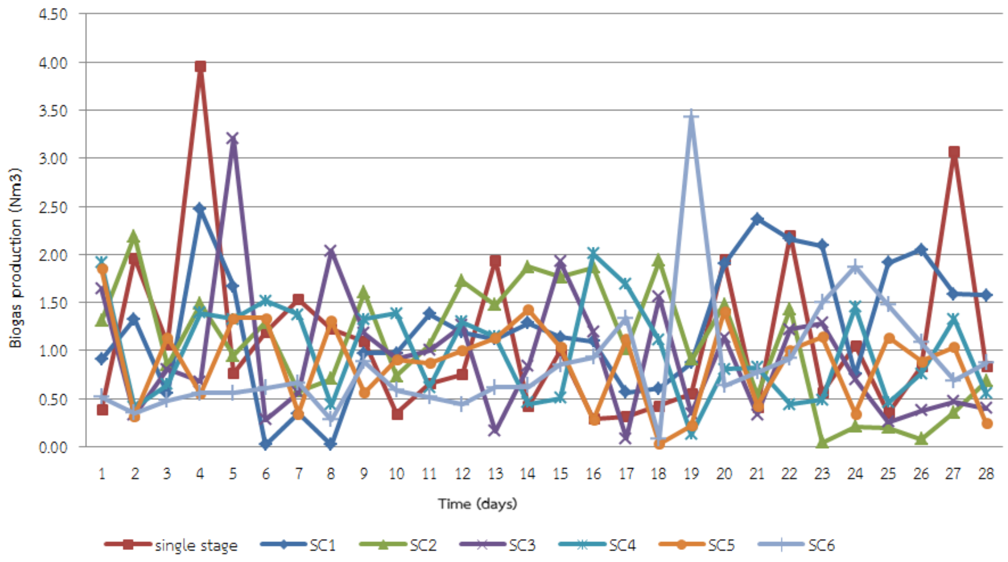


**Figure 4.3** Biogas production in single-stage system and combined system with different conditions

Comparison of biogas production is done as in Figure 4.3 by the variation of single-stage and combined system of food waste and sludge from OD-MBR wastewater treatment plant. The result was found that the combined system SC1 has the highest average daily biogas production in stationary phase was 1.2471 $Nm^3$. In single-stage, the average daily biogas production in stationary phase was 1.1137 $Nm^3$. The average biogas production was decreased in SC2-SC6 approximately about 1.0818 $Nm^3$ 0.9344 $Nm^3$ 0.9914 $Nm^3$ 0.8720 $Nm^3$ and 0.8620 $Nm^3$, respectively. The result shows that combined system of food waste and sludge from OD-MBR which equal to C/N ratio 21.55 was the optimal condition for highest biogas production in this experiment.

#### 4.2.1.3 Percentage of methane composition

The methane content was found to be at 53.30-65.98%. The highest average methane show in single-stage was about 65.98% and the lowest was about 53.30% in combined system running with HRT 12 hr water velocity 0.3 m/s (SC5) as shown in Table 4.4 and Fig 4.4.

**Table 4.4** Percent methane composition

| Conditions | Percent methane |
|---|---|
| Single-stage | 65.98±1.41 |
| Combined SC1 | 65.17±0.91 |
| Combined SC2 | 61.35±1.11 |
| Combined SC3 | 62.36±0.49 |
| Combined SC4 | 59.10±2.06 |
| Combined SC5 | 53.30±2.40 |
| Combined SC6 | 53.52±2.23 |

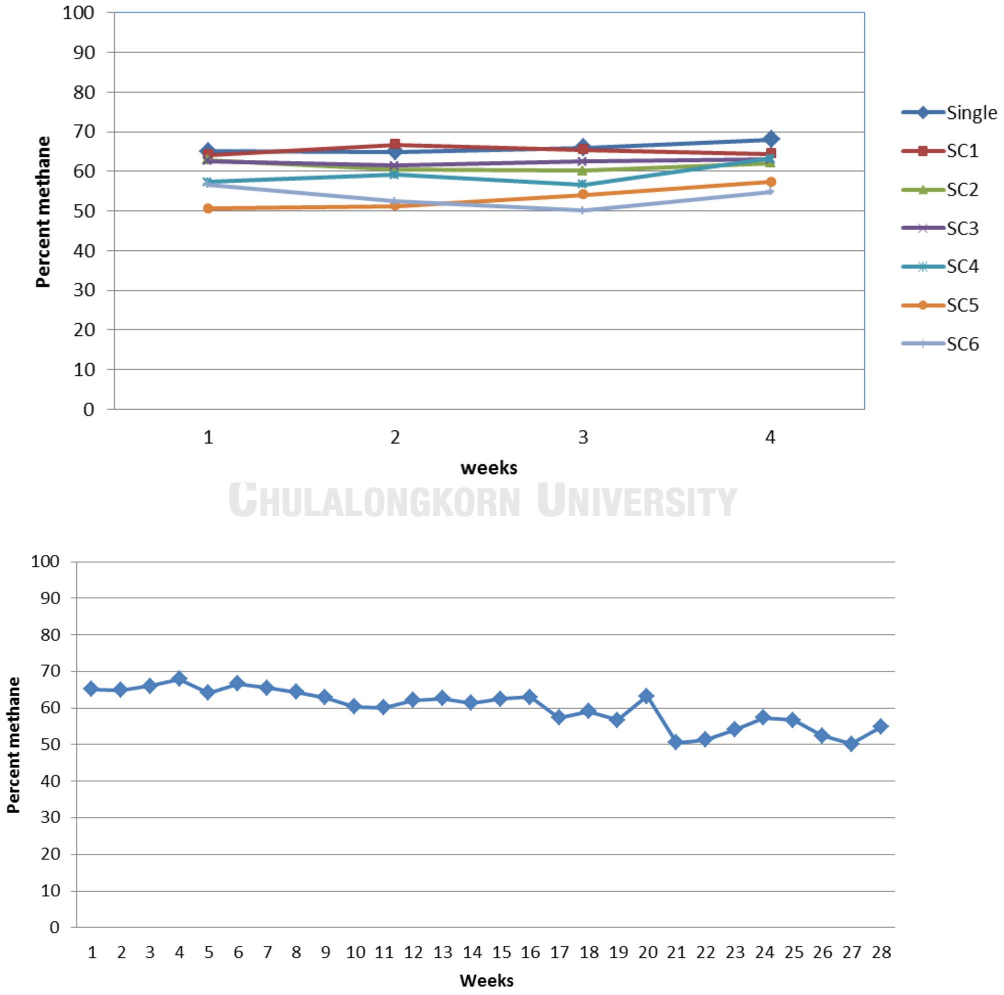


**Figure 4.4** Percentage of methane under different condition

Considering Figure 4.4, it was clear that when solely running the anaerobic digester system, proportion of methane product appeared to be close to that of the combined system which already mixed the sludge from the OD-MBR system at 10:1, food waste per sludge, ratio. Such production of methane content was approximately 65%. On the other hand, running the combined system under different condition yielded lower percentage of methane. This was due to the daily fluctuation in sludge proportion compared to the amount of food waste entering the system and this yielded varied biogas production and methane content in the combined system. Nonetheless, co-digestion the sludge with food waste helped reduce the excess sludge which could obstruct or prevent the system of wastewater treatment from continuing to run. In addition, it could also reduce the maintenance frequency of the such system. According the a study of (Ratanatamskul, Wattanayommanaporn, & Yamamoto, 2015), it was found that a 7:1 ratio of co-digestion between food waste and sewage sludge could produce higher amount of biogas and methane when compared to the 1:1, food waste per sludge, ratio. This implied that the more food waste proportion in fermenting of food waste with sludge, the greater the amount of methane as food waste contains high C/N ratio (>20) when compared to sewage sludge which generally has low C/N ratio.

#### 4.2.1.4 Methane yield

From the experiment showed the final results introduce different patterns in these wastes related with the methane production. The single-stage showed the waste biodegradation 85% VS removal with methane production 31.18 $Nm^3$ at the end of 28 day. This proposes the highest specific methane yield of 1.32 $m^3CH_4$/kg VS removed (Fig.4.5 and Table4.5). Consider with R. Zhang et al. (2007) studied the methane yield after 10 and 28 days of digestion was 348 and 435 mL/g VS, respectively. The average methane content of biogas was 73%. The average VS destruction was 81% at the end of the 28-day digestion test. Similar with Li, Chen, and Li (2009) showed the methane yield of kitchen waste about 0.313 $m^3$/kg VS. The results of this study indicate that the food waste is a highly desirable substrate for anaerobic digesters with regards to its high biodegradability and methane yield.

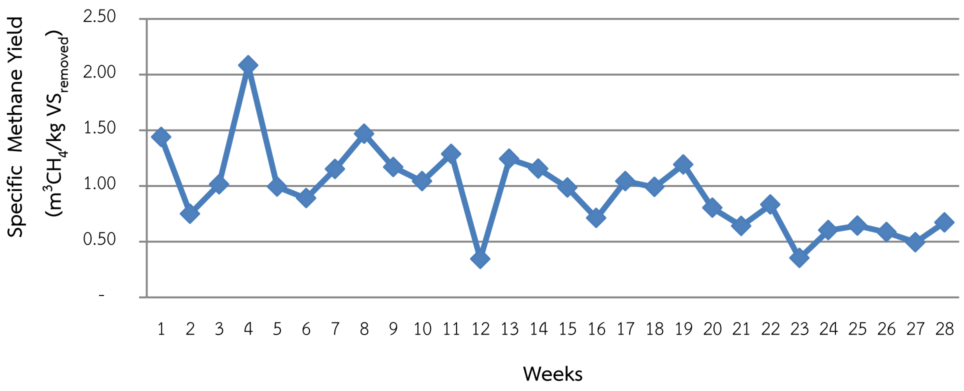


**Figure 4.5** Methane yield in different condition

**Table 4.5** The specific methane yield in each condition

| Conditions | Specific Methane production yield ($m^3$ $CH_4$/kg VS removed) |
|---|---|
| Single-stage | 1.32 |
| Combined SC1 | 1.12 |
| Combined SC2 | 0.96 |
| Combined SC3 | 1.02 |
| Combined SC4 | 1.01 |
| Combined SC5 | 0.61 |
| Combined SC6 | 0.60 |

The biogas yield is affected by many factors including type and composition of substrate, microbial composition, temperature, moisture and digester design (Khalid et al., 2011). Furthermore, the rate of biogas generation also depend on the carbon content of the inoculum and substrate, which are not always degraded or convert to biogas through anaerobic digestion (Imu & Samuel, 2014). Nevertheless, a biogas production was decreased in the case of fruit and vegetable waste because of these waste can cause an acidification in the reactor (Khalid et al., 2011).

### 4.2.2 Composition of liquid digestate from single-stage AD and combined system

#### 4.2.2.1 Composition of liquid digestate from single-stage AD

The study of composition of the liquid digestate from single-stage AD shown in Table 4.6. It has been found that the liquid digestate resulting from fermentation of food waste have contains pH about 7.63±0.03. Moreover, they are rich in COD (29,160.25±1,368.75 mg/l), TN (443.59±42.98 mg/l), Nitrate (54.82±2.80 mg/l), and TP (112.79 mg/l±2.12). According to Zeshan (2012) reported liquid digestate have rich in nutrients such as N > 6% and $NH_4$-N > 2%.

#### 4.2.2.2 Composition of liquid digestate from combined system

The key missions of the single-stage AD combined with OD-MBR system in an anaerobic digestion process for food waste were not only to produce utilizable biogas, but also the liquid digestate which could, in general, be used as soil conditioner. However, this study, further treated using an OD-MBR where the effluent water could be reused for plant watering. This was purposely to achieve zero organic waste.

According to Table 4.6, a composition study of liquid sludge derived from the combined system, the result revealed the following data: The pH value was at 7.59±0.02, COD was 32,739.17±2,578.32 mg/l, TN was 581.95±27.47, Nitrate was 78.69±7.05 mg/l, Nitrite was 47.67±11.93, and TP was 87.44±3.59 mg/l. It was indicative that COD, TN, Nitrate, and Nitrite values of liquid digestate derived from the combined system were higher than that of solely from the anaerobic digester system. This was due to the fact that the combined system co-digestion both the food waste and sludge from the oxidation-ditch membrane bioreactor system (OD-MBR) at a ratio of 10:1. As the sludge from the OD-MBR treatment system contained high concentration of organic substance, when it was filled into to the combined system, the organic concentration increased.

**Table 4.6** Composition of liquid digestate

| Parameters | Single-stage | Combined system |
|---|---|---|
| pH | 7.63±0.03 | 7.59±0.02 |
| COD | 29,160.25±1,368.75 | 32,739.17±2,578.32 |
| Total N | 443.59±42.98 | 581.95±27.47 |
| Nitrate | 54.82±2.80 | 78.69±7.05 |
| Nitrite | ND | 47.67±11.93 |
| Total P | 112.79±2.12 | 87.44±3.59 |

### 4.3 Oxidation ditch membrane bioreactor and combined system experiment

Since the study on OD-MBR wastewater treatment performance where raw wastewater from toilets in Chulachakrabongse Building, this section of the study will elaborate further the results of water quality through the OD-MBR system. The combined system received both the raw wastewater from toilets of Chulachakrabongse Building and liquid digestate was obtained from a single-stage AD which was daily fed with 20 liters of liquid digestate.

The experiments were set with different hydraulic retention time (HRT) and water velocity as described in Table 4.7

**Table 4.7** The operation conditions use in this study

| System | Experiment | Conditions | |
|---|---|---|---|
| | | HRT | Water velocity |
| OD-MBR | Raw wastewater *(RW)* without liquid digestate | 24 hours | 0.3 m/s |
| Combined scenario1 *(SC1)* | RW+liquid digestate | 24 hours | 0.3 m/s |
| Combined scenario2 *(SC2)* | RW+liquid digestate | 24 hours | 0.6 m/s |
| Combined scenario3 *(SC3)* | RW+liquid digestate | 18 hours | 0.3 m/s |
| Combined scenario4 *(SC4)* | RW+liquid digestate | 18 hours | 0.6 m/s |
| Combined scenario5 *(SC5)* | RW+liquid digestate | 12 hours | 0.3 m/s |
| Combined scenario6 *(SC6)* | RW+liquid digestate | 12 hours | 0.6 m/s |

### 4.3.1 Performance of OD-MBR and combined system

#### 4.3.1.1 Water quality and efficiency of OD-MBR system

Oxidation-ditch membrane bioreactor was divided into two compartments, the inner loop for anoxic/anaerobic treatment. Later, the wastewater ran through the outer loop for aeration and membrane microfiltration. The efficiency of OD-MBR system in term of percent removal COD, Total nitrogen and total phosphorous as shown in Table 4.8.

**Table 4.8** The efficiency of OD-MBR system

| Parameters | Influent | Effluent | % removal |
|---|---|---|---|
| DO (mg/l) | 0.4±0.1 | 4.00±0.2 | - |
| COD (mg/l) | 164.69±23.67 | 23.41±2.18 | 85.78 |
| TKN (mg/l) | 45.72±5.63 | 16.95±1.17 | 62.92 |
| Nitrate (mg/l) | 0.03±0 | 0.11±0.01 | - |
| Nitrite (mg/l) | 0.00 | 0.17±0.02 | - |
| Total P (mg/l) | 9.00±1.03 | 5±0.41 | 44.44 |

According to Table 4.7, the OD-MBR system which took in wastewater from toilets in Chulachakrabongse Building contained the wastewater that entered the system with COD, total nitrogen, nitrate, nitrate, total Kjeldahl nitrogen, and total phosphorus values of 164.69 45.75 0.03 45.72 and 9 mg/l, respectively. Through OD-MBR system, COD removal efficiency was as high as 85.78% while total nitrogen, TKN and total phosphorous were 62.15, 62.92 and 44.44%, respectively. Due to the fact that the membrane porous being small, removal of organic matter in wastewater became efficient. In terms of nitrate and nitrite, the amount that entered the system was relatively minimal. Nevertheless, the system outflow water contained a higher amount. This could be due to a nitrification effect caused by microorganism which was consistent with a study by Tiranuntakul, Jegatheesan, Schneider, and Fracchia (2005) which examined the performance of oxidation ditch (OD) retrofitted with a membrane bioreactor (MBR) used to treat residential wastewater. The study discovered that it was able to eliminate ammonia at the rate of 100%. In terms of COD and BOD, the removal efficiency were 91.6% and 97.0%, respectively. However, efficiency of nitrate and phosphate had not yet been realized.

4.3.1.2 Water quality and efficiency of combined system

The efficiency of the combined system which received wastewater from toilets and liquid digestate 20 liters per day from AD. This was conducted to compare the performance of the combined system at 24, 18 and 12-hr hydraulic retention times and at water velocity 0.3 and 0.6 m/s, respectively. The performance was as follows:

4.3.1.2.1 Removal of organic substance in a form of COD

Considering at organic substance in a form of Chemical Oxygen Demand (COD) as one of the parameters of wastewater treatment system, it was found that the variation influent COD of SC1-SC6 were between 2,738.50- 3,975.08 mg/l and the average concentration throughout the experiment was 3,142.83 mg/l. The COD concentrations in the effluent were 171.17±18.27 299.18±55.09 277.61±45.79 332.95±36.97 360.42±24.28 and 428.75±28.97 mg/l with the experimental conditions SC1-SC6 after 30 days of system accustom. This was clear that COD concentration was relatively high and suitable with an OD-MBR system which could accommodate higher load as the raw wastewater and liquid digestate which use in this experiment. The COD removal efficiencies were 93.77 92.47 91.85 89.07 86.84 and 85.44%, respectively whereas the highest COD removal efficiency at HRT 24-hour and water velocity at 0.3 m/s (SC1) as shown in Figure 4.6. Therefore, adding liquid digestate from the AD could enhance the efficiency of organic substance in a form of COD removal. Because liquid digestate was rich in carbon and nitrogen, which an essential food and energy source that promoted a healthy growth to microorganism. As a result, higher treatment efficiency was achieved. Whereas the running with HRT at 18 and 12-hr, the efficiency of COD removal was declined. In terms of water velocity, it is recommended to be less than 0.6 m/s for optimal filtration performance. (Bérubé & Lei, 2004)

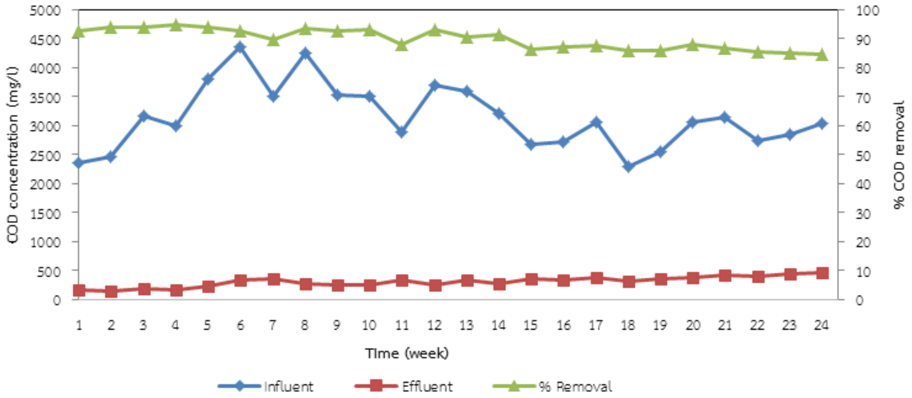


**Figure 4.6** Efficiency of COD removal by the combined system under different condition

4.3.1.2.2 Nitrogen removal

Nitrogen contamination in wastewater is correlated with the occurrence of eutrophication which is a major cause of reduction of dissolved oxygen in rivers and canals. This occurs due to rapid multiplication of microorganisms, seaweed and aquatic plants. Nitrogen removal relies on the differentiation principle of water's dissolved oxygen and the type of bacteria where both factors can influence the reactions in the wastewater treatment system including nitrification and denitrification (Trivedi, 2009). The study on nitrogen removal performance analyzed water quality factors which included TKN-N, nitrite ($NO_2$-N), and nitrate ($NO_3$-N). According to Figure 4.7 exhibiting TKN-N nitrogen removal performance, the result indicated that the inflow wastewater entering the system contained high nitrogen contamination rate. Through the test period, TKN ranged 313.14-402.75 mg/l with an average of 354.07±16.50 mg/l. Nitrogen removal performance of the first test yielded removal efficiency of 85.57% which was the highest efficiency rating when compared to the 2nd-6th experiments. This was because the first test employed 24-hour hydraulic retention time at 0.3 m/s water velocity which was a suitable condition for TKN treatment of OD-MBR. Nitrite analysis results in the treated water were found to be extremely low during all experiments whereas experiment 4-6 were non detected as shown in Fig. 4.8. In terms of nitrate results in the treated water were also low at

0.10±0.01, 0.12±0.05, 0.02±0.02, 0.10±0.03, 0.11±0.05, and 0.14±0.03 mg/l respectively in experiment 1-6. This explains the occurrence of nitrification and denitrification reactions which were the nitrogen removal process of the membrane bioreactor system where the process began with having ammonia oxidized into nitrite or nitrate which the amount of nitrite or nitrate in the water that exited the system was averagely less than 1 mg/l. It was possible that nitrification rate diminished since under such aeration condition, microorganisms consumed oxygen to oxidize organic substance, nitrogen and ammonia. Once system's dissolved oxygen reduced, the nitrification rate also reduced (Liu & Wang, 2015). As a result, some of the ammonia contaminated in wastewater was not oxidized and converted into nitrite or nitrate.

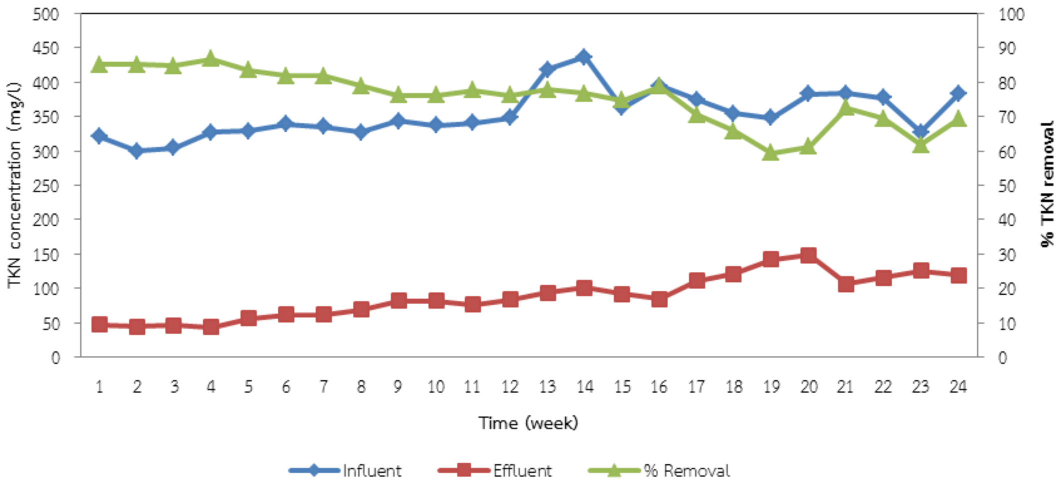


**Figure 4.7** Efficiency of TKN removal by the combined system under different condition

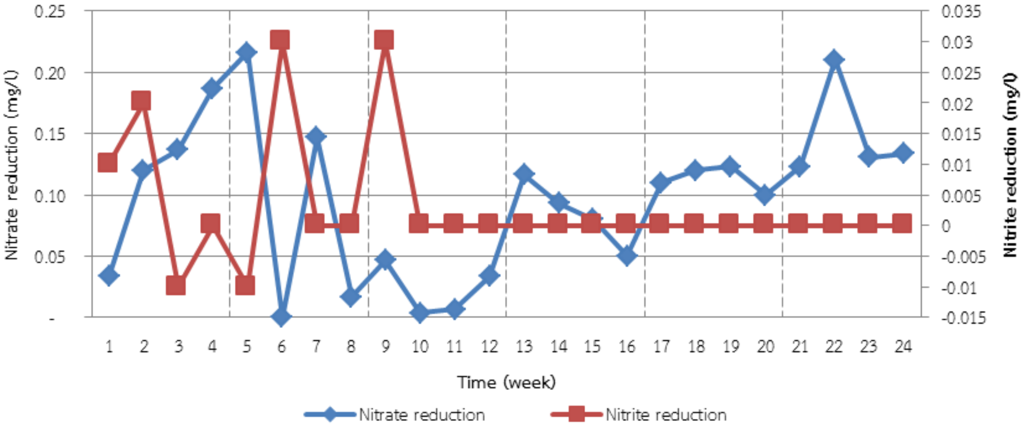


**Figure 4.8** Potential for stable nitrite and nitrate by the combined system under different condition

4.3.1.2.2 Phosphorous removal

During the whole operation period for the combined system, changes in concentration of total phosphorous in the feed and effluent are shown in Fig 4.9. Total phosphorous concentration in the feed raw wastewater and liquid digestate could be found in range of 8.14-21.95 mg/l. The amount of phosphorous removal achieved with the OD-MBR system. The phosphorous concentration in effluent water from the OD-MBR system were 8.31±1.93 8.88±1.84 5.74±0.93 5.18±0.67 5.21±0.59 and 13.05±1.56 mg/l with the experimental condition SC1-SC6, respectively. Phosphorous removal efficiencies were 47.93, 46.88, 51.17, 44.00, 47.31 and 35.63%. The main phosphorous removing process was due to the process of combined system that the liquid digestate could enhance the phosphorous concentration.

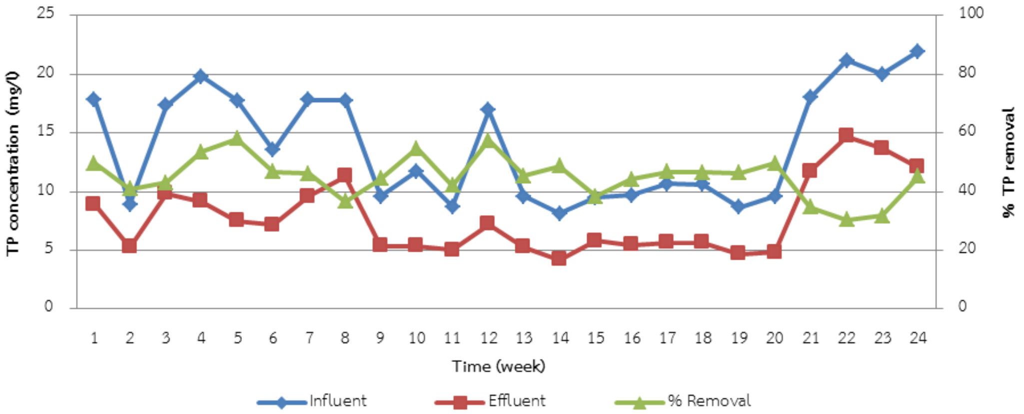


**Figure 4.9** Efficiency of TP removal by the combined system under different condition

## 4.4 Overall performance of combined system

The study on the efficiency of anaerobic digester combined with OD-MBR aimed at zero organic waste in the building by applying anaerobic digester method with food scraps and using liquid digestate obtained from wastewater treatment from the toilet with OD-MBR system. Water from the treatment would be used for watering. Study results of wastewater concentration influent and effluent of the system and the efficiency of treatment at the different condition were shown in Table 4.9.

When evaluating the efficiency of wastewater treatment from the building and the sludge at each parameter at the different system condition, and analyzed the difference with statistical method, it could be concluded as follows.

The combined treatment system had higher efficiency in organic treatment in a form of TKN, Nitrate-Nitrite, and Phosphorus than the control system without liquid digestate (receiving wastewater from the building only) with statistical significance. Therefore, adding liquid digestate to wastewater from the building maximized the organic matter in the system which enhanced the function of microorganism that would result in the higher efficiency of treatment. Although food scrap had the potential organic matter for producing high volume methane, the solely decomposition of food scraps in the fermentation tank caused the imbalanced nutrient; there was insufficient trace elements such as Zn, Fe, Mo, and etc. whereas there were exceeding macronutrients such as Na, and K (C. Zhang, Su, Baeyens, & Tan, 2014). This was in accordance with Zhang's research stating that the combined fermentation of food scrap and other organic matters such as sewage sludge, waste water, animal droppings, and plant residues, would maximize the output of biogas and methane. The study of Zhang (2013) indicated that to ferment food scraps with animal droppings would result in the higher methane in semi-continuous fermentation. Besides, it would increase organic loading rates. In addition, Kim, Nam, and Shin (2011) illustrated that combined fermentation of sewage sludge and food scraped containing organic loading rates would enhance the efficiency of VS disposal (76.5-44.2%) as a result of higher efficiency of changing organic matter to methane gas process, OLR at 6.1 gVS/L/d.

Microbial concentration in oxygenation system is the factor indicating growth and fission rate of microorganism in the system which signifies the efficiency of organic carbon, Nitrogen, and Phosphorus treatment, which microorganism use in cells production and as energy source. The experiment revealed that the operation of OD-MBR had low average of MLSS, 894.65±25.41 mg/l. Further, MLSS of Combined system SC1-6 experiment had increasing change as liquid digestate was added from the anaerobic digestion tank to OD-MBR. The average of experiment 1-6 (SC1-SC6) was 1,011.725±65.03 1,062.65±114.50, 942.98 ±79.87 mg/l, 1,072.23 ±141.79, 908.75±55.06, and 1,064.03±224.91 mg/l respectively. In regard to the design of oxidation ditch wastewater management, the appropriate MLSS concentration for contaminant treatment of wastewater management was 1,500-5,000 mg/l (Shammas & Wang, 2009). AD and OD-MBR system required that the exceed sludge should be removed every day to control the quantity of sludge in oxygenation of OD-MBR system. Consequently, the concentration of MLSS was lower than the standard of oxidation ditch.

When comparing the efficiency of organic matter treatment in a form of COD TKN at the six different system conditions, it was found that the combined system with HRT 24 hr. water velocity 0.3 m/s had the highest treatment efficiency. It showed that HRT decreased while water velocity increased. Consequently, waste water treatment efficiency decreased, except Phosphorus that had the highest treatment efficiency with HRT 18 hr. water velocity 0.3 m/s.

**Table 4.9** Water quality of combined system in different condition

| Parameters | Efficiency of the combined system | | | | | |
|---|---|---|---|---|---|---|
| | SC1 | SC2 | SC3 | SC4 | SC5 | SC6 |
| COD (mg/l) | $93.77^{a}$ | $92.47^{ab}$ | $91.85^{b}$ | $89.07^{c}$ | $86.84^{d}$ | $85.44^{d}$ |
| TKN (mg/l) | $85.57^{a}$ | $81.47^{b}$ | $76.54^{c}$ | $77.06^{c}$ | $64.31^{d}$ | $68.39^{e}$ |
| Nitrate (mg/l) | 54.17 | 40.82 | 49.09 | 47.22 | 51.32 | 52.34 |
| Nitrite (mg/l) | 50.00 | 25.00 | ND | ND | ND | ND |
| TotalP (mg/l) | $47.93^{a}$ | $46.88^{a}$ | $51.17^{a}$ | $44^{a}$ | $47.31^{a}$ | $35.63^{b}$ |

The different superscript letters within column are significantly different (*p*<0.05) according to Duncan’s multiple range test.

The overall performance in OD-MBR and combined system suggested that the combined system has superior effectiveness to treat organic substances in forms of COD, TKN, nitrate, and total phosphorus when compared to the OD-MBR system which solely took wastewater from toilets in Chulachakrabongse Building. In addition, the use of the combined system by adding liquid digestate, the leftover waste from the single-stage AD, could be treated via the OD-MBR system which yielded effluents suitable for water reuse and recycling. Typical processes were modified, combined, and innovated to meet the requirements of the diverse influent characteristics and lower energy consumptions to achieve zero organic waste at Chulachakrabongse Building.

### 4.4.1 COD Balance

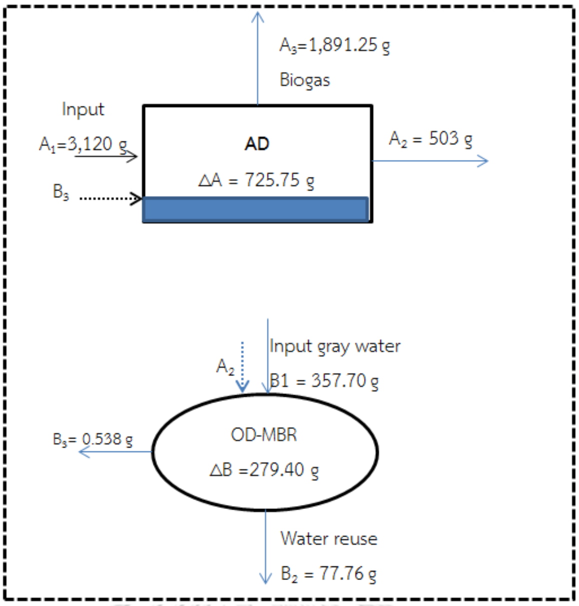


**Figure 4.10** COD balance in combined system (unit in g/d)

System mass balance was performed in terms of the COD balance in grams per day during 28 days of observation under steady-state conditions. The COD balance for the system can be represented with the following equation:

$$A_1 + B_3 = A_2 + A_3 + \Delta A \quad (1)$$

$$B_1 + A_2 = B_2 + B_3 + \Delta B \quad (2)$$

where

$A_1$ represents the influent COD loading in the AD reactor,

$A_2$ represents COD output from the AD reactor

$A_3$ represents COD as biogas

$\Delta A$ represents the accumulate COD in AD reactor

$B_1$ represents the COD loading from gray water to OD-MBR

$B_2$ represents the COD output for water reuse

$B_3$ represents COD return to AD reactor

$\Delta B$ represents the accumulate COD in OD-MBR reactor

According to the calculated mass balance in term of COD, a mass flow diagram was prepared in Fig.4.10. In combined system show the zero organic waste prototype, the incoming COD to AD digester from food waste was 3,120 g/d output COD were 503 g/d and 1,891.25 g/d accumulate COD in AD was 725.75 g/d. In the OD-MBR gray water input was 357.70 g/d and of accumulate COD was found with a value of 279.4 g/d. Out of which 77.76 g/d of COD was found in the effluent and also, 0.538 g/d found in sludge.

### 4.4.2 Carbon balance

Buswell created an equation in 1952 to estimate the products from the anaerobic breakdown of a generic organic material of chemical composition $C_cH_hO_oN_nS_s$ Carbon content of a feed material can be used in combination with the Buswell equation (as below) to estimate methane production.

$$C_c\,H_h\,O_o\,N_n\,S_s + 1/4(4c - h - 2o + 3n + 2s)\,H_2O \longrightarrow 1/8(4c - h + 2o + 3n + 2s)\,CO_2 + 1/8(4c + h - 2o - 3n - 2s)\,CH_4 + nNH_3 + sH_2S$$

Use the Buswell equation to calculate the theoretical biogas composition and go on to apply a carbon balance to calculate the specific methane production. An analytical of food waste has element composition of 0.5, 0.05, 0.38, 0.05 and 0.0004 of carbon, hydrogen, oxygen, nitrogen, and sulphur respectively. Then calculated coefficient for $CO_2$ and $CH_4$ as followed: (C=12, H=1, O=16, N=14, S=32)

$$1/8(4c - h + 2o + 3n + 2s)\,CO_2 = 0.022$$

$$1/8(4c + h - 2o - 3n - 2s)\,CH_4 = 0.0197$$

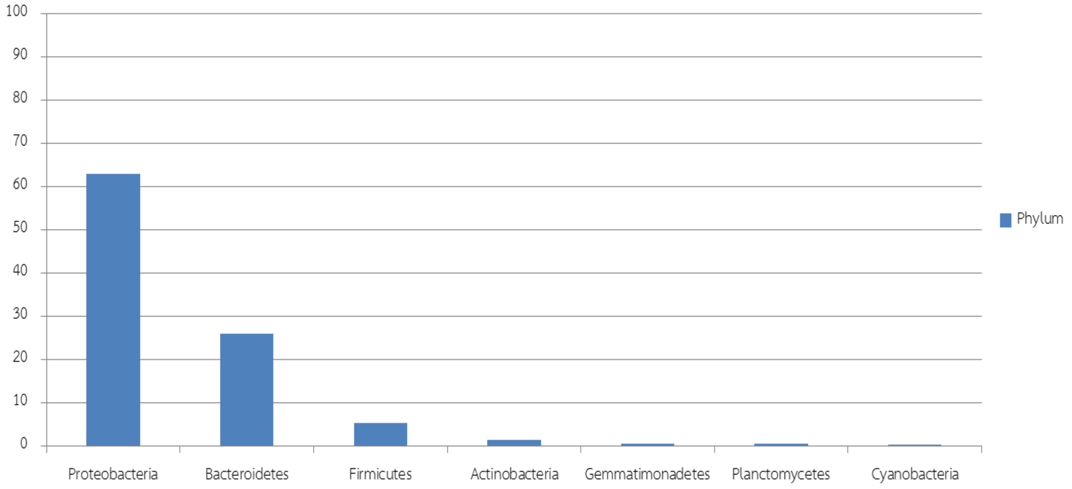
So, the theoretical methane and carbon dioxide equal 47.2% and 52.8%, respectively. The carbon balance 47.2% of carbon is converted to methane equal 0.177 gC/gVS and the specific methane production about 0.33 litre/gVS.

### 4.4.3 Community structure of microorganisms in OD-MBR

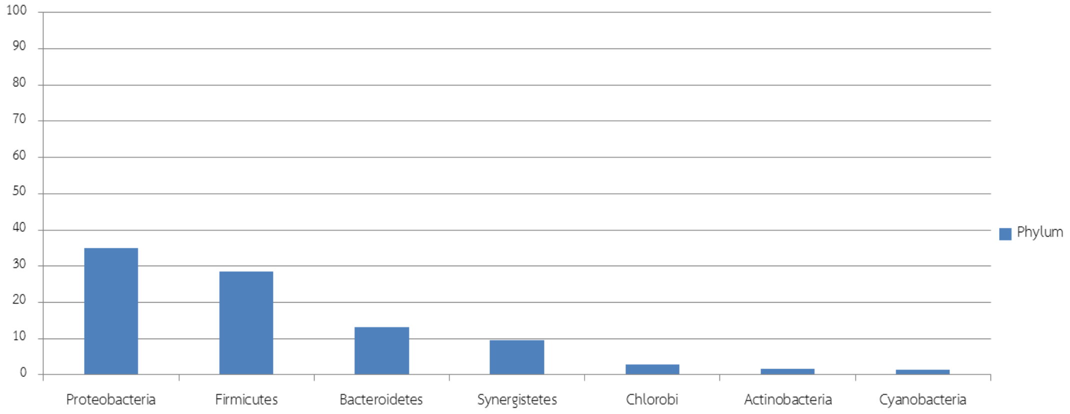
Community structure of microorganisms from OD-MBR system was observed in the aerated zone and inclined tube. The water samples were sent to OMIC Science and Bioinformatics Center, Chulalongkorn University, to analyze by Metagenomics method. These differences in environmental conditions could affect the structure of microorganism’s community.

In an aerated zone, significant growth-related dynamic changes in bacterial community structure were mainly associated with phylum Proteobacteria (63%), Bacteroidetes (26%) and Firmicutes (5.33%) as shown in Fig. 4.11 (a) (mainly genus Chitinophaga, Thermomonas and Phenylobacterium as shown in Fig. 4.12 (a)), indicating that different growth stages affected the bacterial community composition in wastewater. The most species detected in the dominant genus were *Chitinophaga soli* (12.65%), aerobic bacteria with rod- shaped within the genus Chitinophaga of the class Spingobacteriia followed by *Phenylobacterium koreense* (3.5%) with in the genus Caulobacteraceae this is found in activated sludge from wastewater treatment plant

Furthermore, bacterial community was found in wastewater sample in inclined tube predominance of phylum Proteobacteria (34.89%), Firmicutes (28.5%) and Bacteroidetes (13.14%) as shown in Fig. 4.11 (b) . At genus level, many of the dominant Allochromatium, Clostridium and Thermococcus (as illustrated in Fig.4.12 (b)), the most species were *Allochromatium vinosum* (3.97%) *Clostridium alkalicellulosi* (2.76%). *Allochromatium vinosum* is a Gram negative, sulfide and thiosulfate oxidizing. Borkenstein and Fischer (2006) studied the mutant *Allochromatium vinosum* strain 21D, this mutant was used as a biocatalyst in a biotechnological process to eliminate sulfide from synthetic wastewater and to recycle elemental sulfur as a raw material.

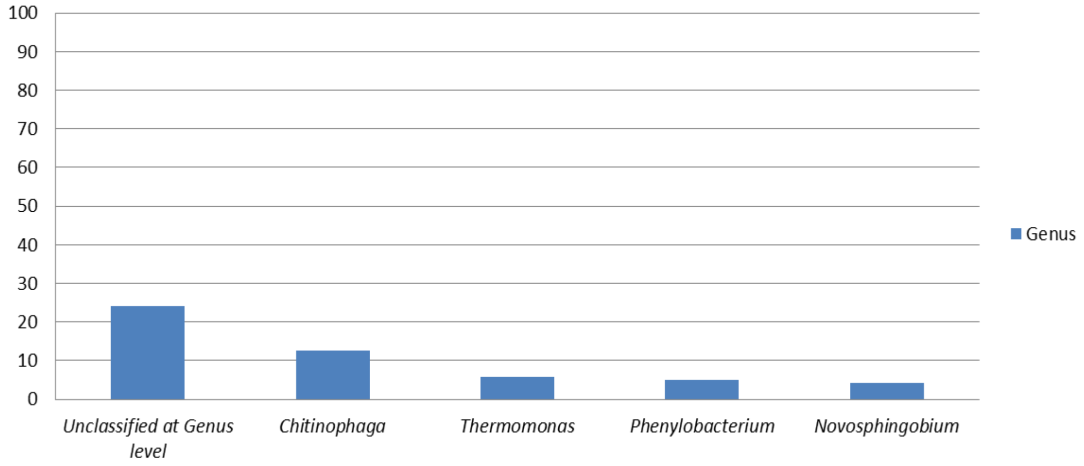


(a) Aerated zone

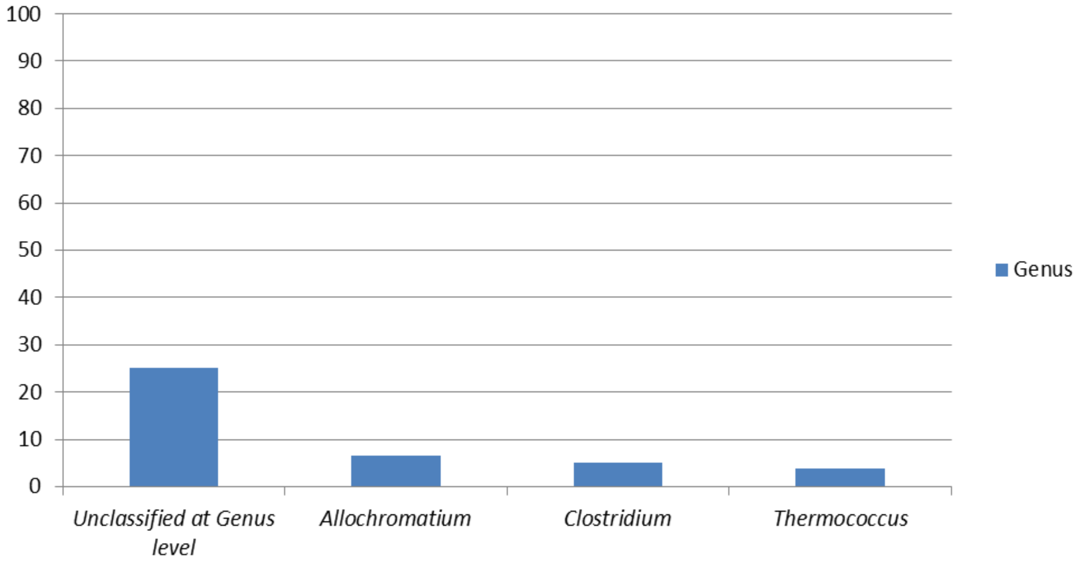


(b) Inclined tube

**Figure 4.11** Percentage of bacterial community of each phylum from OD-MBR water samples



(a) Aerated zone



(b) Inclined tube

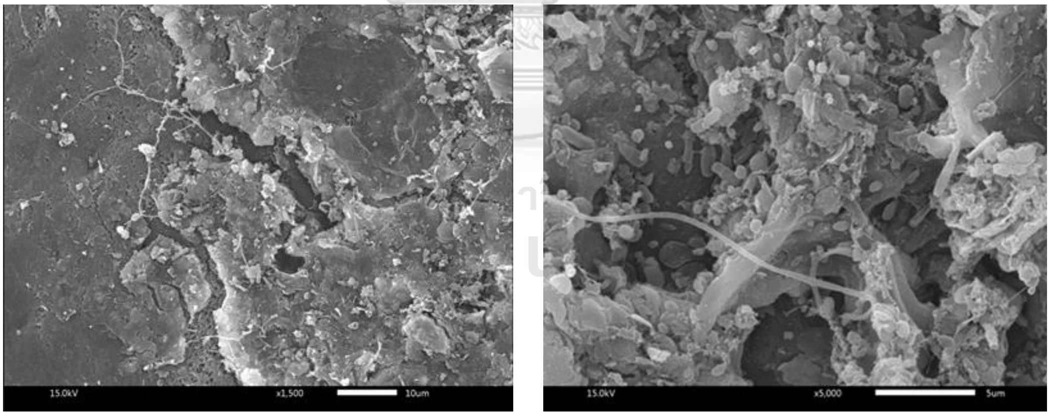
**Figure 4.12** Percentage of bacterial community of each genus from OD-MBR water samples

## 4.5 Membrane Fouling

Use of the membrane in wastewater treatment process is the advanced technology to increase the efficiency in undesirable suspended sediment and solution removing from the system. It is widely applied to sedimentation process by porous size classification (Radjenović, Matošić, Mijatović, Petrović, & Barceló, 2008). However, the filter process by the membrane still has the limitation of the system operation. That is the blocking of the surface and filter of the membrane (Interior pore blocking) especially the ultra-filtration and micro-filtration membrane. However, it depends on the pollutant in the system as well. Organic matter which usually causes the fouling for micro-filtration has the molecular size bigger than 100 kDa (Fabris, Lee, Chow, Chen, & Drikas, 2007) such as Proteins Amino Sugars Polysaccharides and Polyhydroxyaromatics (Wiesner et al., 1992) Colloid/Particle Fouling which the size is 1 nm to 1 μm (Pottset al., 1981) that contains inorganic compound, Organic colloid, algae, and bacteria. These can cause the blocking at the surface of the membrane, the blocking from the microbiology, the blocking from the microorganism which is the result of the compaction of small creatures at the surface of the membrane. When bacteria contact the filter membrane longer, it will cause EPS or Extracellular Polymeric Substance which is mud or gel-like. The characteristic of EPS consists of Carbohydrates and the density of the charge which the gel will protect bacteria from the shear of the water and chemicals such as chlorine.

The blocking analysis of the membrane by the Scanning Electron Microscope (SEM) by considering the membrane surface and inside of the filter membrane shows that the morphology of microorganism is Spherical and Rod (Fig. 4.13 a,b). The group of microorganisms which is the biology film will generate the sticky substance like the glue for the adhesion among microorganisms. Moreover, it protects themselves and their group or Extracellular Polymeric Substances (EPS) which are the polymer outside cells. The structure of the released polymer is the complex compound which polysaccharide and protein are the main components. Moreover, it contains others compounds such as humic acid, nucleic acid, Lipid, and uronic acid. These components of EPS are microbial sediment. This biofilm on the surface of the membrane will increase water permeability and decrease filtration flux. However, the amount of generated EPS depends on the species of microorganisms. This study will classify only the shapes of microorganisms only not the species of them in the bioreactor system which affect the cake layer generation and porous blocking.

The increasing of small sediment particles in the aeration zone can create the accumulation of the cake layer on the membrane surface easier. Moreover, these sediments can pass the membrane surface and block the gap between pore. As a result, the filtration pressure will increase as shown in Fig 4.14.



(a)1500X (b) 5000X

**Figure 4.13** Outer morphology of PVDF hollow fiber membrane

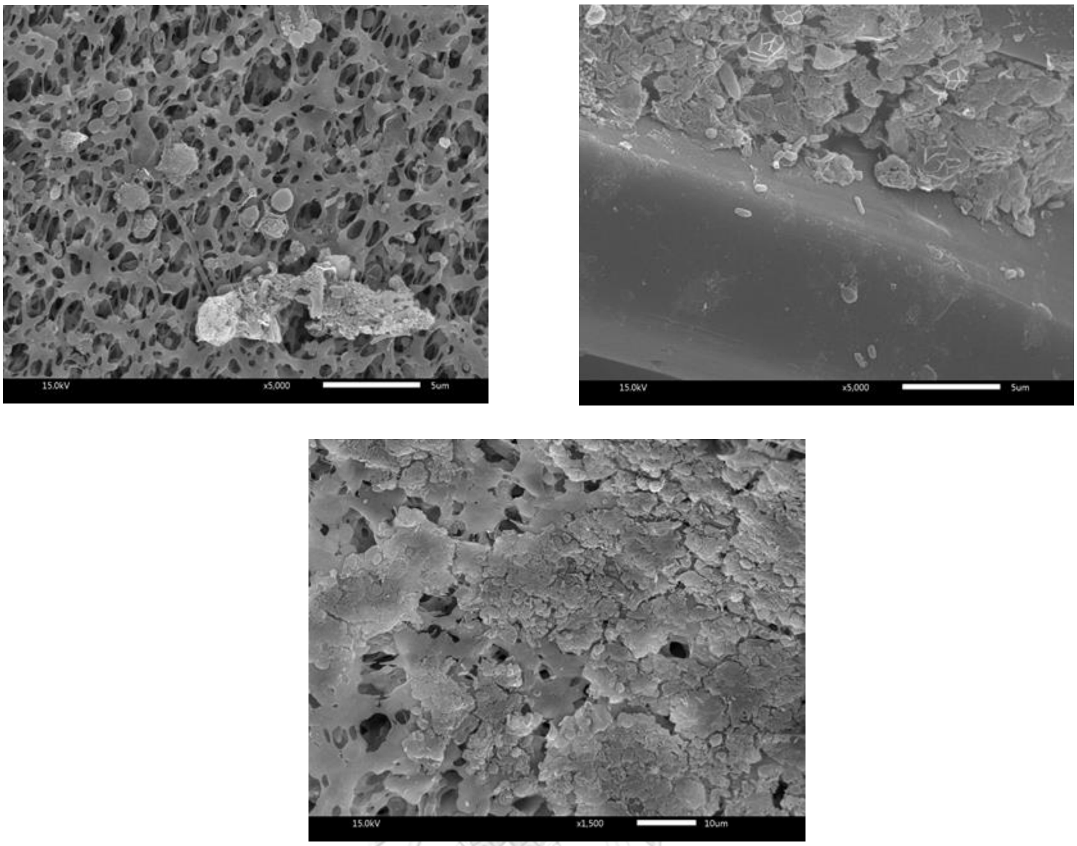


**Figure 4.14** Inner morphology of PVDF hollow fiber membrane

Membrane blocking analysis by Fourier-Transform Infrared Spectroscopy (FT-IR) is the technique to classify molecules which are sedimental components which block pores and membrane surface in the bioreactor system. From the analysis of microbial sediment at the membrane surface in the aeration by analyzing EPS with FT-IR at infrared absorption frequencies of 400-4000 $cm^{-1}$ as shown in Fig.4.15, infrared absorption of stain on the micro-filtration membrane is infrared absorption which the frequency of C-O bonding is 1219.14 and 1071.54 $cm^{-1}$. H-N Stretching bonding has the frequency of 3286.17 $cm^{-1}$. It can be evaluated that the substances which block the membrane are Polysaccharides and proteins which is the molecular structure that blocked by microorganisms cell wall.

From the analysis, that is an amino acid function which is the protein molecule (Sajjad, Kim, & Kim, 2016). The peak is at 3286.17 $cm^{-1}$. The characteristic of N-H bonding (N-H Stretching), C-O bonding (C-O Stretching) and O — H bonding (Stretching O-H) are the peak which relates to Hydroxyl (M. Zhang et al., 2013). At the peak of 1219.14 and 1071.54 $cm^{-1}$, it is C-O bonding as Carbonyl. The characteristic which identified the polysaccharide molecule or polysaccharide-like substances, protein, and polysaccharide are the component of bio-polymer which block the surface and pores of the membrane in the bioreactor system.

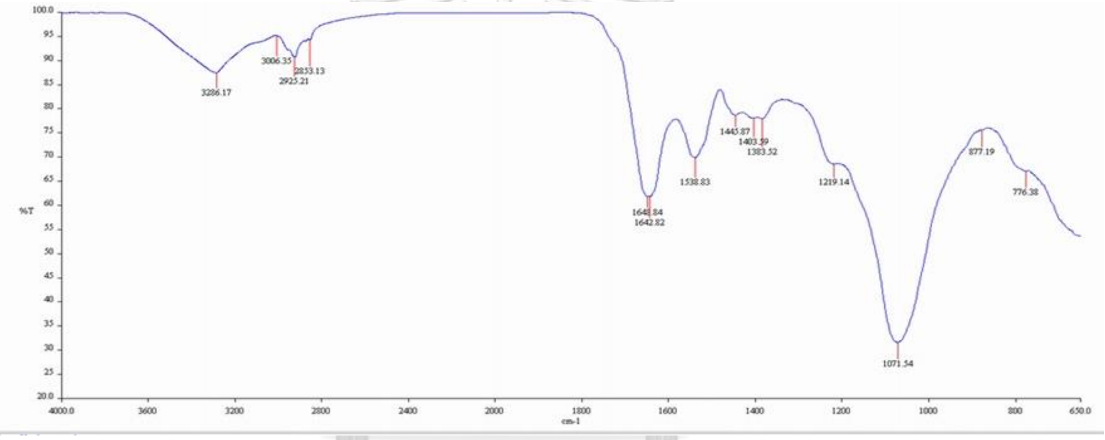


**Figure 4.15** FT-IR spectra of PVDF hollow fiber membrane

### 4.6 Energy Balance

There were two parts of the energy balance calculation for the single-stage and combined system, which include, operating the AD-OD/MBR system, and the post digestion. The generated energy was calculated by converting biogas to heat for cooking.

Energy balance calculation conditions. (1) Food waste: is the waste from canteen Chulachakrabongse building near the plant, so the energy for waste transport was not calculated; (2) the combined system: biogas produced in the AD system was provided to the canteen for cooking, and the digestate was treated by OD-MBR system before used in the garden. The energy to run the combined system included power and heat loss of the digestion tank was based on the literature; (3) the fuel and material used for post digestion were converted into consumption energy. All energy calculation equations are shown in equation (1) and (2).

$$\text{Net energy} = \text{Energy Output} - \text{Energy Input} \qquad (1)$$

For energy balances calculations, a combined treatment system was used. This combined system includes anaerobic digestion (AD) and wastewater treated using an oxidation ditch membrane bioreactor (OD-MBR) system, after the digestion of food waste. The entire system, including the treatment of food waste from canteen using the combined AD-OD/MBR system, followed by using treated water as for gardening, was calculated. Sludge from OD-MBR was used as feed mixed with food waste (1:10 of total amount of feed). The calculation of energy balance includes energy for combined system (AD-OD/MBR) operation, whereas the energy invested in the AD-OD/MBR system plant construction were not calculated. The calculation boundaries of the combined systems and boundary of the combined system are shown in Figure 4.16 and Figure 4.17, respectively.

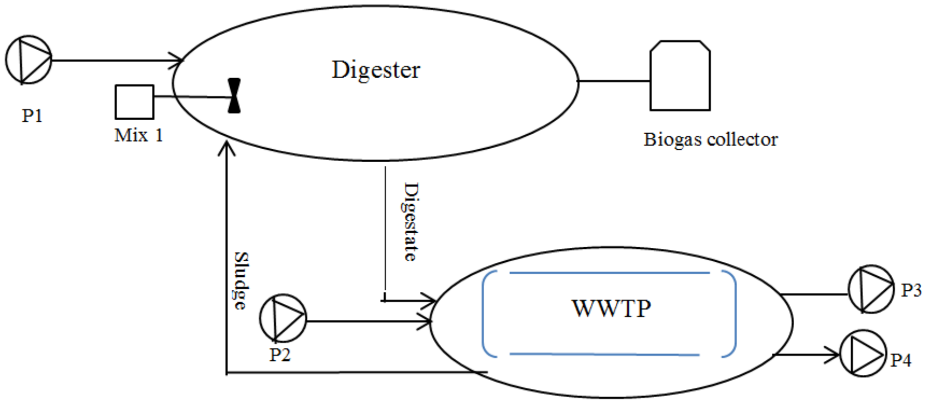


**Figure 4.16** Calculation boundary of combined system

Note: P1 digester feed pump (0.75 HP), Mix1 tank mixer (0.5 HP), P2 wastewater feed pump (1 HP), P3 wastewater discharge pump (0.5 HP), P4 air pump (0.5 HP)

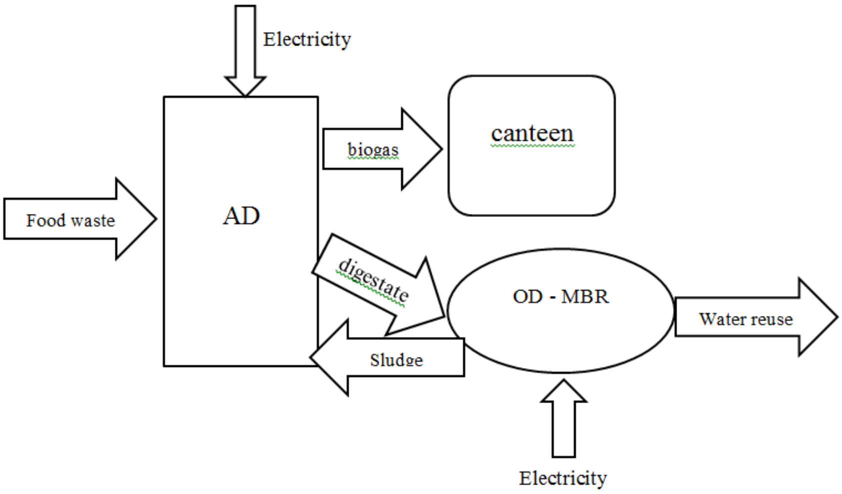


**Figure 4.17** Boundary of the combined system

### 4.6.1 Energy Input

**Table 4.10** Direct energy in single-stage and combined system

| Electricity | Energy (GJ) | Energy Input (GJ/year) |
|---|---|---|
| Single AD | 0.0016 | 0.384 |
| SC1 | 0.0497 | 11.928 |
| SC2 | 0.0497 | 11.928 |
| SC3 | 0.0576 | 13.824 |
| SC4 | 0.0576 | 13.824 |
| SC5 | 0.0656 | 15.744 |
| SC6 | 0.0656 | 15.744 |

### 4.6.2 Energy Output

$$EHO = BY \times Me \times Q\text{net} \times CEH \times 365/10^3 \qquad (2)$$

Where: EHO: Energy of heat output (GJ/year)

BY: Biogas yield (Nm3/day)

Me: Methane content (%)

$Q$net: Net calorific power of methane (MJ/ Nm3)

CEH: Recovery efficiency of heat (%)

**Table 4.11** Energy output of single-stage and combined systems with different condition

| Energy of heat output (GJ/year) | Single-stage AD | Combined system | | | | | |
|---|---|---|---|---|---|---|---|
| | | SC1 | SC2 | SC3 | SC4 | SC5 | SC6 |
| Energy output | 5.50 | 6.08 | 4.96 | 4.36 | 4.38 | 3.48 | 3.45 |

### 4.6.3 Energy Balance

**Table 4.12** Net energy yield of single-stage and combined systems with different condition (GJ/year)

| Conditions | Net energy balance |
|---|---|
| **Single-stage AD** | 5.116 |
| **SC1** | -5.848 |
| **SC2** | -6.968 |
| **SC3** | -9.464 |
| **SC4** | -9.444 |
| **SC5** | -12.264 |
| **SC6** | -12.294 |

The net energy yield in single-stage AD was the highest because this system not consumed the energy of the OD-MBR system. Whereas the combined system, indicating that the generated energy was lower than the consumed energy by the entire system. The major reason was the biogas yield increased in the single-stage and combined system running with HRT 24 hr water velocity 0.3 m/s (SC1). Furthermore, the heat recovery efficiency for energy balance calculation was 52% (Zhou, Zhang, Zou, Riya, & Hosomi, 2015). According to the literature, heat efficiencies of 45-50% can be achieved, which can improve energy balance (Kaparaju & Rintala, 2011).

The heat output highest in combined system running with HRT 24 hr water velocity 0.3 m/s (SC1), caused by the increasing biogas yield. However, although the biogas yield increased with single-stage AD and combined system, the net energy yield (Table 4.12) was negative.

The percentage of methane in single-stage AD and combined system were 67.33-61.75 except in the running with SC4 and SC5 were lower than 60%, so the biogas is 60% of methane it has an energy value of 6.0 kWh/m$^3$ that caused the high energy output.

As a result, there is an opportunity to improve the sustainability of energy production in tropical regions by converting this locally abundant food waste into bioenergy products using anaerobic digestion. It was concluded that canteen and restaurant waste showed very high methane potential. Most studies show use of sludge from anaerobic digester as inocula or seed (L. Zhang, Lee, & Jahng, 2011). Million tons of solid waste is produced from agriculture, industries and municipal sources. It is nowadays problem as rate of generation is greater than rate of degradation under natural conditions. According to Yu, Tay, and Fang (2001), 1MT of grass waste may release 50–110 carbon dioxide and 50–140 of methane. It will increase the global temperature up to 1–2% per year (Solomon, Qin, Manning, Averyt, & Marquis, 2007).

## 4.7 Life cycle impact assessment

For LCA calculation the overall scope of the LCA study is shown. The system boundary implies the margin of inflow and outflow. Brief information on LCI and LCIA are also presented. Methodological choices made in this study are described according to software procedures.

LCA consists of the system boundary and life cycle inventory by using the SimaPro 8 Software.

### 4.7.1 Goal and functional unit

The goal of this part of study is to evaluate zero organic waste management systems from perspective of GHG emissions.

The functional unit (FU) is the definition of the functional outputs of the process single-stage AD, OD-MBR and combined system. The function of this study is defined as the resource recovery from wastes. For data calculation, the reference flow is defined as the 1 kg of sludge produced.

Scenario 1 Base case: Anaerobic digestion for food waste, with produced biogas for cooking, digestate from AD disposed to drainage. And wastewater treated by OD-MBR for gardening.

Scenario 2 Combined case: “Zero waste” digestate is treated with OD-MBR and sludge from OD-MBR returned to AD.

### 4.7.2 System boundary

In terms of system boundaries, the food waste generation depicts only waste that is disposed in canteen at Chulachakrabongse building, Chulalongkorn campus and manual sorting by housekeeper. Wastewater comes from Chulachakrabongse Building and sludge is generated from OD-MBR system. The collection and transportation steps are excluded from the system boundary, and the burdens from consumption of water and chemicals as well as processes of construction and demolition of facilities are ignored. Chemical treatment, water consumption and electricity in operation process are collected to estimation life cycle inventory. All energy generated from waste and biogas can be utilized for cooking in canteen replaces commercial LPG gas. Water effluent from the system also collected and estimated as life cycle inventory. The system boundary was shown in Fig 4.18

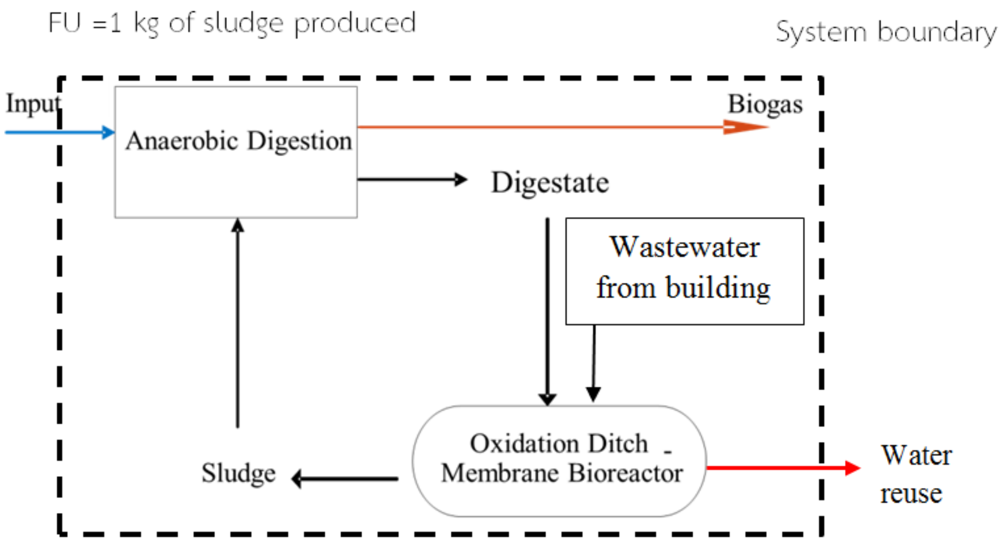


**Figure 4.18** System boundary

### 4.7.3 Life cycle inventory data

Table 4.13 lists the Life Cycle Inventory (LCI) of the system under study. Data external to the system boundary (Fig.4.18) are not included in the analysis. Experimental data regarding the AD combined with OD-MBR operation and treatment efficiency were collected and used from the system. The Ecoinvent 3.01 database was the preferred option to calculated the LCI of the combined system. Moreover, the local electricity mix, the electric motors and the submerge membranes unit were used data from literature review since they are not available in SimaPro's LCI datasets. In addition, the membrane cleaning is used with sodium hypochlorite (NaOCl) 10%.

**Table 4.13** Life Cycle Inventory (LCI) of the AD combined with OD-MBR prototype (per FU)

| **Experimental setup** | **Unit** | **AD** | **OD-MBR** | **Combined case (SC1)** |
|---|---|---|---|---|
| Electricity | kWh | 0.221 | 1.579 | 1.8 |
| Chemical used for membrane cleaning (10% NaOCl). | Kg | 0 | 0.222 | 0.29 |
| Water emission | | | | |
| COD | kg | 0.232 | 5.90 | 0.03 |
| TKN | kg | 0.00352 | 1.02 | 0.01 |
| Nitrate | kg | 0.00044 | 0.00013 | 0.00002 |
| Nitrite | kg | 0 | 0.00020 | 0 |
| Phosphate | kg | 0.0009 | 0.155 | 0.00125 |

### 4.7.4 Life cycle impact assessment

LCIA is a process to translate emissions into defined impacts by assigning each emission with a specific characterization factor and sum the characterized impact for each impact category. This study indicated that consistent results can be obtained for global impact categories (i.e. global warming, resource depletion and ozone depletion). However, discrepancies were found in more regional and local impact categories (i.e. acidification, eutrophication, human and eco-toxicity).

The schematic flows and parameters in each system are presented in Fig.4.16. All predicted environmental burdens were classified and characterized into 11 impact categories with CML –IA baseline v 3.02 method: global warming (GWP100 in kg $CO_2$ eq.), acidification (AP in kg $SO_2$ eq.), and eutrophication (EP in kg $PO_4^{3-}$ eq.).

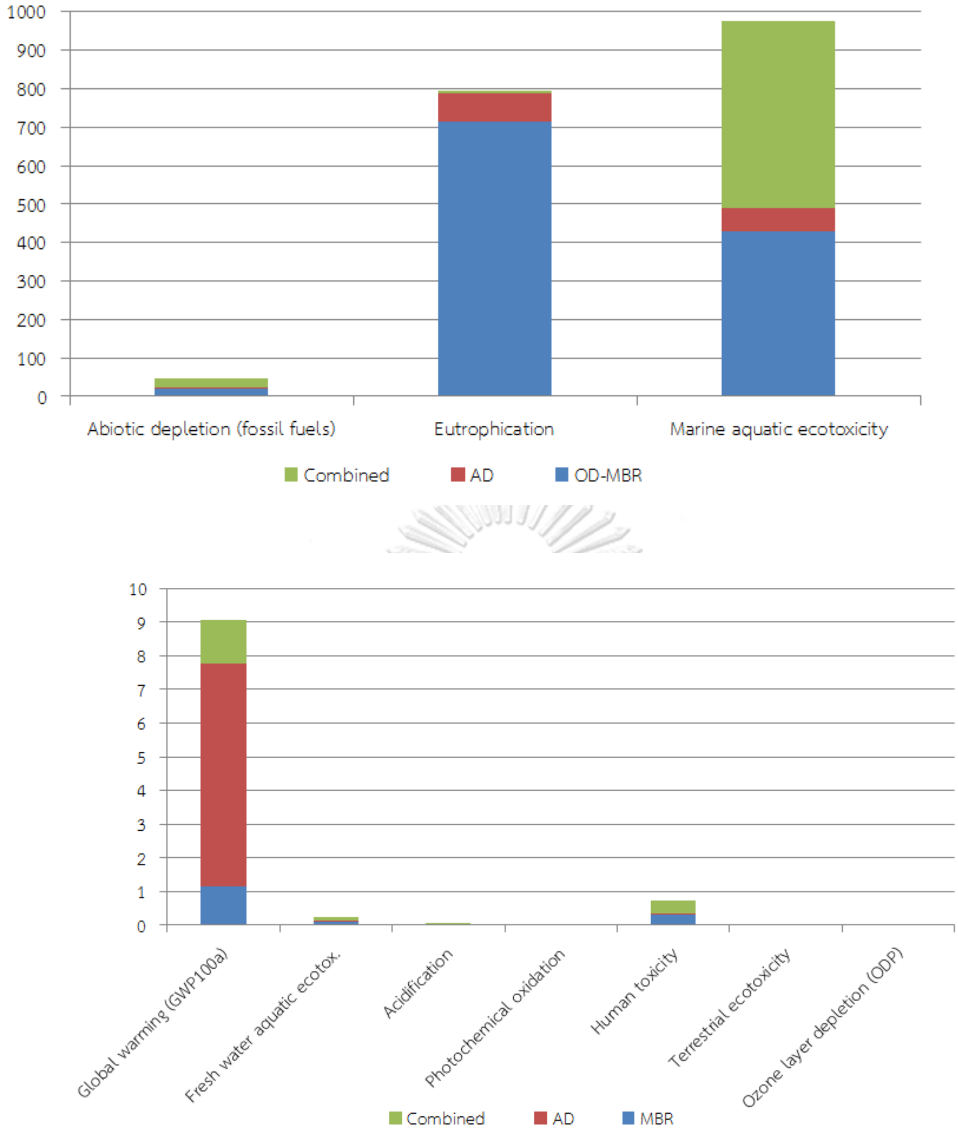


**Figure 4.19** Percent contribution of each system according to the CML –IA baseline v 3.02 methodology

**Table 4.14** Environmental impacts of each system

| Categories | Unit | Single-stage AD | OD-MBR | Combined |
|---|---|---|---|---|
| Abiotic depletion | kg Sb eq | 0 | 0 | 0 |
| Abiotic depletion (fossil fuels) | MJ | 2.792039 | 19.94855 | 22.74059 |
| Global warming (GWP100a) | kg $CO_2$ eq | 6.611673 | 1.13726 | 1.296433 |
| Ozone layer depletion (ODP) | kg CFC-11 eq | 8.95E-14 | 6.39E-13 | 7.29E-13 |
| Human toxicity | kg 1,4-DB eq | 0.044115 | 0.315194 | 0.359309 |
| Fresh water aquatic ecotox. | kg 1,4-DB eq | 0.015761 | 0.112606 | 0.128367 |
| Marine aquatic ecotoxicity | kg 1,4-DB eq | 59.89526 | 427.9395 | 487.8347 |
| Terrestrial ecotoxicity | kg 1,4-DB eq | 1.02E-05 | 7.29E-05 | 8.31E-05 |
| Photochemical oxidation | kg $C_2H_4$ eq | 0.001809 | 0.000495 | 0.000564 |
| Acidification | kg $SO_2$ eq | 0.001581 | 0.011293 | 0.012874 |
| Eutrophication | kg $PO_4$ eq | 75.12446 | 713.7691 | 4.659801 |

LCI results obtain from each system are present in Table 4.13, and the environmental impacts characterizing the results are presented in Fig. 4.19. In the global warming category, OD-MBR showed the least impact (about 1.14 kg $CO_2$ eq. per FU) approximate to combined system (1.29 kg $CO_2$ eq. per FU). Combined system has lower impact of $CH_4$ emission because of closed system during process. GWP shows a strong similarity to primary energy demand. Rehl and Müller (2011) studied life cycle impact assessment of biogas digestate they illustrated that belt drying has the highest GWP about 0.1 kg$CO_2$ eq./FU, whereas physical-chemical treatment composting and solar drying showed best environmental performance. This affected by $CO_2$ emissions from the combustion of lignite in power plant to produce electricity. In the acidification category, single-stage AD showed the least potential impact within the OD-MBR and combined system. The eutrophication impact OD-MBR has a greatest potential impact due to the contribution of the nitrogen source and organic compound of the digestate. Kim (2010) studied and evaluated of food waste disposal in term of global warming and resource recovery through LCA method. The result showed that 200 kg of CO2eq produced from dry feeding process, 61 kg of $CO_2$eq from wet feeding process, 123 kg of $CO_2$eq composting process, and 1010 kg of $CO_2$eq from landfilling. It can conclude that feed manufacturing and composting are the environment friendlier than other methods.

# CHAPTER 5

# CONCLUSION AND RECOMMENDATION

## 5.1 Conclusion

This study aims to develop the prototype of the combined system between anaerobic digester and oxidation ditch membrane bioreactor to reduce organic waste to zero for buildings. The study consists of the study of anaerobic digester (AD) efficiency to substitute LPG by biogas for buildings and the study of wastewater treatment efficiency of building with liquid digestate from AD. The treated water will be watered plants. Moreover, LCA is used to evaluate the environmental impact in terms of global warming potential AP and Eutrophication potential. The results of the study can be concluded as follows;

### 5.1.1 The optimize operating conditions

The suitable condition for the combined system between AD and OD-MBR by setting 6 experiments. The results show that the combined system with water retention times of 24 hours and water velocity of 0.3 m/s provide the highest specific methane yield of 1.12 $m^3CH_4$/kg VS removed

The control factors of the system consist of pH, dissolved oxygen (DO), temperature, and the concentration of MLSS. From the study, the temperature of the system is 28-35 $^OC$. However, there is the change depend on the experimental season. pH of the wastewater which accesses to the system is constant of 7-7.5. For DO, the aeration is always done during the treatment process so DO is in the standard. However, at the beginning of the OD-MBR process, the first stage is the air limitation condition and shortens. Therefore, Denitrification reaction takes place in the system. In the second stage, oxygen is excess to the system to create Denitrification reaction which affects the organic and nitrogen treatment rates because microorganism in the aerobic part use oxygen to degrade the organic matter are generate new cells. For the analysis of MLSS, it is the indicator of used organic substance and nutrient from the wastewater which accesses to the system. The average amount of MLSS for every experiment (SC1-SC6) is 942.98-1072.23 mg/l and the value is quite constant during the experiment.

From the study of treatment efficiency of COD, TKN, and TP of the combined system, the experiment which has the highest treatment efficiency of COD and TKN are Experiment 1 (SC1) HRT 24 hr, water velocity 0.3 m/s which the treatment percentage is 93.77 and 85.57 respectively. For the efficiency of phosphorus treatment, the value is low for every experiment. When comparing all experiments, the Experiment 3 (SC3) HRT 18 hr, water velocity 0.3 m/s has the highest phosphorus treatment's efficiency which is equal to 51.17%.

### 5.1.2 Membrane fouling analysis

Surface characteristic and morphology of membrane at the beginning of the filtration process, microbial sludge will group and create colony at the outside of the membrane. The shapes are rod and fiber as the layer of biofilm because microorganisms in the system release sticky substance called Extracellular Polymeric Substances (EPS) or EPS which acts like the glue to bond each microbial cell. When the operation duration increasing, microbial cake will be more cumulative as well. EPS is a polymer. The outside of cells contains a complex of protein and polysaccharide as the main component. The amount of EPS depends affects the grouping of microbial sludge and cohesion at the membrane surface. When investigating the characteristic of sludge by a compound microscope, sludge is disrupted because of the shear of air bubble and variance of flow in the system.

### 5.1.3 Energy Balance

The calculation of energy balance of the combined system between AD and OD-MBR consists of input and output energy including the net energy in terms of direct. From the study, in single-stage AD show the highest net energy, however in the combined system the total energy use is higher than energy from every experiment (SC1-SC6). Therefore, the net energy is negative. However, when considering the LPG saving, for Experiment 1, SC1 can save LPG the most or 4,428 THB/year.

### 5.1.4 Life cycle assessment

The evaluation by LCA with SimaPro 8 software for global warming potential (GWP), acidification potential (AP), and eutrophication potential (EP) shows that the combined system between AD and OD-MBR has the global warming potential of 1.29 kg $CO_2$ eq. per FU, acidification potential of 0.0128 kg $SO_2$ eq per FU, and eutrophication potential EP of 4.659 kg $PO_4$ eq per FU. The combined system can reduce the trend of GWP from the operation of AD only. Although the combined system has higher Acidity than ODMBR, when considering the benefit, it can circulate the water for the agriculture to water plants and be the guideline of water pollution reduction or avoid Eutrophication. Moreover, it can be used for soil improvement to reduce the pollution in the agriculture.

## 5.2 Recommendation

For the sustained operation of OD-MBR system, the procedure should be use physical screening of liquid digestate before derived to system for the reason to decreased sediment.

In term of high water treatment efficiency, OD-MBR system should be supplementary all of the wastewater for complete water treatment. Researcher should be study the suitable ratio of liquid digestate and optimum volume of sludge in laboratory-scale before set up in full-scale.

LCA is the technique for evaluated environmental impact from cradle to grave so that apply to large scale it should be done by collect raw data and transportation should be simulated for select the appropriated material and procedure.

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# APPENDIX

Table A-1 Pressure and temperature

| Conditions | Day | Pressure (hPa) | Temperature ($^{O}$C) |
|---|---|---|---|
| Single-AD | d1 | 992 | 29 |
| | d2 | 1002 | 30 |
| | d3 | 1009 | 30 |
| | d4 | 999 | 30 |
| | d5 | 1001 | 31 |
| | d6 | 1000 | 31 |
| | d7 | 997 | 29 |
| | d8 | 1012 | 27 |
| | d9 | 998 | 26 |
| | d10 | 996 | 33 |
| | d11 | 996 | 29 |
| | d12 | 1001 | 26 |
| | d13 | 997 | 33 |
| | d14 | 995 | 33 |
| | d15 | 999 | 32.5 |
| | d16 | 995 | 31.5 |
| | d17 | 996 | 33 |
| | d18 | 998 | 31.5 |
| | d19 | 998 | 29 |
| | d20 | 1000 | 32 |
| | d21 | 998 | 33 |
| | d22 | 998 | 32.5 |
| | d23 | 997 | 32.5 |
| | d24 | 1007 | 28 |
| | d25 | 1007 | 30 |
| | d26 | 1011 | 28 |
| | d27 | 998 | 31 |
| | d28 | 1014 | 31 |

| Conditions | Day | Pressure (hPa) | Temperature ($^{O}$C) |
|---|---|---|---|
| SC1 | d1 | 1005 | 28 |
| | d2 | 998 | 33 |
| | d3 | 998 | 33 |
| | d4 | 1003 | 31 |
| | d5 | 1011 | 28 |
| | d6 | 996 | 28 |
| | d7 | 1003 | 31 |
| | d8 | 1011 | 28 |
| | d9 | 1000 | 32 |
| | d10 | 993 | 33 |
| | d11 | 1014 | 34 |
| | d12 | 996 | 32 |
| | d13 | 999 | 29 |
| | d14 | 1000 | 33 |
| | d15 | 1023 | 24 |
| | d16 | 1003 | 25 |
| | d17 | 1001 | 28 |
| | d18 | 1000 | 30 |
| | d19 | 999 | 31 |
| | d20 | 1010 | 32.5 |
| | d21 | 1005 | 30 |
| | d22 | 997 | 28 |
| | d23 | 1000 | 33 |
| | d24 | 998 | 32.5 |
| | d25 | 1010 | 33 |
| | d26 | 1005 | 31 |
| | d27 | 995 | 32 |
| | d28 | 998 | 33 |

| Conditions | Day | Pressure (hPa) | Temperature ($^{O}$C) |
|---|---|---|---|
| SC2 | d1 | 1003 | 33.5 |
| | d2 | 1007 | 32 |
| | d3 | 995 | 34 |
| | d4 | 1013 | 33 |
| | d5 | 1000 | 34.5 |
| | d6 | 1000 | 32.5 |
| | d7 | 1011 | 34 |
| | d8 | 1009 | 34.5 |
| | d9 | 1012 | 33 |
| | d10 | 1003 | 34 |
| | d11 | 1005 | 35 |
| | d12 | 1008 | 32 |
| | d13 | 1005 | 35 |
| | d14 | 1003 | 36.5 |
| | d15 | 1012 | 35.5 |
| | d16 | 1005 | 37 |
| | d17 | 1008 | 36 |
| | d18 | 1010 | 37.5 |
| | d19 | 1007 | 38 |
| | d20 | 1008 | 36 |
| | d21 | 1008 | 37 |
| | d22 | 999 | 35.5 |
| | d23 | 994 | 36.5 |
| | d24 | 1000 | 35 |
| | d25 | 1003 | 36 |
| | d26 | 998 | 37.5 |
| | d27 | 1000 | 37 |
| | d28 | 1002 | 38 |

| Conditions | Day | Pressure (hPa) | Temperature ($^{O}$C) |
|---|---|---|---|
| SC3 | d1 | 1001 | 37.5 |
| | d2 | 1001 | 36 |
| | d3 | 997 | 37 |
| | d4 | 999 | 36.5 |
| | d5 | 1000 | 36.5 |
| | d6 | 1003 | 36 |
| | d7 | 1002 | 36.5 |
| | d8 | 1002 | 37 |
| | d9 | 1001 | 37.5 |
| | d10 | 998 | 38 |
| | d11 | 1004 | 37 |
| | d12 | 1003 | 37.5 |
| | d13 | 999 | 37 |
| | d14 | 1006 | 38 |
| | d15 | 1002 | 38 |
| | d16 | 1005 | 37 |
| | d17 | 999 | 37.5 |
| | d18 | 1007 | 35 |
| | d19 | 1004 | 35.5 |
| | d20 | 997 | 33 |
| | d21 | 1010 | 30.5 |
| | d22 | 1006 | 29.5 |
| | d23 | 1008 | 30 |
| | d24 | 1005 | 30.5 |
| | d25 | 1003 | 29 |
| | d26 | 1008 | 29.5 |
| | d27 | 1005 | 29 |
| | d28 | 1003 | 30 |

| Conditions | Day | Pressure (hPa) | Temperature ($^{O}$C) |
|---|---|---|---|
| SC4 | d1 | 1007 | 29.5 |
| | d2 | 1005 | 31 |
| | d3 | 1002 | 32 |
| | d4 | 1004 | 30 |
| | d5 | 1006 | 29 |
| | d6 | 1005 | 34 |
| | d7 | 1006 | 25 |
| | d8 | 1006 | 29 |
| | d9 | 1005 | 34 |
| | d10 | 1004 | 33 |
| | d11 | 1003 | 33.5 |
| | d12 | 1003 | 33 |
| | d13 | 1007 | 33 |
| | d14 | 1007 | 33 |
| | d15 | 1004 | 37 |
| | d16 | 1004 | 34 |
| | d17 | 1006 | 35 |
| | d18 | 1007 | 33 |
| | d19 | 1005 | 36 |
| | d20 | 1005 | 32 |
| | d21 | 1000 | 32 |
| | d22 | 1003 | 33 |
| | d23 | 1000 | 33.5 |
| | d24 | 1003 | 34 |
| | d25 | 1002 | 35 |
| | d26 | 1001 | 34 |
| | d27 | 1001 | 34 |
| | d28 | 1007 | 25 |

| Conditions | Day | Pressure (hPa) | Temperature ($^{O}$C) |
|---|---|---|---|
| SC5 | d1 | 1004 | 34 |
| | d2 | 1003 | 33 |
| | d3 | 1003 | 33 |
| | d4 | 1008 | 34 |
| | d5 | 1000 | 33 |
| | d6 | 1003 | 32 |
| | d7 | 1002 | 30 |
| | d8 | 1002 | 32 |
| | d9 | 1000 | 32.5 |
| | d10 | 1001 | 38 |
| | d11 | 998 | 37 |
| | d12 | 990 | 36.5 |
| | d13 | 995 | 36 |
| | d14 | 992 | 34 |
| | d15 | 980 | 35.5 |
| | d16 | 975 | 35 |
| | d17 | 978 | 34 |
| | d18 | 979 | 31 |
| | d19 | 980 | 32 |
| | d20 | 980 | 34 |
| | d21 | 981 | 30 |
| | d22 | 982 | 30.5 |
| | d23 | 980 | 29 |
| | d24 | 979 | 33 |
| | d25 | 977 | 35 |
| | d26 | 977 | 31 |
| | d27 | 978 | 26 |
| | d28 | 978 | 29 |

| Conditions | Day | Pressure (hPa) | Temperature ($^{O}$C) |
|---|---|---|---|
| SC6 | d1 | 982 | 30 |
| | d2 | 982 | 29 |
| | d3 | 982 | 28 |
| | d4 | 981 | 26 |
| | d5 | 982 | 25 |
| | d6 | 982 | 30 |
| | d7 | 982 | 29 |
| | d8 | 980 | 32 |
| | d9 | 981 | 31 |
| | d10 | 982 | 29 |
| | d11 | 982 | 32 |
| | d12 | 982 | 32 |
| | d13 | 984 | 29 |
| | d14 | 985 | 30 |
| | d15 | 984 | 30 |
| | d16 | 985 | 30 |
| | d17 | 983 | 30 |
| | d18 | 983 | 33 |
| | d19 | 982 | 32 |
| | d20 | 988 | 29 |
| | d21 | 981 | 30 |
| | d22 | 982 | 34 |
| | d23 | 984 | 31 |
| | d24 | 984 | 32 |
| | d25 | 984 | 33 |
| | d26 | 990 | 31 |
| | d27 | 988 | 31 |
| | d28 | 984 | 32 |

Table A-2 VFA and Alkalinity

| Conditions | VFA (mg/l) | Alk (mg/l) | VFA/Alk |
|---|---|---|---|
| Single-AD | 1452 | 15342 | 0.09 |
| Single-AD | 1706 | 15017 | 0.11 |
| Single-AD | 1532 | 15873 | 0.10 |
| Single-AD | 1669 | 16370 | 0.10 |
| SC1 | 1648 | 14236 | 0.12 |
| SC1 | 1637 | 15439 | 0.11 |
| SC1 | 1792 | 15312 | 0.12 |
| SC1 | 1481 | 16809 | 0.09 |
| SC2 | 2013 | 17336 | 0.12 |
| SC2 | 1629 | 16957 | 0.10 |
| SC2 | 1497 | 15263 | 0.10 |
| SC2 | 1661 | 17459 | 0.10 |
| SC3 | 1969 | 17628 | 0.11 |
| SC3 | 2158 | 16892 | 0.13 |
| SC3 | 1636 | 17335 | 0.09 |
| SC3 | 1199 | 15386 | 0.08 |
| SC4 | 1504 | 14450 | 0.10 |
| SC4 | 1761 | 13436 | 0.13 |
| SC4 | 1944 | 13882 | 0.14 |
| SC4 | 1825 | 14363 | 0.13 |
| SC5 | 1995 | 16500 | 0.12 |
| SC5 | 1621 | 15349 | 0.11 |
| SC5 | 1493 | 14231 | 0.10 |
| SC5 | 1526 | 16639 | 0.09 |
| SC6 | 1769 | 17453 | 0.10 |
| SC6 | 1656 | 16673 | 0.10 |
| SC6 | 1864 | 15090 | 0.12 |
| SC6 | 1907 | 16004 | 0.12 |

### Calculation biogas production in Normal cubic meter

Conversion procedures of biogas from Normal conditions to Standard conditions are presented below. Fluctuation of room temperature and atmospheric pressure during the measurement of gas can contribute errors in volume calculations. Therefore, to apply corrections, the record of change of atmospheric pressure and temperature is important. The gas pressure inside the tube collected over the liquid solution is the sum of the biogas pressure and the vapor pressure. The pressure of biogas, (Pbio) can be obtained by subtracting the vapor pressure of liquid (Pw) at the temperature of measurement from the pressure of collected moist gas (P).

$$\mathrm{Pbio} \quad = \quad \mathrm{Pw}-\mathrm{P}$$

The produced biogas volume in normal condition can be converted to STP using Combine Gas law:

$$\mathrm{Vo} \quad = \quad \mathrm{V} \times (\mathrm{To}/\mathrm{T}) \times (\mathrm{Pbio}/\mathrm{P})$$

V is the measured gas volume, Vo is the volume of gas in standard temperature and Pressure, Po is the standard pressure, T is gas temperature at the time of measurement, and To is the standard temperature. Modified (Buck, 1981) Equation can be suggested for the calculation of vapor pressure

Table A-3 Operating conditions of OD-MBR

| Conditions | | MLSS (mg/l) |
|---|---|---|
| OD-MBR | wk1 | 860.4 |
| | wk2 | 920.1 |
| | wk3 | 905.3 |
| | wk4 | 892.8 |
| SC1 | wk1 | 957.1 |
| | wk2 | 1020.3 |
| | wk3 | 969.3 |
| | wk4 | 1100.2 |
| SC2 | wk1 | 1232.4 |
| | wk2 | 1027.6 |
| | wk3 | 985 |
| | wk4 | 1005.6 |
| SC3 | wk1 | 996.4 |
| | wk2 | 830.7 |
| | wk3 | 941.2 |
| | wk4 | 1003.6 |
| SC4 | wk1 | 965.1 |
| | wk2 | 935.2 |
| | wk3 | 1182.9 |
| | wk4 | 1205.7 |
| SC5 | wk1 | 896.4 |
| | wk2 | 938.9 |
| | wk3 | 962.6 |
| | wk4 | 837.1 |
| SC6 | wk1 | 1026.4 |
| | wk2 | 1392.1 |
| | wk3 | 934.9 |
| | wk4 | 902.7 |

Table A-4 COD removal

| Conditions | COD (mg/l) | | |
|---|---|---|---|
| | Inf. | Eff. | %Removal |
| SC1 | 2,346.67 | 170.67 | 92.73 |
| | 2,466.67 | 156.00 | 93.68 |
| | 3,171.00 | 197.00 | 93.79 |
| | 3,003.67 | 161.00 | 94.64 |
| SC2 | 3,802.33 | 236.51 | 93.78 |
| | 4,346.00 | 329.15 | 92.43 |
| | 3,507.67 | 358.80 | 89.77 |
| | 4,244.33 | 272.26 | 93.59 |
| SC3 | 3,529.00 | 257.05 | 92.72 |
| | 3,512.33 | 249.53 | 92.90 |
| | 2,885.33 | 346.07 | 88.01 |
| | 3,696.67 | 257.78 | 93.03 |
| SC4 | 3,598.67 | 338.92 | 90.58 |
| | 3,198.00 | 280.33 | 91.23 |
| | 2,678.67 | 366.46 | 86.32 |
| | 2,709.00 | 346.11 | 87.22 |
| SC5 | 3,063.67 | 380.00 | 87.60 |
| | 2,293.67 | 325.00 | 85.83 |
| | 2,550.00 | 366.67 | 85.62 |
| | 3,046.67 | 370.00 | 87.86 |
| SC6 | 3,148.67 | 418 | 86.72 |
| | 2,735.67 | 397 | 85.49 |
| | 2,853.33 | 434.3333 | 84.78 |
| | 3,040.33 | 465.6667 | 84.68 |

Tabla A-5 Nitrogen removal

| Conditions | TKN (mg/l) | | | $NO_3^-$ (mg/l) | | $NO_2^-$ (mg/l) | |
|---|---|---|---|---|---|---|---|
| | Inf. | Eff. | %Removal | Inf. | Eff. | Inf. | Eff. |
| SC1 | 320.60 | 47.25 | 85.26 | 0.13 | 0.10 | 0.02 | 0.01 |
| | 300.04 | 43.95 | 85.35 | 0.22 | 0.10 | 0.02 | ND |
| | 304.12 | 45.80 | 84.94 | 0.23 | 0.09 | ND | 0.01 |
| | 327.80 | 43.68 | 86.68 | 0.30 | 0.11 | ND | ND |
| SC2 | 329.15 | 54.82 | 83.34 | 0.32 | 0.10 | 0.01 | 0.02 |
| | 339.34 | 61.63 | 81.84 | 0.14 | 0.19 | 0.03 | ND |
| | 334.95 | 61.03 | 81.78 | 0.24 | 0.09 | ND | 0.01 |
| | 328.04 | 69.18 | 78.91 | 0.12 | 0.10 | ND | ND |
| SC3 | 344.61 | 82.02 | 76.20 | 0.10 | 0.05 | 0.02 | 0.02 |
| | 336.89 | 80.32 | 76.16 | 0.01 | 0.01 | ND | ND |
| | 340.91 | 76.15 | 77.66 | 0.02 | 0.01 | ND | ND |
| | 347.91 | 82.95 | 76.16 | 0.05 | 0.02 | ND | ND |
| SC4 | 418.05 | 92.99 | 77.76 | 0.25 | 0.13 | ND | ND |
| | 436.45 | 100.56 | 76.96 | 0.20 | 0.11 | ND | ND |
| | 362.23 | 91.94 | 74.62 | 0.17 | 0.09 | ND | ND |
| | 394.25 | 84.01 | 78.69 | 0.10 | 0.05 | ND | ND |
| SC5 | 374.24 | 110.32 | 70.52 | 0.20 | 0.09 | ND | ND |
| | 354.80 | 121.15 | 65.85 | 0.29 | 0.17 | ND | ND |
| | 348.51 | 141.59 | 59.37 | 0.23 | 0.11 | ND | ND |
| | 383.19 | 148.33 | 61.29 | 0.16 | 0.06 | ND | ND |
| SC6 | 384.77 | 105.89 | 72.48 | 0.23 | 0.10 | ND | ND |
| | 376.57 | 115.32 | 69.38 | 0.33 | 0.12 | ND | ND |
| | 327.08 | 125.28 | 61.70 | 0.29 | 0.16 | ND | ND |
| | 383.19 | 118.73 | 69.02 | 0.29 | 0.16 | ND | ND |

Tabla A-6 Total phosphorous removal

| Conditions | TP (mg/l) | | |
|---|---|---|---|
| | Inf. | Eff. | %Removal |
| SC1 | 17.86 | 8.97 | 49.76 |
| | 8.91 | 5.26 | 40.94 |
| | 17.30 | 9.85 | 43.05 |
| | 19.79 | 9.17 | 53.67 |
| SC2 | 17.78 | 7.48 | 57.94 |
| | 13.51 | 7.19 | 46.80 |
| | 17.83 | 9.61 | 46.12 |
| | 17.75 | 11.25 | 36.64 |
| SC3 | 9.62 | 5.34 | 44.49 |
| | 11.74 | 5.32 | 54.68 |
| | 8.71 | 5.07 | 41.81 |
| | 16.96 | 7.23 | 57.35 |
| SC4 | 9.58 | 5.24 | 45.30 |
| | 8.14 | 4.18 | 48.65 |
| | 9.50 | 5.84 | 38.50 |
| | 9.75 | 5.44 | 44.19 |
| SC5 | 10.64 | 5.67 | 46.76 |
| | 10.59 | 5.65 | 46.65 |
| | 8.68 | 4.66 | 46.31 |
| | 9.61 | 4.84 | 49.60 |
| SC6 | 18.00 | 11.75 | 34.75 |
| | 21.16 | 14.72 | 30.42 |
| | 20.00 | 13.66 | 31.69 |
| | 21.95 | 12.08 | 44.96 |

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