Innovative Zero-Waste System for Building Wastewater Recycling and Food Waste Management

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A Dissertation Submitted in Partial Fulfillment of the Requirements
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นวัตกรรมระบบซีโรเวสต์สำหรับการรีไซเคิลน้ำเสียร่วมกับการจัดการเศษอาหารในอาคาร

น.ส.ธรรมนัญญา ศักดิ์เจริญ

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรดุษฎีบัณฑิต
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ธรรมนัญญา ศักดิ์เจริญ : นวัตกรรมระบบซีโรเวสต์สำหรับการรีไซเคิลน้ำเสียร่วมกับการจัดการเศษอาหารในอาคาร. (Innovative Zero-Waste System for Building Wastewater Recycling and Food Waste Management) อ.ที่ปรึกษาหลัก : รศ. ดร.ชวลิต รัตนธรรมสกุล, อ.ที่ปรึกษาร่วม : ศ.กิตติคุณ ดร.อัจฉรา จันทร์ฉาย

การขยายตัวของเมืองนำไปสู่ความกังวลถึงผลกระทบสิ่งแวดล้อมที่เพิ่มขึ้นจากปริมาณขยะอาหารและน้ำเสียจากกิจกรรมต่างๆ แนวคิดซีโรเวสต์โดยมีพื้นฐานว่าของเสียมีมูลค่าและสามารถนำกลับมาใช้ประโยชน์จึงได้กำลังเป็นที่สนใจและถูกคาดหวังว่าจะเป็นทางเลือกเพื่อพัฒนาไปสู่เมืองที่ยั่งยืน การศึกษานี้ได้พัฒนานวัตกรรมระบบซีโรเวสต์สำหรับการจัดการน้ำเสียและเศษอาหารในอาคาร โดยการบูรณาการระหว่างบ่อหมักแบบไม่ใช้ออกซิเจนขั้นตอนเดียว และ Moving Bed Biofilm Reaction-Membrane Bioreactor (MBBR-MBR) การศึกษาเป็นการวิเคราะห์เชิงลึกเพื่อพัฒนานวัตกรรมระบบซีโรเวสต์ ประกอบด้วย (1) สำรวจและสัมภาษณ์กลุ่มตลาดเป้าหมาย (มหาวิทยาลัย) เพื่อประเมินถึงปัจจัยที่ส่งผลต่อความสนใจในการนำระบบซีโรเวสต์ไปใช้งาน (2) พัฒนาต้นแบบนวัตกรรมระบบซีโรเวสต์และเดินระบบเพื่อวัดประสิทธิภาพ (3) ประเมินประสิทธิภาพระบบซีโรเวสต์โดยใช้หลักการประเมินพลังงานและก๊าซเรือนกระจกตลอดวัฏจักรชีวิต และ (4) วิเคราะห์โมเดลธุรกิจและแนวทางการทำการค้าของระบบซีโรเวสต์ที่ถูกพัฒนาขึ้น ผลการศึกษาชี้ให้เห็นว่าระบบซีโรเวสต์มีประสิทธิภาพในการผลิตก๊าซชีวภาพที่สูงขึ้นจากหมักร่วมขยะอาหาร ผักผลไม้ และตะกอนจากระบบบำบัดน้ำเสีย ขณะที่น้ำเสียที่ผ่านระบบบำบัดยังผ่านเกณฑ์คุณภาพ US-EPA ในการนำน้ำกลับมาใช้งาน ระบบมีประสิทธิภาพด้านคาร์บอนเครดิตและลดการใช้พลังงานฟอสซิล และมีความคุ้มค่าทางเศรษฐศาสตร์ ระบบซีโรเวสต์จึงเป็นหนึ่งในทางเลือกของการจัดการของเสียสำหรับอาคาร การศึกษาได้วิเคราะห์และนำเสนอคุณค่า ความได้เปรียบทางการแข่งขัน โอกาสทางการตลาด รวมถึงจัดทำแผนการนำนวัตกรรมระบบซีโรเวสต์ที่พัฒนาขึ้นไปสู่ธุรกิจและสังคม

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Urbanization leads to concerns about environmental impacts due to the increasing food waste and wastewater generation. The study aims to develop an innovative zero-waste system for food waste and wastewater management in the building using the combination of a single-stage anaerobic digester and the Moving Bed Biofilm Reaction-Membrane Bioreactor (MBBR-MBR). The comprehensive analysis for innovative zero-waste system development is conducted including (1) survey and interview the target market group (universities) to determine the factors affecting the intention to use the zero-waste system; (2) develop a zero-waste system prototype, and test operation for measuring the performances; (3) evaluate the system performance using life-cycle energy and GHG emissions; and (4) analysis of commercialization plan. The results show that the system's biogas production efficiency increase for co-digestion of food waste, vegetable waste, and wastewater sludge. The treated wastewater has passed the US-EPA reclaimed water quality standard. The system brings about carbon credits, fossil energy reduction, and economic performance. The zero-waste system can be a promising alternative for waste management. The value proposition, competitive advantage, market opportunity, and commercialization plan are analyzed to bring the innovative zero-waste system into business and society.

Field of Study: Technopreneurship and Innovation Management		Student's Signature ....
Academic Year: 2020		Advisor's Signature ....
		Co-advisor's Signature ....

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Dedication

In the loving memory of my grandmother, Lamied Kaewkrajang

Thammanaya Sakcharoen

TABLE OF CONTENTS

Page

LIST OF TABLES

Page

LIST OF FIGURES

Page

CHAPTER 1
INTRODUCTION

1.1 Rational

Urbanization leads to increased concerns about environmental impacts caused by resource use and wastes generation. Food waste and wastewater are recognized as municipal wastes, which are generally created from human activities inside the living and working places such as the building. The growing economic development, population, and urbanization can be seen by the increasing numbers of buildings, which in turn the buildings' waste needs to be sustainably managed. Especially, the amount of food waste is increasing, dumping food waste without proper management can cause several drawbacks, e.g. natural degradation causing odors, germs, and the nuisance to people living nearby. The landfill will require much space, causing contamination of leachate into the groundwater source and may be resisted by people in that area. Managing solid waste by using a kiln will incur high costs from both the construction costs and maintenance costs. Besides, it also causes air pollution according to incomplete combustion. Furthermore, building's wastewater produced by residents' daily activities generally contains the organic matters and potentially deteriorates the natural water body if it is not treated correctly before discharge.

The zero-waste concept is gaining interest as a promising option for the sustainable development of society. Zero-waste management is a concept with the principle that “waste has an economic value, and it can be recycled” (Romano, Rapposelli, & Marrucci, 2019). The target of zero-waste management is that waste should be minimized as much as possible by using existing management technologies or effective technologies (Song, Li, & Zeng, 2015). Techniques for food waste and wastewater management and recycling are essential to fulfilling zero waste management of buildings. This is especially for the bioenergy production expected by the government to help improve the country's environmental and socio-economic impacts (Silalertruksa & Gheewala, 2011).

University is one of the communities that consists of the numbers of people, activities, as well as buildings inside the boundary. Therefore, the university becomes a major source of food waste and wastewater, which if those wastes were not properly managed, it would impact the environment. Anaerobic digestion of organic is one technique that is gaining attraction as the measure to reduce and manage organic waste by converting organic waste into renewable energy, i.e., biogas (Digman & Kim, 2008). Several previous studies have investigated using anaerobic co-digestion technology to produce biogas from food waste and sludge (Ratanatamskul, Onnum, & Yamamoto, 2014; Ratanatamskul, Wattanayommanaporn, & Yamamoto, 2015); (Ratanatamskul & Manpetch, 2016); (Wang et al., 2014); (Islas-Espinoza, De las Heras, Vázquez-Chagoyán, & Salem, 2017)). Nevertheless, it was found that the anaerobic process to produce biogas by bacteria will occur during pH 6 to 8. The food wastes containing a high amount of fruits and vegetables will potentially cause the digester's acidity, which will affect the reduction of bacteria in the digester and further will fail the anaerobic process. Hence, the fruits & vegetable wastes need to be fed at a proper ratio when using the digester unit.

For domestic wastewater treatment and recycling, traditionally, there are various types of wastewater treatment system used in building e.g. aerobic processes such as activated sludge, anaerobic processes such as septic tank and anaerobic filter (AF), and combination process as septic tank + AF + aeration tank + disinfection or septic tank + AF + disinfection. However, those conventional systems still have limitations e.g. the large space and long residence time are required. The final effluent's quality depends on the hydrodynamic conditions in the sedimentation tank, which is difficult to control. This leads to the requirement of further treatment such as filtration, carbon adsorption for wastewater reuse. Moving Bed Biofilm Reaction-Membrane Bioreactor (MBBR-MBR) is one of the technologies that can be used to treat and recycle wastewater of buildings (Zinatizadeh & Ghaytooli, 2015). There are several benefits of MBBR-MBR as the wastewater treatment system, i.e.

saving areas for reusing water, and it is suitable for the building (Bering et al., 2018). Nevertheless, the study still lacks the survey of using membrane bioreactor technologies to treat and recycle wastewater from both the building's domestic wastewater and the leachate of the anaerobic digester from the food waste treatment system of the building.

The study aims to develop an innovative zero-waste system for building's wastewater recycling and food waste management using the combination system of MBBR-MBR and the single-stage anaerobic digester. The proposed innovative system consists of wastewater recycling and the Chulachakrabonse building's biogas production, Chulalongkorn University. With this system, the fruit and vegetable wastes grinding machine will be proposed to prepare the fruit and vegetable waste with a proper ratio for feeding into a single-stage anaerobic digester for biogas production. For this research, the a membrane bioreactor system in conjunction with the moving bed biofilm reaction (MBBR) process is proposed because it is a space-saving system and can produce good quality effluent and reuse water in the building. The MBBR-MBR will be used to treat and recycle the combined wastewater from the building and the digester unit of the Chulachakrabonse building.

1.2 Objectives

(1) To study the factors affecting the decision to use the zero-waste system for wastewater and food waste management in public universities
(2) To develop an innovative zero-waste system for food waste and wastewater management using a single-stage anaerobic digester equipped with the fruit and vegetable wastes grinding machine and the MBBR-MBR for wastewater recycling
(3) To apply the Life Cycle Assessment (LCA) for assessing life cycle GHG emissions and carbon credits of the zero-waste system proposed
(4) To propose the commercialization model for the zero-waste system

1.3 Scope of work

The zero-waste system developed in the project consists of (1) a system that the food waste shredder and a single-stage anaerobic digester are integrated for fruit and vegetable waste management and (2) an MBBR-MBR for recycling the building's wastewater. A single-stage anaerobic digester system with the grinded fruit and vegetable then fermented along with the building's wastewater by using Moving Bed Biofilm Reaction-Membrane Bioreactor (MBBR-MBR) treatment to reuse water (**Figure 1**).

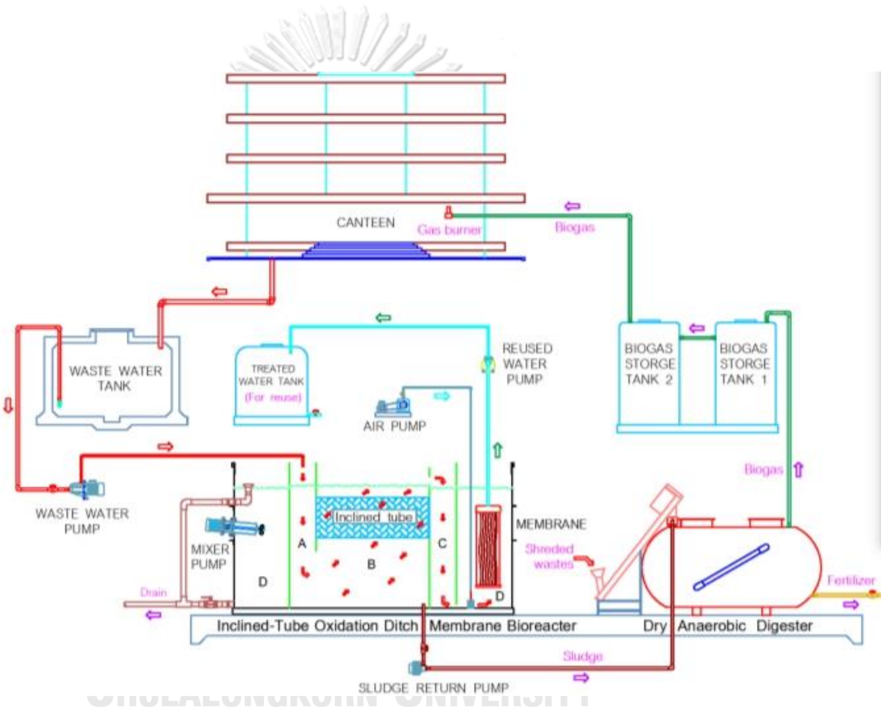


Figure 1 The innovative zero-waste system of a single-stage anaerobic digester combined with MBBR Membrane Bioreactor

1.4 Expected Benefits

The expected outputs from the research classifying by the CUTIP criteria. Descriptions of the outputs and their benefits are shown in Table 1.

Table 1 Expected outputs

	Expected outputs
Technology	• The integrated system of food waste management via grinding machine and anaerobic digestion system and wastewater management via MBBR-MBR
Innovation	• The zero-waste system for wastewater recycling and food waste management in building
Management	• Life cycle assessment of the zero-waste system to support decision making on environmental sustainability of the zero-waste system • Conceptual model to analyze the factors for interest/acceptance of the zero-waste system for food waste and wastewater management • Commercialization model for the zero-waste system

CHAPTER 2
LITERATURE REVIEW

The increased concerns on the eco-friendly society nowadays result in the demands for the technology and innovation that can sustainably manage those two waste streams. Wastes recycling and resource efficiency, therefore, become increasingly important. A building generally has a complex community inside because many people and diverse activities are incorporated in the same coverage area. Food waste and wastewater are known as the two waste streams produced in large quantities especially from the buildings which can affect the environment.

2.1 Wastewater from buildings

Wastewater from the building is classified as "domestic wastewater" which is produced from the human activities inside, e.g. toilets, kitchen, sinks, and laundry. Some buildings might have their specific activities and have unique characteristics of wastewater.

2.1.1 Amount of wastewater

Table 2 shows the amount of wastewater classified by the type of buildings. In 2017, the wastewater per person-day in the Central, North, Northeast, and South of Thailand was about 189-482, 316, 318-322, and 275 L/person-day, respectively (PCD, 2019). However, the Pollution Control Department (PCD) of Thailand has also set a proxy estimation of the amount of wastewater from households and building, assuming it would be around 80% of the water use.

Table 2 Amount of wastewater classified by types of building

Types of buildings	Unit	L/day-unit
Condominium/households	Unit	500
Hotel	Room	1000
Dormitory	Room	80
Services	Room	400
Housing estate	Person	180

Types of buildings	Unit	L/day-unit
Hospital	Bed	800
Restaurant	m^2	25
Market	m^2	70
Department Store	m^2	5.0
Office	m^2	3.0

Source: PCD (2019)

2.1.2 Characteristics of wastewater

Domestic wastewater, physically, contains solid content around 0.1%. The solid material is a mixture of feces, food particles, toilet paper, grease, oil, soap, salts, metals, detergents, sand, and grit. The wastewater, chemically, is composed of organic (70%) and inorganic (30%) compounds as well as various gases. Biologically, it contains various microorganisms, e.g., bacteria, fungi, protozoa, algae, plants, and animals. Tables 3 and 4 show the characteristics of wastewater classified by types of buildings including the data from Chulachakrabonse building of Chulalongkorn University.

Table 3 Characteristics of wastewater classified by types of buildings

Parameters	Dormitory		Restaurant	Fresh market	Office		Shopping center	Condo-minium
	Toilet	Other			Toilet	Other		
pH	8.55	7.78	6.54 - 6.74	6.67	8.10	7.4	7.51	7.20
COD(mg/L)	1,290	135	1,785 - 3,164	2,528	392	96	253	221
BOD(mg/L)	723	75	919 - 1,759	1,172	181	41	81	151
TKN(mg/L)	329	19.2	55.1 - 63.2	76.5	44.1	9.7	66.8	33.7
PO_4 (mg/L)	6.8	3.9	2.6 - 3.2	5.1	2.0	0.4	10.1	2.0
SS (mg/L)	666	29	401 - 913	662	158	26	61	63
FOG(mg/L)	377	411	1,136 - 1,570	897	455	527	577	473

Source: PCD (2019)

Table 4 Characteristics of wastewater of the office building

Parameters	Office building[1/]				Chulachakrabonse building, CU[2/]
	Max.	Min.	Average	SD	Range
Temperature (°C)	29.60	28.00	29.02	0.50	
pH	7.61	6.79	7.23	0.19	7.0 - 7.8
ORP (mV)	-8.00	-155.00	-87.87	34.31	
SS (mg/L)	96.00	44.00	67.54	14.84	
COD (mg/L)	233.12	150.40	190.02	26.96	120 – 300
TKN (mg/L)	72.24	46.32	56.21	6.76	35 – 120
TP (mg/L)	5.99	4.04	5.09	0.51	3.8 – 10.0

Source: 1/Bouted and Ratanatamskul (2019); 2/Ratanatamskul and Kongwong (2017)

The wastewater reuse for building such as toilet-flushing and garden watering is gaining attraction nowadays due to a large amount of water demand for many buildings. However, the treated wastewater before reuse must comply with the reuse water quality criteria that are set for different purposes of water reuse. Table 5 shows the quality requirements for water reuse for different purposes. For example, the reuse water quality criteria for toilet flushing and garden water are set to the parameters such as pH, suspended solids, odor, appearance and E. Coli.

Table 5 Guidelines for water reuse

Reuse category/ Description	**Treatment**	**Reclaimed Water Quality**
Urban Reuse		
<u>Unrestricted</u> Use for nonpotable applications in municipal settings where public access is not restricted.	Secondary Filtration Disinfection	pH = 6.0-9.0; ≤ 10 mg/l BOD ≤ 2 NTU; No detectable fecal coliform /100 ml 1 mg/l Cl_2 residual (min.)

Reuse category/ Description	Treatment	Reclaimed Water Quality
Restricted		
Use for nonpotable applications in municipal settings where public access is controlled or restricted by physical or institutional barriers, such as fencing, advisory signage, or temporal access restriction	Secondary Disinfection	pH = 6.0-9.0; ≤ 30 mg/l BOD ≤ 30 mg/l TSS ≤ 200 fecal coliform /100 ml 1 mg/l Cl_2 residual (min.)
Agricultural Reuse		
Food crops		
Use for surface or spray irrigation of food crops which are intended for human consumption, consumed.	Secondary Filtration Disinfection	pH = 6.0-9.0; ≤ 10 mg/l BOD ≤ 2 NTU; No detectable fecal coliform/100 ml 1 mg/l Cl2 residual (min.)
Processed food crops		
Use for surface irrigation of food crops which are intended for human consumption, commercially processed.	Secondary Disinfection	pH = 6.0-9.0; ≤ 30 mg/l BOD ≤ 30 mg/l TSS ≤ 200 fecal coli/100 ml 1 mg/l Cl_2 residual (min.)
Non-food crops Use for irrigation of crops which are not consumed by humans, including fodder, fiber, and seed crops, or to irrigate pasture land, nurseries, and sod farms.		
Industrial Reuse		
Once-through cooling	Secondary	pH = 6.0-9.0; ≤ 30 mg/l BOD

Reuse category/ Description	Treatment	Reclaimed Water Quality
		≤ 30 mg/l TSS
		≤ 200 fecal coliform/100 ml
		1 mg/l Cl_2 residual (min.)
Recirculating cooling tower	Secondary	Variable, depends on
	Recirculating	recirculation ratio;
	Cooling	pH = 6.0-9.0;
	Towers	≤ 30 mg/l BOD
	Disinfection	≤ 30 mg/l TSS
		≤ 200 fecal coliform/100 ml
		1 mg/l Cl_2 residual (min.)

Source: US-EPA (2012)

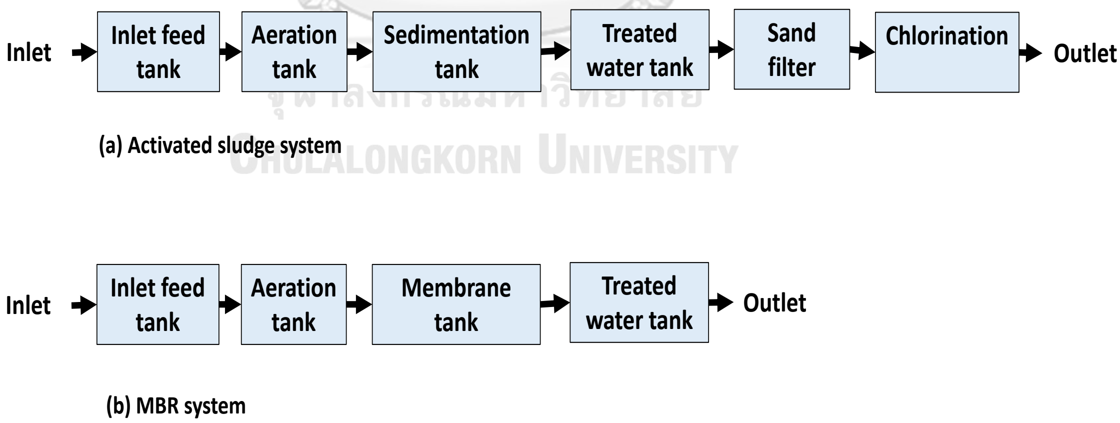
2.1.3 Membrane bioreactor for wastewater treatment

Recycling wastewater nowadays becomes one of the promising options for enhancing water resource efficiency. By working procedure, the wastewater treatment of building can be classified into three stages i.e. (1) primary treatment, secondary treatment and disinfection. There are various types of conventional wastewater treatment system used in building e.g. (1) aerobic process such as activated sludge; (2) anaerobic process such as septic tank and anaerobic filter (AF); and (3) combination process such as septic tank + AF + aeration tank + disinfection or septic tank + AF + disinfection. However, the quality of the final effluent from the conventional biological treatment system highly relies on the hydrodynamic conditions in the sedimentation tank and the sludge's settling characteristics, which it is difficult to control. Large volume sedimentation tanks to offer several hours of residence time is required to obtain adequate solid/liquid separation.

Over the past decades, the technology so-called membrane bioreactor (MBR) is gaining attraction as the technology that is ideal for a wide range of municipal and industrial wastewater treatment applications, including water reuse. MBR provides biological treatment with membrane separation. MBR offers several advantages over the conventional process such as the activated sludge process (ASP), i.e. (Iorhemen, Hamza, & Tay, 2016); (Visvanathan, Aim, & Parameshwaran, 2000); (Nilthong, 2002):

- A compact wastewater treatment process combining a single sludge aerobic biological treatment process with an integrated, immersed membrane for liquid-solid separation
- Excellent quality of effluent that can be reused for either industrial processes or secondary household process
- Reduction of sludge production for better process reliability
- Higher volumetric loading rates, shorter hydraulic retention time (HRT)
- Longer solid retention time (SRT), less sludge production, and
- Potential for simultaneous nitrification/denitrification in long SRTs

Figure 2 shows the general process of the conventional wastewater treatment (activated sludge) and MBR system. Nevertheless, the use of MBR technology has disadvantages, including higher energy costs, the need to control membrane fouling problems, and potentially high costs of periodic membrane replacement (Iorhemen et al., 2016).



Source: (Iorhemen et al., 2016)

Figure 2 Comparison of activated sludge system and MRB system

2.1.3.1 Principle and types of MBR

Bioreactors are reactors that convert or produce materials using functions naturally endowed to living creatures. Membrane Bioreactor (MBR) systems essentially consist of a combination of membrane and biological reactor systems. An MBR, therefore, can displace the two physical separation processes by filtering the biomass through a membrane. As a result, the product water quality is significantly higher than that generated by conventional treatment, obviating the need for a further tertiary disinfection process. It can produce high-quality effluent with up to 98% BOD removal, complete denitrification and partial denitrification. Treated effluent has low turbidity values (<0.3 NTU) and SDI values (<3.0) and water can be reused for landscaping, flushing or feed to NF or RO Systems for complete water purification (Visvanathan et al., 2000). There are different types of MBRs developed for wastewater treatment and recycling. Examples are as follows:

2.1.3.2 MBR

The conventional membrane bioreactor (MBR) is a novel wastewater treatment technology, especially improving biological treatment efficiency. An MBR system has a high concentration of bacteria (held within the membrane) that is 4-5 times higher than MBBR systems. Depending on the size of the membrane's pore diameter, even germs can be separated from the water. Negative pressure is required to support the wastewater flow through the membrane, which is an energy-intensive process and can be expensive. Furthermore, it is necessary to backwash the membrane in set intervals, and the membrane needs to be replaced occasionally. This system requires regular professional maintenance and servicing.

2.1.3.3 MBBR

Moving bed biofilm reactor (MBBR) is a biofilm wastewater treatment technology developed based on a combination of biological contact oxidation and biological fluidized bed (Di Trapani, Di Bella, Mannina, Torregrossa, & Viviani, 2014). MBBR plants contain particles (e.g. produced from UV-stabilised polyethylene), on which bacteria grow, developing a biofilm on the free moving particles, which reduce the impurities and, therefore, the sludge mass (but not as effective as an MBR plant).

Besides biofilm systems, the carriers also apply to integrated fixed-film activated sludge (IFAS) technologies. The main difference between MBBR and IFAS is that the active biomass is mainly supported on the carriers in the MBBR, but part of the IFAS biomass is suspended and partly supported. The MBBR plant requires 30-40% less space than the traditional wastewater treatment systems, e.g. activated sludge. This means that adoption of MBBR will have less site activity, quick installation and commissioning, ease in transportation and relocation, easy maintenance and minimal upkeep cost and civil work.

2.1.3.4 Biofilm MBR

Biofilm MBR is the combination of biofilm and MBR. The biofilm system will reduce the concentration of suspended biomass to reduce the membrane fouling while improving the process's efficiency (Khan, Ilyas, Javid, Visvanathan, & Jegatheesan, 2011). There are two ways of working for Biofilm–MBR system, which defined as follows (Duan et al., 2015):

(1) Biofilm membrane bioreactor (BF-MBR), i.e. no recycling from the MBR to MBBR in a BF-MBR because the suspended carriers are directly added into MBR.

(2) Integrated fixed-film activated sludge system (IFAS–MBR), i.e. the activated sludge is recycled between MBBR and MBR. The MBBR unit contains carriers, and the MBR unit includes a submerged membrane unit.

A study on comparison of the bioreactor performance and membrane fouling between integrated fixed-film activated sludge membrane bioreactor (IFAS–MBR), and MBR for municipal wastewater with continuous operation revealed that both systems had the same high removal efficiency of ammonium, while the IFAS–MBR showed a higher ability to remove COD. The transmembrane pressure in the MBR was higher than that in the IFAS–MBR during the entire operation due to a higher total modified fouling index of the mixed liquor and the resultant higher membrane fouling potential. The IFAS–MBR showed a lower membrane fouling tendency during the whole operation (Duan et al., 2015).

Table 6 Performance comparisons of the conventional wastewater treatment system (Activated sludge) with the MBR, MBBR and MBBR-MBR

	Activated Sludge	**MBR**	**MBBR**	**MBBR-MBR (Expected)**
Effluent water quality	Moderate quality for reuse	Superior	Acceptable for irrigation	Superior
Overall costs	Medium	High	Medium	Medium
Energy consumption	Medium	High	Medium	Medium
Handling of the system	System relies on the settling characteristics of sludge which it is difficult to control	Reduction of sludge production for better process reliability	Reduction of sludge production for better process reliability	Reduction of sludge production for better process reliability; Reduce concentration of biomass to prevent membrane fouling
Handling of an electrical shutdown	Up to 24 hours	Up to 24 hours without problems	Up to 10 hours. Afterward, bacteria will form cake	Up to 10 hours
Grease leak	Moderate sensitive	Sensitive	Sensitive	Sensitive
Required space	High	Low	Low	Low

Source: modified from https://clearfox.com/comparison-mbr-mbbr-fbbr/

2.2 Food waste from building

Canteen is a major source of food waste of buildings. Food waste refers to food appropriate for human consumption discarded, whether after it is kept beyond its expiry date or left to spoil. Food waste is, nowadays, a global issue. The UN Food and Agriculture Organisation (FAO) estimated that approximately 1.3 billion tonnes of food is wasted each year, amounting to one-third of all food produced globally for human consumption (FAO, 2011). The US Environmental Protection Agency (EPA), food waste represents the single most extensive type of waste is entering landfills (Morone, Koutinas, Gathergood, Arshadi, & Matharu, 2019). As well as Thailand, in 2017, the amount of municipal solid waste (MSW) generated in Thailand was around 27 Mt or approximately 73,973 t/day (PCD, 2018). Food waste is the most massive waste stream accounting for 39.25% of total MSW (Ratanatamskul et al., 2014). Specifically for Chulalongkorn University, the average food waste composition was found to be 18% (during the semester starts) and 33% (during the semester ends) of the total waste (from plastic, paper, and food) as shown in Table 7.

Table 7 The types and ratio of waste at Chulalongkorn University

Period	Plastic waste	Paper waste	Food waste
Semester starts	35%	30%	18%
Semester ends	23%	20%	33%

Source: Zero-Waste (2018)

2.2.1 Amount of food waste, fruits, and vegetable wastes

The food waste production per capita in canteens varies from 0.06 to 0.3 kg/d/person (Liwei et al., 2013) and 0.15 kg/d/person (De Clercq, Wen, Fan, & Caicedo, 2016). However, a study of (Huiru, Yunjun, Liberti, Pietro, & Fantozzi, 2019) has used the figure about 0.17 kg/d/person or 51 kg/year/person as the reference value to assess the technical and economic feasibility analysis of an anaerobic digestion plant fed with canteen food waste of the Huazhong University of Science and Technology (HUST), Wuhan of China (Huiru et al., 2019). More specifically, for Chulalongkorn University, (Ratanatamskul et al., 2014) reported that the average food waste generated from a canteen in Chulachakrabonse Building, Chulalongkorn University was found to be 80 kg per day, which was composed of residues, grain, fruits, vegetables, starch, and grease. Waste composition from canteens includes 64% of vegetable and food waste, 28% of plastic bags, wood, foam, glass, and others, 6% of recycling plastic and 2% of paper (Zero-Waste, 2018).

Fruit and vegetable wastes are accounted for a large portion of the food waste. For example, in the year 2011, there were around 449,315 t/day of MWS collected in China, in which the organic ingredients including fruit/vegetable waste (FVW) and kitchen waste (KW) accounted for 50–60% (Wang et al., 2014). The amount of fruits and vegetable waste (FVW) is expected to increase continuously due to the global trends of healthy food. Fruit and vegetable wastes (FVWs) are a very important class of residues because they are produced in very large amounts in all the wholesale markets and other activities in the world and their landfill disposal is quite difficult due to their very high perishability (Scano et al., 2014). FVWs can generate high environmental complications even for short-term disposal because it is quickly degraded by contaminating microorganisms. For the food producing country like Thailand, FVWs management is, therefore, a challenge for the country.

2.2.2 Characteristic of food, fruit and vegetable wastes

Several factors especially the dietary behaviors, can vary characteristics of food waste in each place. Table 8 shows the reviewed food waste characteristics used in the AD system from different studies.

Table 8 Characteristics of food waste (FW) in previous studies

Parameters	Food waste (Ratanatamskul et al., 2014)	Canteen food waste (Huiru et al., 2019)	Fruit & vegetable waste (Pavi, Kramer, Gomes, & Miranda, 2017)
TS	80,676 mg/L	31.0% ±0.1	19.54%
SS	72,410 mg/L		
TVS	78,823 mg/L	27.5% ±0.2	18.80%
COD	232,795 mg/L	496 g/L±11	

Parameters	Food waste (Ratanatamskul et al., 2014)	Canteen food waste (Huiru et al., 2019)	Fruit & vegetable waste (Pavi, Kramer, Gomes, & Miranda, 2017)
VFA	2957.8 mg/L		216 mg/L acetic acid eq.
pH	4.7	3.92 ±0.1	4.66
TP	926 mg/L	1065 mgP/L ±0.3	0.18%TS
TKN	6275 mg/L	21,072 mgN/L ±1.2	904.78 mg/L
ISS		35,431 mg ISS/L±0.9	
Ca		< 1 mg/L	
Mg		< 1 mg/L	
Alkalinity		n.a.	140 mg/L HCO_3^-
Moisture			80.46%
TOC			180.32 mg/gTS
NH_4-N			7.36 mg/L

2.2.3 Anaerobic digestion for biogas production

Anaerobic digestion (AD) is the natural process that breaks down organic matter in the absence of oxygen to release a gas known as biogas, leaving an organic residue called digestate. Biogas is a mixture of methane, carbon dioxide, trace gases, and water and can be used to produce electricity and heat or used as a natural gas substitute. Digestate is a nutrient-rich by-product of AD and can be used as a fertilizer and soil improver. AD is gaining interest as a promising way for organic waste management and energy recovery in the form of methane (biogas). Several benefits of AD for organic waste treatment include reduce greenhouse gas emissions, produce biogas, treat food waste appropriately and reduce the reliance on landfills (Li, Loh, Zhang, Tong, & Dai, 2018); (Mezzullo, McManus, & Hammond, 2013). In general, there are three types of an anaerobic digester, i.e. one-stage, two-stage and batch digester systems.

2.2.3.1 The single-stage anaerobic digester system

The waste will be fed via plug flow inside the reactors. The methanization of organic wastes will be accomplished by a series of biochemical transformation with the following steps, i.e. (1) Hydrolysis, acidification, and liquefaction take place; (2) Acetate, hydrogen and carbon dioxide are transformed into methane. For a single-stage anaerobic digester system, all those reactions will simultaneously take place in a single reactor. The advantages of single-stage systems are as follows: smaller reactor, less investment; complete hygiene; plug flow movement help to prevent shock load failure due to a slow movement which can divide zone of bacteria reaction. However, the disadvantages are the loss of bacteria when release sludge can lead to the loss of methane production efficiency, and the pre-treatment is required before feeding waste into the reactor.

2.2.3.2 Two-stage anaerobic digestion system

With this digester system, anaerobic degradation process will be separated into two phases. The first phase is the acid fermentation phase where liquefaction-acidification reactions occur lead to the production of the intermediate products predominated by the volatile organic acid. The second phase is the methane fermentation phase which the intermediates substances will be converted to methane. The separation of reactor like two-stage digester is useful because each phase that might suit the different bacterial varieties will be separated for the suitable conditions to get the better biogas yield. The advantages of two-stage systems are the greater biological reliability for waste; the optimum condition for each bacteria can be obtained, decreasing methanogen loss as the acidogenic has a faster growth rate. However, the disadvantages are such as the complex design, larger investment and larger space are required.

2.2.3.3 Factors affecting the AD process

(1) Temperature

Anaerobic digestion can be developed for different temperature ranges including Psychrophilic, Mesophilic, and Thermophilic. Table 9 shows the optimum temperature for bacterial growth. Methanogen is sensitive to environmental changes. The changing of temperature may lead to occur slower reaction rates, lower gas production, and lower rates of destruction of pathogens. Operating temperature has limitations from different weather. In cold area may need to control the temperature with heater. However, the weather in Thailand, which is hot and humid with the temperature around 20-35^{o}C is very suitable for Mesophilic operation without adding any heat.

Table 9 Temperature ranges for bacterial growth

Type	Temperature (^{o}C)	Optimum temperature (^{o}C)
Psychrophilic	10-30	12-18
Mesophilic	20-50	25-40
Thermophilic	35-75	55-65

Source: Manpetch (2014)

(2) pH

pH is important because methanogenic bacteria are very sensitive to acidic conditions. Their growth and methane production is inhibited in an acidic environment. It has been proven that the optimal range of pH for obtaining maximum biogas yield in anaerobic digestion is 6.5-7.5, the range is relatively wide in the plants, and the optimal value of pH varies with substrate and digestion technique

(3) Alkalinity

The buffering capacity of an anaerobic digester is determined by the amount of alkalinity present in the system. Enough buffering capacity means that the system can withstand moderate shock loads of volatile fatty acids. Bicarbonate ion (HCO_3^-) is the major source of buffering capacity to control the system's pH of about 6.5 – 7.6. HCO_3^- concentration generally associated with the $\%CO_2$ in gas phase. Generally, it can before the pH drop, the acid/alkalinity ratio will change and this can be used as the indication for the beginning changes of pH. The increasing of acids can further fail the digester operation. Hence, the volatile acid to alkalinity ratio should be kept below 0.4. If the VA/Alkalinity value closes to 0.8, the system can fail immediately due to the weak buffering capacity.

(4) Volatile fatty acid

The concentration of all VFA increased during the digestive process, the rise in acetate concentration, and the decreased pH. The acetate concentration and the propionate to acetate ration (P/A ratio) can be seen from the ratio as valuable indicators to predict process failure.

(5) Toxic

A variety of substances can be inhibitory to the anaerobic digestion processes which in turn can cause the problems such as low methane yield and process instability. The common inhibitors present in the anaerobic digester are ammonia, light metal ions, heavy metals, sulfide and organic compounds such as solvents and pesticides in the waste. Uncontrollable of pH within the appropriate range can cause reactor failure even though ammonia is at a safe level. It was recommended that the control of pH within the growth optimum of microorganisms can reduce ammonia toxicity (Manpetch, 2014).

Ammonia is known as one of the intermediate substances originate from hydrolysis and formed during the degradation of nitrogenous organic materials such as proteins and urea. Ammonium ion (NH_4^+) or free ammonia (NH_3) are produced in solution can partly be converted into ammonium bicarbonate (NH_4HCO_3). NH_3 could be found more if pH is higher 7.2. This can cause the inhibition of microorganism activity when the concentration reaches 7,000-9,000 mg/L.

2.2.4 Biogas composition

Most of the biogas composition from the AD system is methane 50-80%. Other composition consists of carbon dioxide (CO_2) hydrogen sulfide (H_2S) nitrogen (N_2) oxygen (O_2) vapor (H_2O) as shown in Table 10.

Table 10 Typical biogas composition

Type	Ratio
Methane (CH_4)	50 - 80% vol.
Carbon dioxide (CO_2)	34 - 50% vol.
Hydrogen sulfide (H_2S)	50 - 5,000 ppm
Ammonia (NH_3)	0 – 300 ppm
Oxygen (O_2)	< 1% vol.
Nitrogen (N_2)	1- 4 % vol.
Vapor	2 – 5 % wt

Source: Manpetch (2014)

2.3 Influences of technological attributes, environmental and consumer behaviors on technology commercialization

Technology commercialization (TC) is the process of moving a technology or innovative concept from laboratory to market acceptance and use (C.-J. Chen, Chang, & Hung, 2011). TC is thus the essential process to structure of technology production, competitive market advantages, opportunities for trade, and growing standards of living to the users. From the innovation-diffusion perspective, the rate of technology diffusion or so called “rate of adoption” of the technology is correlatively associated with the attributes of innovations or technologies of its technology. One of the recognized model to confirm the important of the technology attribute to the acceptance of the innovation is the study on technology acceptance model (Davis, 1989); (Venkatesh & Davis, 1996) which suggested that user’s motivation can be predicted or explained by two factors, i.e. perceived ease of use and perceived usefulness. Those perceived ease of use and perceived usefulness are generally the important factor of the technology attributes. However, the reviewed literature over the past decades have shown the several barriers to commercialization of technology especially for the environmental or green technologies (Fraj-Andrés, Martinez-Salinas, & Matute-Vallejo, 2009); (Balachandra & Nathan, 2010). Several studies therefore suggest the model to understand the market potential for adoption in relationship with the technology attributes.

2.3.1 Technology attributes

Technological attributes are the actual characteristics of a technology that can influence various aspects of adoption (Williams, Suen, Rzasa, Heikkila, & Pennock-Roman, 2003). There were many studies on technology attributes that influence to the adoption decision so far. For example, Tornatzky and Klein (1982) proposed the three attributes that found to be significantly related to adoption i.e. relative advantage, complexity, and compatibility. Rogers (2010) concludes that a technological innovation has at least some degree of benefit or advantage for its potential adopters when the technology is being developed. There are five attributes of technology influence adoption decisions i.e. relative advantage, compatibility, complexity, trial-ability, and observability. Those technological attributes will affect market potential, which will perceive or predict the population of potential adopters due to particular reference to certain technological attributes. Some descriptions about the perceived characteristics of technology (Everett, 1995) are as follows:

- Relative advantage of technology is the degree to which an innovation is seen as better than the idea, program, or product it replaces
- Compatibility of technology is the degree to which a technology is perceived as being consistent with the existing values, past experiences, and needs of potential adopters.
- Complexity of technology is the degree to which a technology is perceived as relatively difficult to understand and use
- Trial-ability of technology is the degree to which the technology can be tested or experimented with before a commitment to adopt is made

- Observability of technology is the degree to which the technology provide tangible results

Hence, innovativeness of technology is one of the key factors that can attract potential adopters or so called "consumers" to use the technology. Although, the characteristics of consumers would be particularly different varied by their knowledge, problem solving skill, creativity, high or low risk acceptance. Hence, the analysis of influences of technological attributes on technology commercialization has been proposed to use it as a step prior to the technology commercialization. Specifically to the innovative waste treatment technologies like the zero-waste system, the technological attributes that generally considered for the consumers in the adoption of a waste treatment system have been surveyed by (IIT, 2010). It is called as the guideline for selecting an appropriate sewage treatment technology. Table 11 showed the consideration factors regarding the sewage technology selection. The study therefore considered those technological factors into account as the technological attributes in the research.

Table 11 Sewage treatment process selection considerations

Consideration factors	Goal
Quality of treated sewage	Production of treated water of stipulated quality without interruption
Power requirement	Reduce energy consumption
Land required	Minimize land requirement
The capital cost of plant	Optimum utilization of capital
Operation & maintenance costs	Lower recurring expenditure
Maintenance requirement	Simple and reliable
Operator attention	Easy to understand procedures
Reliability	Consistent delivery of treated sewage
Resource recovery	Production of quality water and manure
Load fluctuations	With stand variations in organic and hydraulic loads

Source: IIT (2010)

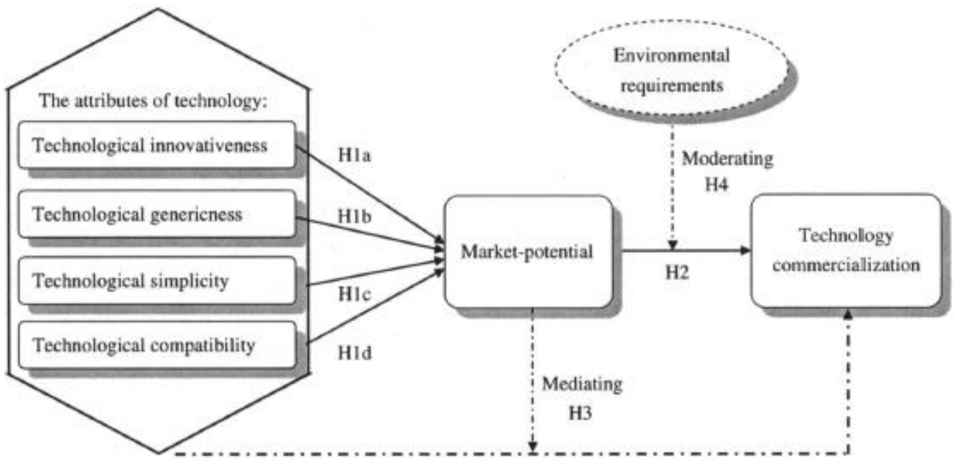
2.3.2 Environmental factors

In the context of global economic structures, the combined pressures of population growth, accelerating energy demand and climate change constraints represent an unprecedented challenge to society and firms. The increasing concerns on environmental problems have led to the trends of global green economy. Carlson and Rafinejad (2008) proposed that the process of TC has to consider environmental factors besides the satisfaction of traditional requirements: efficiency and costs. Many innovative technologies nowadays is therefore developed in order to solve the environmental problem of the existing technologies such as the waste treatment technologies to solve the problem of existing environmental pollution, the renewable energy technologies to solve the problem of fossil resource depletion and climate change due to the fossil fuel combustion. In addition, many countries have set the environmental requirements such as the regulations to cope or to help minimize the use of natural resources, energy consumption, waste generation, health and safety risks, and ecological degradation (Hundal, 2000).

In the past, for consumer perspective, the environmental considerations not only increase initial cost on new product development (NPD) but also decrease the original performance and value which in turn will decrease price competitiveness and market potential. However, nowadays, the rise of environmental concerns worldwide, the environmental technology would not be the cost only but can also be the opportunity to the consumers. There is a trend that societies and firms expect to show an anticipatory attitude by spontaneously adopting "green technologies". The opportunities to the firms or consumers on “green technologies” adoption are not only the technological benefits but also the corporate social responsibility (CSR) benefits to lead the way toward a greener economy.

Over the past decades, the many environmental factors have gained interest in the study of their influences to the decision making of consumers for technology adoption There have the indication of the willingness to pay a higher price for a cleaner technology/product, and simultaneously firms seem to be aware of the growth in green market potential (Arora & Gangopadhyay, 1995). Nevertheless, some studies presented that products which are environmentally compatible have turned out to be energy efficient technologies, but commercialization solely with the advantage of energy efficiency, may not succeed (Awerbuch, 2000). Thus, it appears that environmental factors may have positive impacts for technological market potential as to the likelihood of commercialization.

C.-J. Chen et al. (2011) have integrated the different technological attributes of the developing technology to assess its market potential for adoption as to delineate a technology section criteria applicable in the early stage of technology commercialization (TC). The model to study for understanding how the technological attributes and environmental factors affect the relationships between market potential and TC probability is shown in Figure 3**.** The results conclude that the technology attributes including innovativeness, generalness, compatibility, and simplicity/complexity are important antecedents for technology selection to increase TC probability. In addition, the results also revealed that the environmental requirements have played as the moderating role in the relationship between market potential land technology commercialization. The paper showed that both technology and environmental factors are relevant to the technology commercialization and could be considered in the analysis of the intention of consumers for technology adoption.



Source: C.-J. Chen et al. (2011)

Figure 3 Technological and environmental factors on technology commercialization

2.3.3 Environmentalism and consumer characteristics

There is a number of marketing and psychology studies have investigated that consumer characteristics e.g. the personal innovativeness, the risk taking propensity, have affected to the adoption behavior as an internal motivation stimulus (Everett, 1995); (Webster & Martocchio, 1992); (Agarwal & Prasad, 1998). For example, the higher levels of personal innovativeness help consumers cope better with uncertainty of the new technology and form greater intentions to accept the innovation than consumers with lower levels of innovativeness. For the green technology, the “environmentalism” or environmental concern may influence the attitudes that motivate purchase or adoption (Poortinga, Steg, & Vlek, 2004) although it is not always (Hustvedt, Ahn, & Emmel, 2013).

Ahn, Kang, and Hustvedt (2016) have developed and tested a new model that illustrates the following constructs as the major predictors of the adoption: consumers’ expectancy of technology attributes including performance, effort, compatibleness and hedonic expectancy; as well as specific attitudes and behavioural tendency including social pressure, sustainable innovativeness and environmentalism. The focused is on the sustainable household technology (Figure 4). The results showed that product attributes including performance, compatibleness and hedonic expectancy as well as consumer characteristics, in specific, sustainable innovativeness significantly predicts adoption intent. Conversely, the model testing showed that effort expectancy as well as social pressure and environmentalism are not significant predictors of adoption intention.

The objective of the literature review in this section is to indicate that consumers’ characteristics including environmentalism should be considered as factors that potentially affect to the forming interest in and purchasing the green technology like the “zero-waste system” earlier than other people. Thus, both the technological attributes and consumer characteristics are expected to significantly affect intention to adopt the “innovative zero-waste system” that were developed in the project and both factors would be analyzed in the research.

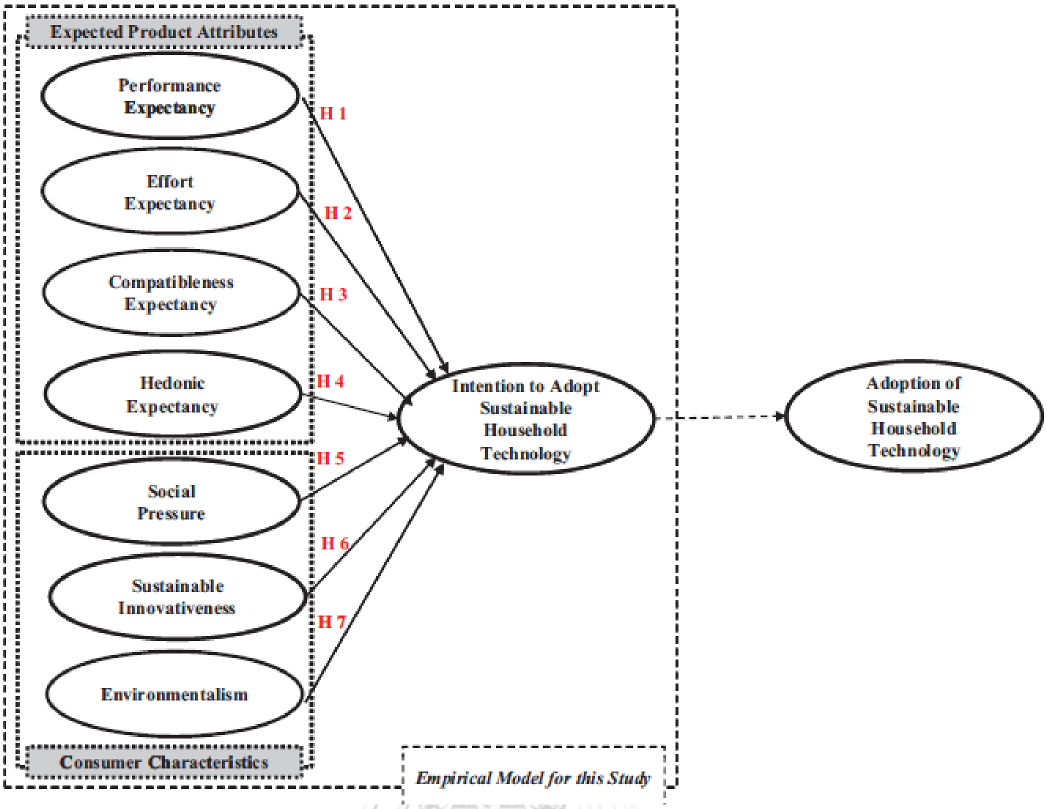


Figure 4 Expected product attributes and consumer characteristics factors on the intention to adopt technology

At present, environmental and waste management issues have become a key concern of the government, the private sector as well as the general public. People nowadays seem to be sensitive to environmental issues and many have a positive attitude toward environmental programs. The attitudes of people is therefore affect to the different participation level and different waste management programs selection by each other. Environmentalism and consumer behavior have influences to the acceptance of the sustainable products.

2.4 Life Cycle Assessment (LCA) of the waste treatment plant

Life cycle assessment (LCA) is a tool for compiling and evaluating the environmental impacts of a product or service system throughout its life cycle. The International Organization for Standardization (ISO) has set the ISO standards on LCA i.e. ISO 14040 and ISO 14044 (2006). It has been applied for assessing the environmental sustainability of waste treatment technology.

For example, Pérez-Camacho, Curry, and Cromie (2018) have used LCA to evaluate life-cycle environmental impacts of substituting traditional anaerobic digestion (AD) feedstocks with food wastes. The results showed that the avoided GHG emissions from substituting traditional AD feedstocks with food waste (avoided GHGeq emissions of 163.33 CO_2-eq). Additionally, the analysis has included environmental benefits of avoided landfilling of food wastes and digestate use as a substitute for synthetic fertilizers. In addition to reducing GHG emissions, the utilization of food waste for AD instead of landfilling can manage the leakage of nutrients to water resources and eliminate eutrophication impacts that occur, typically as the result of field application. (Isola et al., 2018) have also applied LCA for evaluating the environmental performance of the portable two-stage anaerobic digestion of mixed food waste and cardboard.

However, Clavreul, Guyonnet, and Christensen (2012) indicated that the LCA result of waste management is subject to significant uncertainty sources of diverse origins. For instance, the anaerobic digestion could as well be changed to examine the influence of this choice on the results, e.g. ratio of vegetable out of food waste, the water content of waste, methane potential of waste, diesel consumption for collection of organic waste, methane content of biogas in the digester, potential methane yield in the digester and N fertilizer substitution. Slorach, Jeswani, Cuéllar-Franca, and Azapagic (2019) have recently studied anaerobic digestion for recovering energy and fertilizers of household food waste in the UK. The analysis is carried out for two different functional units: (i) treatment of 1 tonne of FW, which is compared to incineration and landfilling; and (ii) generation of 1 MWh of electricity, which is compared to other electricity generation options. The results showed that AD has lower impacts than both incineration and landfilling across 15 of the 19 impacts. However, the application of digestate to land and the release of ammonia and nitrates lead to higher marine eutrophication (ME), terrestrial acidification (TA) and particulate matter formation (PMF). The AD electricity emits 203 kg CO_2-eq./MWh, compared to 357 kg CO_2-eq./MWh for the UK grid mix.

Huiru et al. (2019) have conducted the technical and economic feasibility analysis of an anaerobic digestion plant fed with canteen food waste on the campus of Huazhong University, China. The campus has about 29 canteens and more than 61,700 students. Approximately 3300 tons of food waste are available per year in HUST, transformed into 1136 MWh of electricity by using a biogas plant with an internal combustion engine. The payback period of such a project is 7.8 years, while the equity payback is nine years. However, the development of a Carbon Credit Market can be an essential way to increase economic convenience.

For wastewater recycling of buildings, LCA has also been used of various technologies. Hendrickson et al. (2015) have applied LCA to analyze the energy consumption and greenhouse gas (GHG) emissions of a Living Machine (LM) wetland treatment system to recycle wastewater in an office building compared with the centralized wastewater treatment plant. The comparison revealed that the LM has energy consumption advantages (8% less), and a theoretically improved LM design could have GHG benefits (24% less) over the centralized reuse system. Hasik et al. (2017) have conducted an LCA of the decentralized water system of high performance, net-zero energy, net-zero water building (NZB) and compared the results with two modeled buildings (conventional and water-efficient) using centralized water systems. The results show that, although the NZB performs better in most categories than the traditional building, the water-efficient building generally outperforms the NZB. The lifetime of the NZB, septic tank aeration and use of solar energy are important factors in the NZB's impacts.

However, these findings are specific to the case study building, location, and treatment technologies. Tonini, Martinez-Sanchez, and Astrup (2013) applied the consequential LCA to evaluate a Danish waste refinery solution's environmental performance, comparing different waste technology alternatives, i.e. incineration, mechanical–biological treatment (MBT) and landfill. Overall, the results pointed out that the waste refinery provided global warming (GW) savings comparable with efficient incineration, MBT, and bioreactor landfilling technologies. The main environmental benefits from waste refining were potential for improved phosphorus recovery (about 85%) and increased electricity production (by 15–40% compared with incineration).

In addition, Kalbar, Karmakar, and Asolekar (2012) has developed a framework for technology assessment for wastewater treatment using the multiple-attribute decision-making technique to rank the alternative wastewater treatment technologies. The criteria setting for evaluation includes indicators derived from life cycle assessment (LCA), i.e. global warming potential, eutrophication potential; life cycle costing (LCC); resource constraints (e.g. land requirement, manpower requirement); robustness of the system (e.g. reliability, durability) and sustainability criteria (e.g. acceptability, participation). Nevertheless, so far, there still a lack study on energy and GHG performance assessment of the integrated wastewater recycling and food waste management for biogas as proposed in the zero waste system of this research. LCA is therefore important to the research of "innovative zero-waste system" as the step to validate the environmental sustainability of the zero-waste system in terms of energy and GHG performances.

2.5 Commercialization of new technology

Commercialization is "the process of transforming ideas, knowledge and inventions into greater wealth for individuals, businesses and/or society at large" (Australian-Government, 2003). It is driven by market and profit motives, with firms and others seeking to gain a positive return on investment in research, licensing, product development, and marketing, including through the creation of competitive niche markets. Technology commercialization and implementation process can be classified into two phases which totally consists of 7 steps (MichiganTech, 2020) i.e.

Step 1: Value Proposition

- Identifiable distinct elements of the technology?
- Definable competitive advantage?
- Addressable market opportunity?

Step 2: Competitive Advantage

- Are there proprietary strategies available?

- Do those strategies provide a competitive market advantage?
- How will a competitive advantaged be established and sustained otherwise?

Step 3: Market opportunity

- Clear product-market fit (value proposition connected to distinct customer segments)?
- Addressable barriers to commercial entry?
- Addressable technology risk?
- Sufficient market to justify expected required investments?

Step 4: Commercialization Strategy

- Pre-commercial, milestone based plan
- Engagement of early stage funding sources for university-based milestone accomplishment
- Team development and planning

Step 5: Proprietary Protection

- Collection of necessary experimental data
- Detailed assessment of prior art patent filling

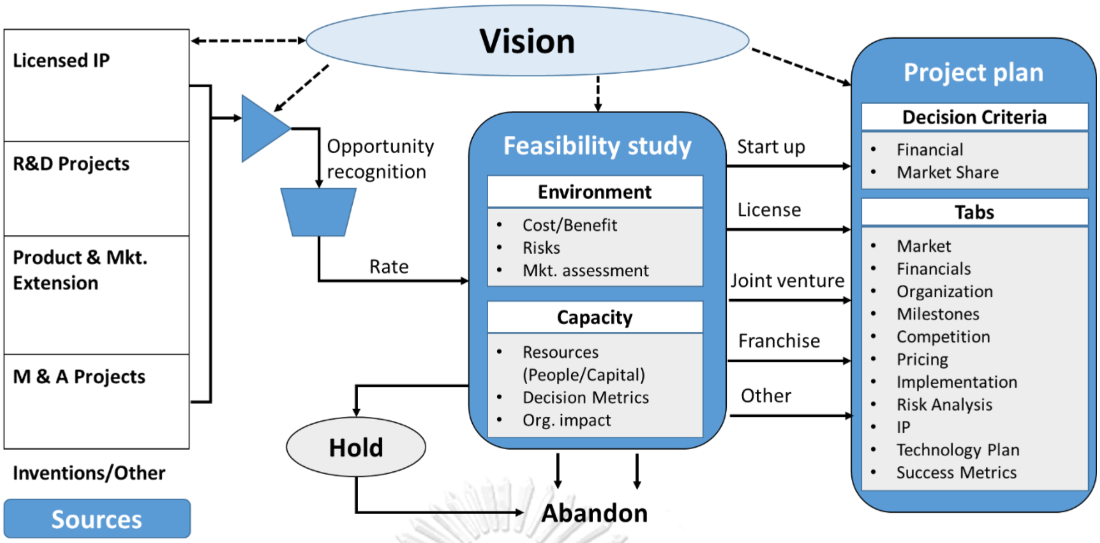
Step 6: Commercialization implementation

- Commercial milestone-based development plan
- Recruitment of funding for commercial technical and business de-risking

Step 7: License Revenue

- Negotiating license terms
- Building strategic partner relationships
- Follow-on milestones

Schaufeld (2015) summarize the commercialization cycle that originate since the vision, identification of sources of innovation, determine the opportunity recognition rate and then further go the feasibility study and make the business plan as shown in Figure 5.



Source: Schaufeld (2015)

Figure 5 Commercialization cycle

For the commercialization of wastewater technologies, the Sanitation and Technology Platform (STeP, 2016) has conducted a study to identify common business models used by sewage treatment plant and wastewater treatment system vendors in India. The objective was to understand the prevalent channels to market and relevant stakeholders to determine the best paths to market for new sewage treatment plants (STP) and wastewater treatment systems. The work has been done by the following five steps: (1) aggregating secondary information sources, (2) analyzing publicly available data, (3) conducting primary research, (4) mapping marketing and sales channels, and (5) characterizing major business models in India. Interviews are starting from the end customer (buyers, i.e., builders) and worked back down the value chain, i.e., system designers and implementers (consultants) and vendors (the STP vendor). The results also revealed that, for going to the market, the key decisive factors of stakeholders in choosing a new STP system are as follows: **Most popular factors:** Affordability; Easy to Operate/Maintain; Proven technology/Familiarity; **Other factors:** Quality of End Effluent; Footprint; Energy Efficiency.

CHAPTER 3
METHODOLOGY

The research methodology consists of four major steps as following:

- **Step 1:** Study on the factors affecting the decision to use the zero-waste system for wastewater and food waste management in public universities
- **Step 2:** Develop and test an innovative zero-waste system for food waste and wastewater management.
    - Setting and operating the zero-waste system consists of a single-stage anaerobic digester, a fruit and vegetable waste (FVW) grinding machine, and the Moving Bed Biofilm Reaction-Membrane Bioreactor (MBBR-MBR) system.
    - Operating and analyses the sample results
- **Step 3:** Evaluate the environmental performance of the zero-waste system using the Life Cycle Assessment (LCA)
- **Step 4:** Propose the commercialization model for the zero-waste system

3.1 Study on factors affecting the decision to use the zero-waste technology for wastewater and food waste management in public universities

To study the factors affecting the decision to use the technology “zero-waste system” in buildings of the public universities in Thailand. The survey includes analyzing the factors that are important to their interest in choosing waste treatment technology classified by various sample groups of universities. The main study questions are as follows: (1) Who is the target market? (2) Is the zero-waste system in demand for waste management in campus buildings? (3) What are the key decision factors for selecting the wastewater treatment and food waste management system?

3.1.1 Target market group

Since the “Innovative zero-waste system” is developed and tested for operating in Chulachakrabonse Building. Chulalongkorn University. The study, therefore, sets the target market for use in buildings within public universities (29 places) according to the statistics of the Office of the Higher Education Commission (OHEC, 2019). Because it is a group that can be used due to the nature of management model, university activity and environment are similar to the environment in which the zero-waste system was tested. In the future, there may be an expanding market to other university groups e.g. Rajabhat University, the Rajamangala University of Technology, and even other office buildings.

3.1.2 Conceptual model and framework to study the factors influencing the selection of zero-waste system innovation

The study's conceptual model is shown in Figure 6, which shows the relationship between the dependent variable and independent variables. The dependent variable is *"an interest in selecting wastewater and food waste management technologies in buildings such as Zero-waste."* The model is to analyze whether the dependent variable depends on the independent variables, which can be categorized as "Technology attributes" (IIT, 2010) and "Consumer characteristics variables (including attitude)" (C.-f. Chen, Xu, & Arpan, 2017).

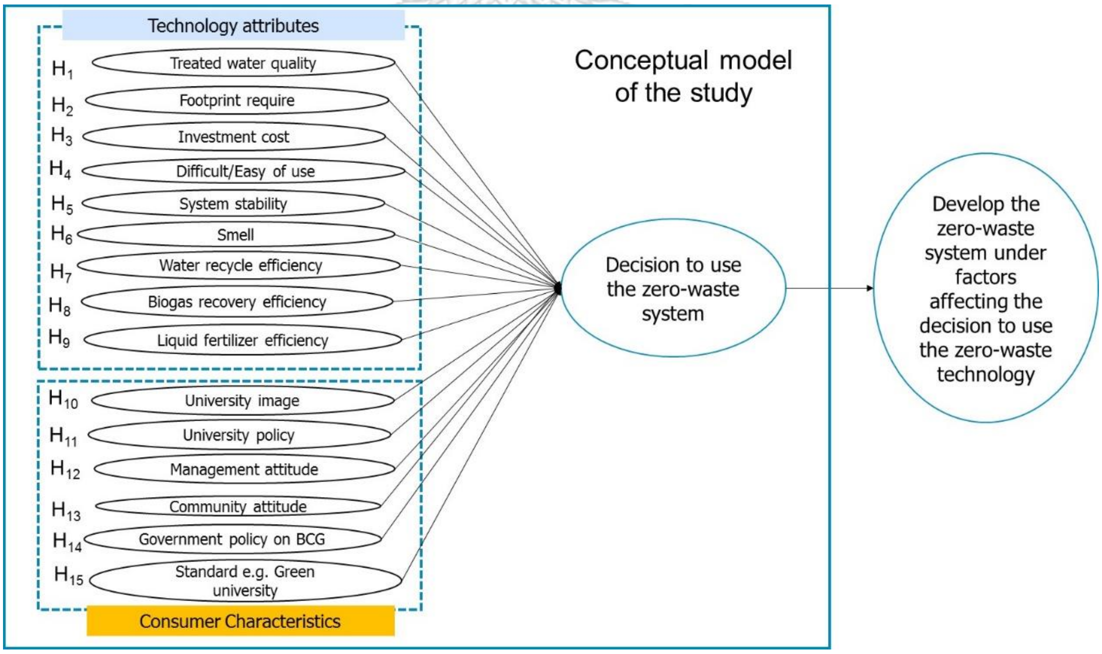


Figure 6 Conceptual model of factors influencing decision to use zero-waste system

3.1.3 Dependent and independent variables

(1) Dependent Variable is the decision to adopt the zero-waste technology for wastewater recycling and waste management in university buildings.

(2) Independent variables are the variables or factors that are expected to influence the sample group's decisions in deciding to use the zero-waste technology in university buildings. Which can be divided into technology variables and consumer characteristic variables.

3.1.3.1 Technology variables

Previous research has identified the factors that consumers use to decide on sewage treatment technology (IIT, 2010); (STeP, 2016). Table 12 shows the nine technology variables that are considered to influence the decision to use the “zero-waste technology” and the research hypotheses.

Table 12 Technology variables and hypotheses

Variables	Hypothesis	Sources
1. Water quality after treatment	H1: Quality of wastewater after treatment influenced in installing the zero-waste system.	Referred from quality of treated sewage of IIT (2010)
2. Space required	H2: The size of the area used influenced in installing the zero-waste system.	Referred from land required of IIT (2010)
3. Cost of the treatment system including operation and maintenance costs	H3: Capital investment and operation expenses influenced in installing the zero-waste system.	Referred from capital, operation & maintenance costs of IIT (2010)
4. Ease of operation and maintenance	H4: Difficulty in operating the system influenced the sample group's interest in installing the zero-waste system.	Referred from technological simplicity of C.-J. Chen et al. (2011)

Variables	Hypothesis	Sources
5. Technology reliability	H5: System stability influenced the sample group's interest in installing the zero-waste system.	Referred from reliability of IIT (2010)
6. Odor surrounding the treatment system	H6: The odor surrounding the treatment system influenced in installing the zero-waste system.	Own proposed adapted from environmental factor of C.-J. Chen et al. (2011)
7. Wastewater recycling efficiency	H7: Efficiency in recycling wastewater influenced in installing the zero-waste system.	Referred from Resource recovery of IIT (2010)
8. Biogas production efficiency	H8: Efficiency in waste for biogas production influenced in installing the zero-waste system.	Referred from Resource recovery of IIT (2010)
9. Fertilizer production efficiency	H9: Efficiency in using wastewater to fertilize influenced in installing the zero-waste system.	Referred from Resource recovery of IIT (2010)

3.1.3.2 Variables on consumer characteristics, pressure, as well as individual's attitude towards the environment

Past studies indicate that factors of environmental awareness and consumer behavior are social pressures. Individual environmentalism affects an interest in choosing to use environmental technology. The study, therefore, investigated the consumer characteristics variables and other external factors that may influence the sample group's interest in selecting the waste treatment technology. It can be divided into six variables. The variables and their hypotheses used in the conceptual model are shown in Table 13.

Table 13 Consumer characteristic variables and hypotheses

Variables	Hypothesis	Sources
10. Organizational image	H10: The organizational image on the zero-waste waste management influenced installing the zero-waste system.	Own proposed by adaptation from consumer environmentalism of Ahn et al. (2016)
11. University policy on environmental management	H11: The university's policy on environmental management influenced in installing the zero-waste system.	Own proposed by adaptation from consumer environmentalism of Ahn et al. (2016)
12. Environmental attitude of university executives	H12: The environmental attitude of the executives influenced in installing the zero-waste system.	Own proposed by adaptation from consumer environmentalism of Ahn et al. (2016)
13. Pressure from surrounding communities on universities	H13: Pressure from surrounding communities on universities to manage wastewater and food waste influenced in installing the zero-waste system.	Referred from social pressure of Ahn et al. (2016)
14. Government Policies on BCG	H14: Government policy on BCG influenced in installing the zero-waste system.	Own proposed by adaptation from social pressure of Ahn et al. (2016)
15. External standards such as Green university	H15: External standards as Green University have influenced installing the zero-waste system.	Own proposed

3.1.4 Population and Sampling Design

According to the study's target market and scope, there are 29 universities located in the central region (Including Bangkok) 14 locations, 5 northern regions, 5 northeastern, 4 southern and 1 eastern region. The sampling design used in the survey is a non-probability sampling. The quota sampling method is referred to determine the sample opinions. The sample groups are classified into four groups as follows:

(1) Executive of the Institute (Top Management)

(2) Building supervisor/ engineer/ officer in charge of building wastewater management/ building designer (Technician) who plays a role in the use of wastewater treatment system and the waste disposal

(3) Lecturers/researchers and

(4) Student

Considering the composition of the sample group from each university, divided into an executive, a building supervisor/engineer/staff, three professors/researchers/ staff, and two students. The questionnaires are sent to each university coordinator to distribute to different groups.

3.1.5 Development of questionnaires and tests

The survey questionnaire (closed-ended questionnaire) has been developed and used to collect the data. The questionnaire was separated into five parts i.e.

- Part 1: General information of the educational institution (3 questions),
- Part 2: General information of respondents (4 questions),
- Part 3: Current Management of Wastewater and Food Waste (6 questions),
- Part 4: Inquiries on factors influencing willingness to pay and selection of waste management technology;
- Part 5: Attitudes towards Environmental Management Issues and innovation; and

Before conducting the actual survey, the questionnaire was tested for suitability (Pre-Test) by the waste management specialist, environmental professionals on campus, and the general public totaling three persons. To assess the understanding, completeness, ease of the question, and the question appropriateness. The corrections of the questionnaire have been done before the actual survey. The validity and reliability of the questionnaire have thus been confirmed before the actual data collection. An example of a questionnaire can be seen in the Appendix A.

3.1.6 Data Collection

Survey questionnaires were submitted with four sample groups in 29 public universities (by e-mail) and sending an internet-based survey to the sample at the public universities that can be contacted and the university coordinator forwarded (Figure 7).

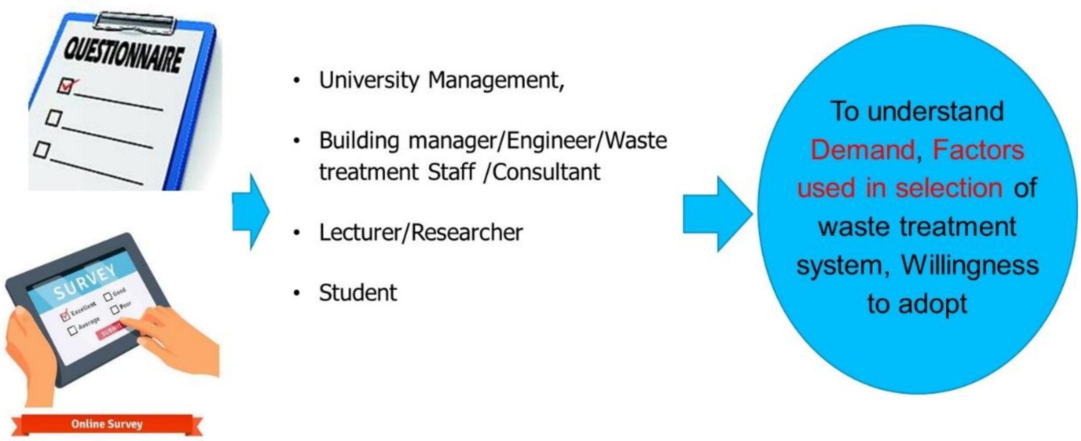


Figure 7 Target groups, inquiries, and study results

3.1.7 Methods for statistical study and analysis

This research was a quantitative research with a tool used to collect data as a closed-ended questionnaire using a *"five-point Likert Scale method"* for a survey of opinions on each factor under the conceptual model. To ask whether the sample group has an opinion on what factors in technology and consumer characteristics are *"most important"* to *"not important"* in their interest in choosing a zero-waste technology. The survey was conducted by submitting questionnaires to 29 public universities, both via e-mail and online-Questionnaire. To give to the sample groups in the university to answer their opinions. The survey results obtained from questionnaires were analyzed using statistical data analysis software (SPSS).

(1) Analysis to test the relationship or effect between independent variables, namely technology issues (9 variables) and consumer characteristics (6 variables) and the dependent variable. The dependent variable is the attention to use the zero-waste innovation for wastewater recycling and food waste management. Multiple Regression Analysis is used to find the relationship between 1 dependent variable and 2 or more independent variables, with a level of significance = 0.05.

(2) An analysis to compare the opinions obtained among the four groups of survey samples on whether there is an interest in implementing a zero-waste system. Whether the opinions on each independent variable were in the same direction or were there differences? The statistical method used is the Kruskal Wallis test with a level of significance = 0.05.

3.2 Development and testing of an innovative zero-waste system for food waste and wastewater management at the Chulachakrabonse building

3.2.1 Development of the innovative zero-waste system

The zero-waste system has been developed and installed for wastewater and food waste treatment at the Chulachakrabonse building. Chulachakrabonse building is the 4^{th}-floor building (around 6,400 sq.m.) located in the Chulalongkorn University of Thailand. The building consists of several faculty clubs and the main canteen. The amount of wastewater and food waste generated is around 2 m^3/day and 60 kg/day. The characteristics of wastewater include COD = 120-300 mg/L, TKN = 35-120 mg/L, TP = 3.8-10 mg/L and pH = 7.0-7.8 (Ratanatamskul & Kongwong, 2017). The characteristics of food waste based on the measurement results are as follows: the average COD = 162,000 mg/L, TS = 129,000 mg/L, TVS = 97,900 mg/L and pH = 4.7. The aims of zero-waste system developed in the study is not only to treat the food waste and wastewater but also to utilize the benefits from the recycled products i.e. biogas and treated wastewater.

The zero-waste system developed in the study consists of three major processes, i.e. (1) the shredder and screw conveyor unit to convey the food waste into the anaerobic digester; (2) the anaerobic digester for treating the shredded food waste along with the biogas production; and (3) the Moving Bed Biofilm Reaction–Membrane Bioreactor (MBBR-MBR) process for wastewater treatment and reuse. The developed system consists of several units as follows:

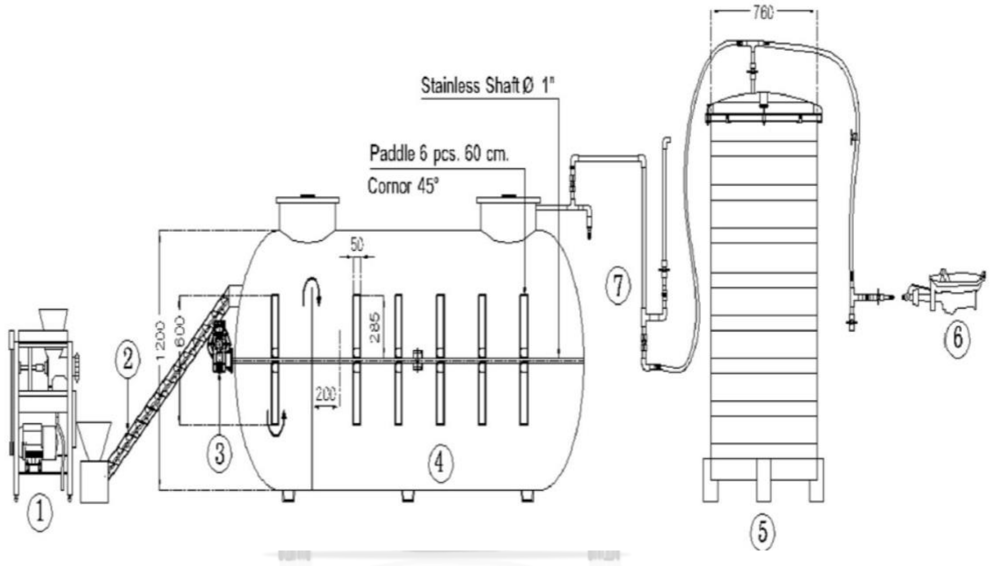
(1) Food waste shredding machine and screw conveyor

The shredder, made of stainless steel (SUS304), is developed to shredding the food, vegetable and fruit waste to reduce the size of the food waste from the canteen. **Figure 8**. The capacity of grinding is 20 kg per 20 minutes.

Figure 8 Shredder and screw conveyor

(2) A single-stage digester tank

A pilot single-stage anaerobic digester developed in the study is the horizontal plug-flow cylinder digester type with 1.2 m in diameter, as shown in **Figure 9**. The volume of the digester is about 2500 L, with the working volume around 1250 L. The prepared substrate will be fed into the digester by a screw conveyor. A paddle type mixer is used for slow mixing at a short period after feeding waste into the digester tank. The biogas generated from the anaerobic activity will then be kept in the biogas holding tank and sent through the pipe to use in the canteen.



Source: Ratanatamskul et al. (2014)

Figure 9 A pilot single-stage anaerobic digester developed in the study

(3) Biogas holding tank

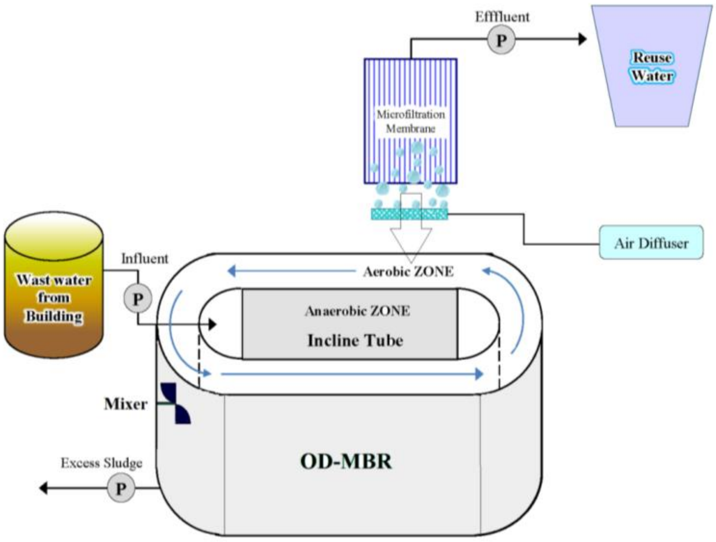
Biogas from the digester will be sent to keep in a biogas holding tank with a floating drum type. The volume of biogas is measured by a gas flow meter that is annexed with the digester tank.

(4) Compressed pressure tank

A compressed pressure tank will be used to increase the biogas's pressure to 2 bar, and then the biogas is pumped to use in the canteen for cooking.

(5) Moving Bed Biofilm Reaction-Membrane Bioreactor (MBBR-MBR)

The study aims to develop a prototype for wastewater recycling and bio-fertilizer production using the MBBR-MBR system with the oxidation ditch shape configuration, as shown in Figures 10 and 11.



Source: Ratanatamskul and Kongwong (2017)

Figure 10 MBBR-MBR system with the oxidation ditch shape configuration

Figure 11 MBBR-MBR system with the configuration of oxidation ditch shape

The MBBR-MBR system is the activated sludge system with attached biofilm growth media that uses membrane filtration to replace a sedimentation tank. The moving bed biofilm carrier is installed inside the aerobic zone. The biofilm carrier will cover nearly 20% of the total volume of the aerobic zone. The microfilter (MF) membrane with a pore size of 0.4 microns is installed in the aerobic zone. The membrane permeation rate was kept at 2 cubic meters per day. The wastewater from the building will be fed in the anaerobic zone with an inclined tube. The small pore of the membrane can capture the bacteria in the system to prevent it from discharged together with the discharged water. Also, the system can use to substitute the bacteria and virus disinfection systems. The viruses that are larger than the porosity of the membrane will not allow to pass the membrane and contaminate the discharged water after the treatment of wastewater in the building. This membrane system is thus gaining attraction for treating and recycling the wastewater of building

3.2.2 Test operation procedures and process measurements

(1) Food waste, FVW sampling, and preparation

Food, vegetable, and fruit waste was used in the study collected from the Chulachakrabonse building's canteen. The mixing ratio of food wastes (FW), fruit and vegetable wastes (FVW), and waste sludge (WS) from the MBBR-MBR system are varied as shown in Table 14.

Table 14 Operational conditions for mixing of FW, VFW, and WS

Experimental Run	Mixing ratio of FW: FVW: WS	Operation Period
Start-up period	25 kg: 0 kg: 0 kg	2 months
Run 1	20 kg: 0 kg: 5 kg	1 month
Run 2	15 kg: 5 kg: 5 kg	1 month

The properties of the prepared organic waste for the digester tank will be analyzed by the methods, as shown in Table 15.

Table 15 Analytical methods for the feeding organic wastes

Parameters	Analytical methods
Moister and Total Solids	Evaporation at 105°C
TVS	Burning at 550 ^{o}C
pH	pH meter
COD	Close Reflux Method

Monitor the systems' changes at the different periods after operation by collecting the samples from the two sampling points (i.e., at the side and the bottom valves of the digester tank) from starting to the end of the digestion. The analyzed parameters include pH, temperature, COD, SS, TS, TVS, VFA, alkalinity, and TKN.

(2) Biogas sampling

Gas (biogas) sampling using a gas needle in a U-shaped glass tube connected with the digester tank to analyze the methane and carbon dioxide composition in the biogas. Sludge after the fermentation will also be analyzed based on the analytical methods shown in Table 16.

Table 16 Analytical methods for the sludge after the fermentation

Parameters	**Analytical methods**
pH	pH Meter
Temperature	Thermometer
Chemical Oxygen Demand (COD)	Closed Reflux
Sustainable Solids (SS)	Glass Fiber Filter Disc (GF/C)
TS	Evaporation (Temperature 105 ^{o}C, 1 hour)
TVS	Burning at 550 ^{o}C
VFA	Direct Titration Method
alkalinity	Direct Titration Method
TKN	Kjeldahl Method
TP	Vanadomolybdophosphoric Acid Colorimetric Method

Parameters	Analytical methods
Biogas production	Gas measurement

(3) MBBR-MBR operating procedures and process monitoring

The MBBR-MBR system is used for treating the combined wastewater from the Chulachakrabonse building at a feeding rate of 2 m^3/day. The waste sludge (WS) from the MBBR-MBR system will be wasted at 5 kg to maintain the aerobic sludge age of the MBBR-MBR system of 200 days. The operational conditions such as the mixing ratio of wastewater and digestate from a single-stage anaerobic digester is shown in Table 17.

Table 17 Operational conditions for MBBR-MBR system

Experimental Run	Mixing ratio of wastewater: Digestate from AD	Operation Period
Start-up period	2 m^3/d : 20 L/d (digestate from FW+ WS)	2 months
Run 1	2 m^3/d : 20 L/d (digestate from FW+ WS in Experimental No.1 of anaerobic digester)	1 month
Run 2	2m^3/d : 20 L/d (digestate from FW+ WS + FVW in Experimental No.2 of anaerobic digester)	1 month

The objectives of sampling and monitoring of wastewater are to assess the COD, N, and P removal efficiency for long-term operation of the system and the potential for liquid bio-fertilizer production. The parameters and analytical methods are listed in Table 18. Wastewater used for this experiment will be taken from the wastewater ponds of Chulachakabonse building and leachate from FVW treatment at the food waste management system. Therefore, the wastewater will come from three main sources, i.e. toilet, canteen, and leachate, from FVW grinder of the buildings. Chulachakabonse's building is the 4th floor building with the total usage areas about 6,403.95 sq.m.. The building consists of Chulalongkorn University Faculty Club, Office of the Faculty Senate, canteen and other clubs. The office will normally open five days a week from office hours 8.00-17.00. Canteen also operates every day, the same as the office hours. However, during the off period of the semester, the shops may not be fully open. The amount of wastewater inlet to the wastewater treatment system is estimated to be around 2 m^3/day.

Table 18 Parameters and analytical methods for MBBR-MBR system

Parameters	**Analytical methods**
Wastewater flow rate	Flow meter
Temperature	Oxygen (in water) measurement (Temperature probe)
pH	pH Meter
Dissolved Oxygen (DO)	DO meter
ORP	Conductivity
COD	Open reflux
Suspended Solids (SS)	Weighting
MLSS	Weighting
NH_3	Titration
NO_4	Colour measurement
Phosphorus	Vanadomolybdate method

3.3 Environmental performance assessment of the zero-waste system using LCA

Life cycle assessment (LCA), one of the recognized environmental sustainability assessment tools, has been used in the study for compilation and evaluation of the environmental impacts of the waste treatment system (Xu, Shi, Hong, Zhang, & Chen, 2015). The International Organization for Standardization (ISO) has set the ISO standards on LCA: ISO 14040 and ISO 14044 (Finkbeiner, Tan, & Reginald, 2011). Life cycle assessment (LCA) is worldwide recognized as a tool for compiling and evaluating the environmental impacts of a product or service system throughout its life cycle. Figure 12 elaborates the four basic steps of LCA outlined in ISO 14040 i.e.

(1) Goal and Scope definition,

(2) Life Cycle Inventory (LCI) analysis

(3) Life cycle impact assessment and

(4) Interpretation.

Step 1 Goal and Scope definition

The step that the working plan of LCA study will be made. The goal of the study is formulated in terms of the exact question, target audience, and intended application. The scope of the study is defined in terms of system boundaries, geographical and technological coverage.

Step 2 Life Cycle Inventory (LCI) analysis

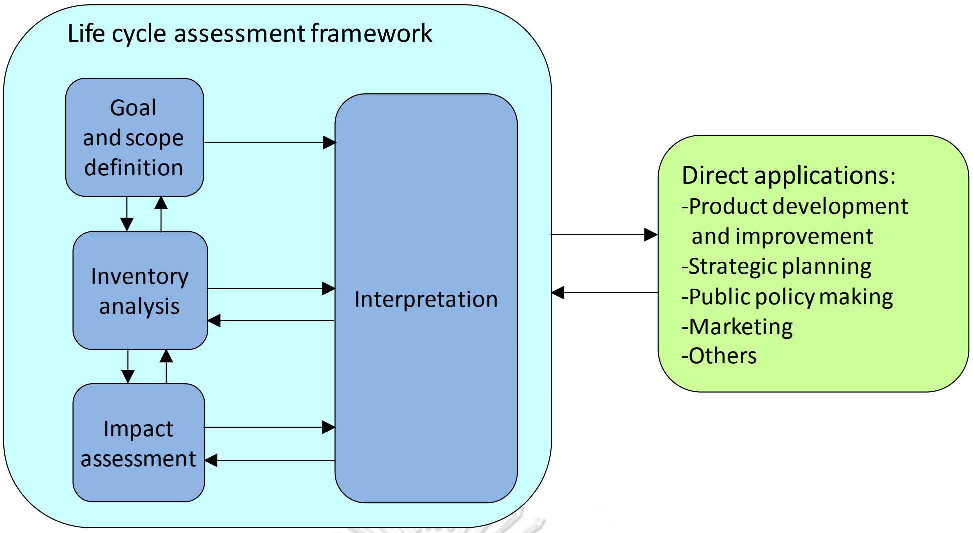
The step in which the studied product/process system is defined, and the consumption of resources and quantities of emissions caused by processes within a product's life cycle are estimated. The identification and quantification of environmental loads involved; e.g., the energy and raw materials consumed, the air emissions, water effluents, and wastes generated.

Step 3 Life cycle impact assessment

The is the step in which the set of results of the inventory analysis is further processed and interpreted in terms of environmental impacts and societal preferences. The evaluation of the potential environmental impacts of these loads can be calculated by using the characterization factors obtained from the life cycle impact assessment (LCIA) method as per selection; and

Step 4 Interpretation

The step in which the available options for reducing these environmental impacts will be made.



Source: ISO14040 (2006)

Figure 12 Framework of ISO-LCA

3.3.1 Goal and scope of the assessment

The study goal is to evaluate life-cycle energy use and GHG emissions of the operating zero-waste system at the Chulachakrabonse building for reusing wastewater and producing the biogas from food waste by comparing to the conventional food waste and wastewater treatment techniques, i.e., landfill of organic waste and the treatment of wastewater using the activated sludge system. The functional unit is set to treat about 60 kilogram of food waste and 2 m^3 of wastewater, which is the average daily waste input into the system.

Figure 13 shows the simplified system boundary for conducting the life cycle analysis of the innovative zero-waste system developed in the study. The scope of assessment covers the “cradle-to-grave” which can be separated into four main life-cycle stages, i.e. (1) production of materials/fuel/energy/electricity used; (2) wastewater treatment and recycling; (3) food waste treatment; and (4) Use of biogas and treated water reuse as well as their environmental credits. The environmental credits from the biogas and treated water reuse are accounted for as the substitution of LPG used for cooking in the canteen and the replacement of tap water used for watering the plants. The key environmental interventions considered are the resources used, materials, and chemicals used for the zero-waste system operation.

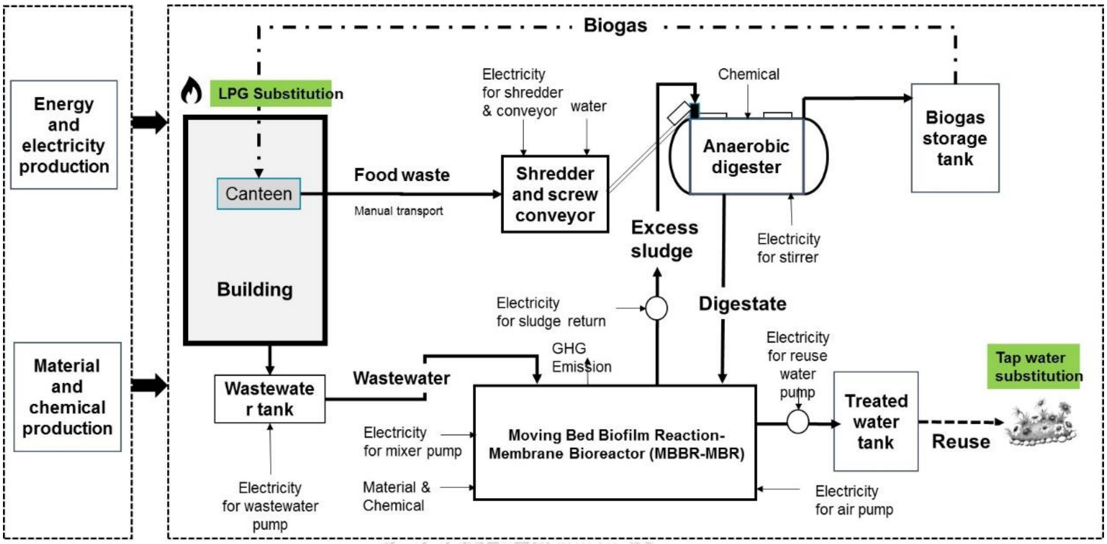


Figure 13 System boundary of the studied zero-waste system

3.3.2 Life-cycle energy use and GHG emissions assessment method

The life-cycle energy use of the zero-waste system is evaluated based on the cumulative energy demand (CED) assessment method of (Frischknecht et al., 2007). This CED indicator is widely used to indicate the primary energy consumption of the process or product system. The study evaluates the total primary energy input of the zero-waste system and comparing its results with total energy outputs or energy credits obtained from the products, i.e., biogas and treated wastewater reuse. To determine the CED indicator, the inventory data on the input material, energy, and chemical during the waste treatment system operation are multiplied with their primary energy consumption. The background data for the productions of material and chemicals used are referred from the Ecoinvent database (Ecoinvent3.0, 2012). The grid electricity data of Thailand is referred from the Thai National LCI database. The total cumulative energy demand of the waste treatment system is shown in the unit of MJ-eq/Functional unit.

Life-cycle GHG emissions of the studied waste treatment system are assessed by focusing on the significant GHG substances, i.e., CO_2, CH_4, and N_2O related to wastewater and food waste treatment processes. Eq (1) shows the scope of life cycle GHG emissions of the waste treatment system ($E_{waste\ treatment\ system}$), which can be classified into three categories, i.e. (1) direct GHG emissions, (2) indirect GHG emissions, and (3) the GHG credits (that obtained from the reuse or recycle of the treated wastes of the system).

$$E_{waste\ treatment\ system} = E_{Direct} + E_{Indirect} - E_{Credit} \qquad \text{Eq. (1)}$$

Where $E_{waste\ treatment\ system}$, in the study, represents the life-cycle GHG emissions of the combination system of the anaerobic digester and MBBR-MBR for food waste and wastewater treatment (kg CO_2-eq/Functional unit). E_{Direct} represents the direct GHG emissions e.g., GHG emissions combustion of fuel, fugitive methane emission at the anaerobic digestion system, fugitive N_2O emissions at the wastewater treatment system. $E_{Indirect}$ represents indirect GHG emissions due to the material, chemical, energy use e.g., the electricity consumption for system operation, the material used for media of MBBR system, the chemical used for the process of anaerobic digestion, membrane as well as the membrane cleaning at the MBBR-MBR system. (3) GHG credits were obtained from the substation of LPG and tap water. For the direct GHG emissions, since the system does not use fuel in operation, only the GHG emissions from the fugitive methane and the GHG emissions from the fugitive N_2O emissions are investigated using Eq (2) and Eq (3).

$$E_{Direct,CH4\ fugitive} = 2\% \times Biogas\ produced\ \times \%\ CH_4\ in\ biogas\ \times 0.66\ \times GWP\ factor \qquad \text{Eq. (2)}$$

$$E_{Direct,N2O\ fugitive} = TKN_{influence}\ \times EF_{N2O}\ \times GWP\ factor \qquad \text{Eq. (3)}$$

The fugitive loss of methane is estimated to be about 2% (WaCCliM, 2018). The biogas produced from the system is 9.3 Nm^3; %CH_4 in biogas is 65% and 0.66 kg methane/Nm^3. For the N_2O emission from the wastewater treatment plant, the primary data about wastewater influent, i.e., $TKN_{influence}$ = 40 mg/L and the N_2O

emission factor (EF_{N2O}) = 0.003 kg N_2O/kg $TKN_{influence}$ (GWRC et al., 2011) are used. The global warming potential (GWP) factors are referred from the ReCiPe method v.1.10 (Huijbregts et al., 2016), i.e., the GWP factors of carbon dioxide, methane, biogenic methane, and dinitrogen monoxide are 1, 25, 22.3, and 298 kg CO_2-eq/kg substance. The construction of the zero-waste system is excluded from the system boundary due to the assumption that its impact would not be significant after distributed to the 20 years lifetime of the equipment. Details of the life cycle assessment of the zero-waste system have been discussion on the chapter 5 of the report.

3.4 Technology commercialization (TC)

Technology commercialization and implementation process can be classified into two phases which totally consists of 7 steps (MichiganTech, 2020) as following:

Assessment Phase

- Step 1: Value Proposition
- Step 2: Competitive Advantage
- Step 3: Market opportunity

Implementation Phase

- Step 4: Commercialization Strategy or Commercialization Plan include
    - Marketing plan
    - Organization and HR plan
    - Operational plan
    - Financial plan
- Step 5: Proprietary Protection
- Step 6: Commercialization implementation
- Step 7: License Revenue

In the study, the value proposition, competitive advantage and market opportunity have been determined by the research output information from the objectives (1)-(3). The commercialization strategy is analyzed and proposed based on the existing common business models used for the waste treatment plant implementation system. Business Model Canvas is used as the tool for preliminary development to of the business model and planning for the zero-waste system commercialization. Details have been discussed on the chapter 6 of the report.

CHAPTER 4
RESULTS OF FACTORS AFFECTING THE DECISION TO USE THE ZERO-WASTE SYTEM

The chapter shows the results obtained from the objective 1 of the research i.e. to study on the factors affecting the decision to use the zero-waste system for wastewater and food waste management in public universities.

4.1 Respondents profile

4.1.1 Respondents characteristics

112 respondents from a sample of 20 universities out of the 29 public universities targeted the survey. The list of universities that received the feedback is shown in the Appendix. From the 112 survey results, that can be categorized into 4 groups of respondents, i.e., 6 university presidents or executive level (5% of the total respondents), 20 building staff (technician/engineer) (18% of the total respondents), 68 lecturers/researchers (61% of the total respondents) and 18 students (16% of the total respondents) as in **Figure 14**.

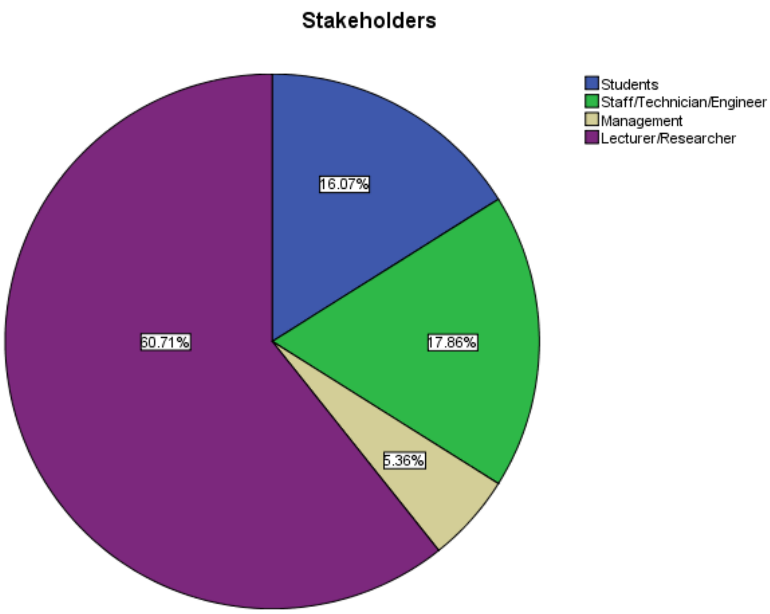


Figure 14 The sample proportion classified by the target group in the university

4.1.2 Number of sample group classified by sex

Table 19 shows the classification of the sample into male and female. The overall sample was 41.1% male and 58.9% female. The result was found that the university management group who responded to the questionnaire were all male. The group of professors/researchers who responded was 70.6% female and 29.4% male. The group of students and technical staff who responded the questionnaire were almost equally between male and female. The lecturer or researcher group was 70.6%. female.

Table 19 Number of samples classified by sex

Samples group		Sex		Total
		Male	Female	
Students	Number	9	9	18
	%	50.0%	50.0%	100.0%
Staff/Technician/Engineer	Number	11	9	20
	%	55.0%	45.0%	100.0%
Management	Number	6	0	6
	%	100.0%	.0%	100.0%
Lecturer/Researcher	Number	20	48	68
	%	29.4%	70.6%	100.0%
Total	Number	46	66	112
	%	41.1%	58.9%	100.0%

4.1.3 Number of samples classified by age

Table 20 shows the classification of the sample by age range. Overall, 40.2% of the sample were aged between 41-50 years, followed by 31-40 years (26.8%), younger than 30 (22.3%). University executives (management group) who responded to the survey, 66.7% were older than 60, while 88.9% of the students who responded to the survey were under 30, except only 11.1% were 31-40 years old who are studying at the doctoral level. Meanwhile, the technician staff around 55.0% have age between 41-50 years.

Table 20 Number of samples classified by age

Sample group		Age (year)					Total
		< 30	31-40	41-50	51-60	> 60	
Students	Number	16	2	0	0	0	18
	%	88.9%	11.1%	.0%	.0%	.0%	100.0%
Staff/Technician/	Number	4	4	11	1	0	20
Engineer	%	20.0%	20.0%	55.0%	5.0%	.0%	100.0%
Management	Number	0	0	1	1	4	6
	%	.0%	.0%	16.7%	16.7%	66.7%	100.0%
Lecturer/Researcher	Number	5	24	33	6	0	68
	%	7.4%	35.3%	48.5%	8.8%	.0%	100.0%
Total	Number	25	30	45	8	4	112
	%	22.3%	26.8%	40.2%	7.1%	3.6%	100.0%

4.1.4 Number of samples classified by educational level

Table 21 shows the classification of the samples by education level. 57.1% of the sample had a doctoral degree, while 26.5% had a master degree and 13.4% had a bachelor's degree or are currently studying at the undergraduate level. It was found that 100.0% of university executives who responded to the questionnaire had a doctorate. Meanwhile, 45.0% of the building operators/technicians/engineers involved in waste management systems had master's degrees, 35.0% at doctoral degrees, and 20.0% at bachelor degrees. Therefore, the sample group is considered to have a certain level of knowledge to understand the questionnaire's technical details.

Table 21 Number of samples classified by educational level

Sample group		Education level			Total
		Bachelor	Master	Doctoral	
Students	Numbers	9	6	3	18
	%	50.0%	33.3%	16.7%	100.0%

Sample group		Education level			Total
		Bachelor	Master	Doctoral	
Staff/Technician/Engineer	Numbers	4	9	7	20
	%	20.0%	45.0%	35.0%	100.0%
Management	Numbers	0	0	6	6
	%	.0%	.0%	100.0%	100.0%
Lecturer/Researcher	Numbers	2	18	48	68
	%	2.9%	26.5%	70.6%	100.0%
Total	Numbers	15	33	64	112
	%	13.4%	29.5%	57.1%	100.0%

4.1.5 Number of samples classified by region

Table 22 shows the classification of samples by region. There were 51.8% of the samples came from universities in Bangkok and the central region. The central region has the highest number of universities, followed by 20.5% and 14.3% of the surveyed respondents from universities in the Northeast and the North, respectively. For the respondents, the group of management who replied the questionnaires came from the university in the Central region including Bangkok i.e. around 83% and the university in the Northeast around 17%. Meanwhile, the group of students came from the Central region around 83.3% and the Southern region around 16.7%. For the group of lecturers or researchers, there were representatives from all regions that answer the questionnaire. This is most likely as the group of engineer/technician that there were the samples from all region (except the Southern region of Thailand).

Table 22 Number of samples classified by region and university location.

Sample group		Region					Total
		Central (+BKK)	East	North	North East	South	
Students	Numbers	15	0	0	0	3	18
	%	83.3%	.0%	.0%	.0%	16.7%	100.0%
Staff/Technician/	Numbers	13	1	3	3	0	20

Sample group		Region					Total
		Central (+BKK)	East	North	North East	South	
Engineer	%	65.0%	5.0%	15.0%	15.0%	.0%	100.0%
Management	Numbers	5	0	0	1	0	6
	%	83.3%	.0%	.0%	16.7%	.0%	100.0%
Lecturer/	Numbers	25	3	13	19	8	68
Researcher	%	36.8%	4.4%	19.1%	27.9%	11.8%	100.0%
Total	Numbers	58	4	16	23	11	112
	%	51.8%	3.6%	14.3%	20.5%	9.8%	100.0%

4.2 Wastewater and food waste management systems used in universities

The current data on wastewater and food waste management technology used for the building of 20 universities could be extracted from the third part of the questionnaire. Table 23 shows the summarized results, which found that, at present, the basic wastewater treatment technology used is the septic tank and grease trap (100%). There were five universities (20%) with other wastewater treatment systems such as Activated Sludge, Dissolved Air Floatation, and Aerated Lagoon. However, only two universities, or 10% of the respondents, have recycled water for watering plants. This can be seen as an opportunity to introduce zero-waste technology for the recycling of building wastewater.

For food waste management, it was found that 100% of the university have the food waste separation to be used as animal feed. Only two universities (10%) use food waste to produce biogas, and the other two universities (10%) use food waste to produce compost. There is also an opportunity to present a zero-waste technology that will help eliminate food waste by producing biogas for further in the building.

Table 23 Survey results of current wastewater and food waste management

Current waste system	**Number of universities**	**Percentage**	Description
Current wastewater treatment system			
• Oil and grease and septic tank	20	100%	
Other wastewater treatment systems apart from oil & grease and septic tank			
• No additional system	15	75%	
• Dissolved Air Flotation System	1	5%	
• Activated sludge and stabilized pond	3	15%	
Aerated lagoon system	1	5%	
Water recycle system			
• No recycle	18	90%	
• Recycle	2	10%	Watering
Food Waste management system			
• No Food Waste management	0	0%	
• Food Waste management	20	100%	
Current food waste management			
• Sold as animal feed	20	100%	
Other food waste management apart from selling as animal feed			
• No additional system	16	80%	
• Biogas	2	10%	
• Fermented fertilizer	2	10%	

4.3 Analysis of factors affecting the decision to use wastewater and food waste management technology

Based on the conceptual model proposed (Figure 5), which is an analysis of the relationship between technology variables (9 variables) and consumer characteristic variables (6 variables) that can affect the interest in the selection of the zero-waste technology in the public university. Multiple Regression Analysis method is used for the analysis. The hypothesis of the experiment consists of

- H0: Technology factor or consumer characteristics studied in the conceptual model did not affect (no effect or no relationship) decision to use the zero-waste technology.
- H1-H15: Each of the factors studied (as shown in Tables 12 and 13) influenced or correlated with the decision to use the zero-waste technology.

Table 24 shows the results of Multiple Regression Analysis to test the above hypotheses. Based on the information from 112 respondents, the results revealed that the factors influencing the decision-making or interest in using zero-waste technology for waste management in public university buildings. Statistically significant at the 0.05 level were: Technological aspects include the quality of treated water (Sig. = 0.002 *), investments and costs (Sig. = 0.001 *), ease of use (Sig. = 0.008 *), system stability (Sig. = 0.009 *), odor disturbances (Sig. = 0.002 *), efficiency of water recycling (Sig. = 0.000 *) and efficiency of biogas production (Sig. = 0.000 *). The consumer characteristics consist of University's Image Issues (Sig. = 0.000 *), University Policy (Sig. = 0.01 *), Management Attitudes on Environmental Issues (Sig. = 0.000 *) and Government Policy (Sig. = 0.019 *).

While the statistically insignificant factors influencing interest or decision-making in choosing the zero-waste technology were the footprint require (Sig. = 0.184), liquid fertilizer efficiency (Sig. = 0.650), Community Pressure (Sig. = 0.111), and Green University Standards (Sig. = 0.730). The negative beta of regression analysis shown in Table 24 implies that the corresponding independent variables i.e. factors are negatively correlated with the dependent variable i.e. interest in the use of the zero-waste system. For example, B = -.154 or β = -.151 for investment cost factor, this implies that when the investment cost increases, the interest to use the zero-waste system will decrease. This negative correlations are also for the nuisance (smell) factor and the difficulty/easy to use i.e. when the smell of waste increases, the interest to zero waste decreases; and when if the difficulty in use of zero-waste increase, the interest to zero-waste will decrease.

Table 24 Multiple Regression Analysis results of technological factors and consumer characteristics that affected interest in using the zero-waste technology

Factors	The sample groups' interests in the use of the zero-waste system						
	B	S.E.	Beta (β)	t	Sig.	Tolerance	VIF
(Constant)	1.849	.284		6.501	.000		
Technology							
Quality of treated water	.225	.072	.207	3.148	.002*	.365	2.737
Footprint require	.081	.061	.078	1.329	.184	.463	2.158
Investment cost	-.176	.054	-.185	-3.249	.001*	.484	2.065
Difficult/easy to use	-.154	.058	-.151	-2.645	.008*	.482	2.076
Stability of the system	.227	.086	.192	2.633	.009*	.296	3.383
Nuisance (smell)	-.192	.063	-.181	-3.043	.002*	.444	2.252
Water recycle efficiency	.365	.067	.380	5.478	.000*	.327	3.055
Biogas recovery efficiency	.298	.084	.274	3.531	.000*	.262	3.820
Liquid fertilizer efficiency	.030	.066	.027	.454	.650	.450	2.221
Consumer characteristics							
University Image	.226	.062	.207	3.663	.000*	.491	2.036
University policy	.167	.065	.159	2.583	.010*	.415	2.412
Management attitude	.322	.068	.319	4.757	.000*	.351	2.852
Community attitude	.085	.053	.092	1.599	.111	.474	2.108
Government Policy on BCG	.146	.062	.162	2.357	.019*	.334	2.996
Green University Standard	.021	.062	.022	.346	.730	.379	2.642

a. Dependent Variable: Interest_ZeroWaste

$R^2 = 0.364$, $F = 15.385$, $P < 0.05$, $N = 112$

* Whereas, the meaning of various symbols is S.E. = Standard Error; t = the statistics used in the hypothesis testing the mean of each equation contained in the equation; B = the regression coefficient of the predictor in the equation written in raw scores. (Unstandardized Coefficients); β = the regression coefficient of the predictor in

standard scores (Standardized Coefficients); Sig. = the statistical values differ significantly at 0.05 level; Tolerance = Proportion of variance in variables not explained by other variables; and VIF = The value at which the conditions of the groups of independent variables in the equation are related.

4.4 Ranking of factors influencing the decision to use zero-waste system

The importance or weight of independent variables affecting the sample's interest in the use of the zero-waste system could be analyzed from the Absolute value of Beta (**β**) in Table 22. The results showed that the efficiency of water recycle (**β** = -0.380) is the key factor affected the interest in installing the zero-waste system, followed by the management's attitude (**β** = 0.319), biogas production efficiency (**β** = 0.274), water quality after treatment (**β** = 0.209), respectively.

R^2 = 0.364 implied that the factors of technology issues and the consumer characteristics affected the sample's interest in using the zero-waste system of about 36.4%, while the remaining 63.6% may be due to other variables. The Multicollinearity inspection revealed that the Tolerance of the independent variable in this study was 0.262-0.491, which was greater than 0.40 (Allison, 1999), and the VIF of the independent variable was 2.036 - 3.820, which was less than 5, indicating that the studied independent variable has no relationship with each other (Zikmund, Carr, & Griffin, 2013). The Tolerance generally ranges from 0 to 1. If the Tolerance approaches 1, the variables are independent of each other, but if the Tolerance values are close to 0 meaning that the variable is related to other independent variables, and if the VIF value is 10 or more, that variable must be omitted from the regression equation. Because that variable has a linear relationship with another independent variable.

4.5 Analysis of the differences of opinions between stakeholders on the interest in using the zero-waste technology and the decisive factors

To test whether the four groups of stakeholders interested in using zero-waste technology based on the same factor or different factor variables. Statistical methods of Kruskal Wallis Test were conducted. The weighting of the sample's significance in each factor variable can be shown by the Mean Rank results of **Table 25**. The results revealed that the group of staff/technician/engineer is the highest interest in the zero-waste technology (Mean Rank = 65.15), followed by the University management group (Mean rank = 57.92), faculty/ researcher/employee group (Mean Rank = 53.81) and lastly student group (Mean Rank = 50.17).

Table 25 Ranking of interests in the zero-waste technology by four sample groups

Issues	Stakeholders	N	Mean Rank
Interest in technology Zero Waste system	Students	18	50.17
	Staff/Technician/Engineer	20	65.15
	Management	6	57.92
	Lecturer/Researcher	66	53.81
	Total	**110**	

Table 26 shows the Mean Rank for each factor in each sample group. The results revealed that each group had different priorities for each factor, as indicated by the different Mean Rank for each factor in each sample group. The staff/technician/engineer group gave weight to the technological matters such as water quality after treatment, space utilization, investment, and efficiency of biogas production. Meanwhile, the university management level weighs on investment, ease of use, and the image of the university. In contrary to the groups of students which put their weight on the issue like the disturbing smells.

4.5.1 Opinions for the technological attributes

(1) **Quality of treated water**

Staff and technician give the important to this quality of treated water highest as comparing to among the other stakeholders, followed by the group of students, lecturer/researcher and management, respectively.

(2) **Footprint require**

Staff and technician also give highest important to the aspect regarding footprint required for the waste treatment plant as comparing to among the other stakeholders, followed by the group of students, management and lecturer/researcher.

(3) **Investment cost**

Staff and technician also give highest important to the aspect regarding footprint required for the waste treatment plant as comparing to among the other stakeholders, followed by the group of management, students, and lecturer/researcher, consecutively.

(4) **Easy to use**

The management attach the highest important to the aspect easy to use as comparing to the other stakeholders, followed by the group of students, staff/technician and lecturer/researcher, respectively.

(5) **Stability of the system**

All stakeholders attach the important to the stability of the system almost equal among the group of stakeholders.

(6) **Smell**

The group of students attach the highest important to the nuisance issue like the smell from the waste treatment plant as comparing to the other stakeholders.

(7) **Water recycle efficiency**

All stakeholders attach the important to the water recycle efficiency of the wastewater treatment play almost equal among the group of stakeholders.

(8) **Biogas recovery efficiency**

Staff and technician also give highest important to the efficiency of biogas recovery by having the mean rank higher than the other stakeholders.

(9) **Liquid fertilizer efficiency**

Staff and technician also give highest important to the liquid fertilizer production efficiency by having the mean rank higher than the other stakeholders. Meanwhile, the management has the lowest mean rank value or giving the lowest important on this aspect comparing to the other stakeholders.

4.5.2 Opinions for the consumer characteristics

(1) **University image**

The group of management as well as the staff/technician give the essential to the zero-waste system in view of university image. The mean rank of those two groups are higher than the group of students and lecturers.

(2) **University policy**

The group of management as well as the staff/technician give the important to the zero-waste system due to the university policy. The mean rank of those two groups are higher than the group of students and lecturers.

(3) **Management attitude**

The group of management, staff/technician and students agree that the management attitude has the high influence to the adoption of the zero-waste system. The mean rank of those two groups are higher than the group of students and lecturers.

(4) **Community attitude**

Students and the staff/technician give the opinion that community attitude has the high influence to the adoption of zero-waste system in the university. Meanwhile, the group of management has lowest weight on this aspect.

(5) **Government policy on BCG**

Almost the group agree that government policy on bioeconomy-circular economy-green economy or so called as “BCG” has influence to the utilization of the zero-waste system in the university building.

(6) **Green university standard**

The group of staff/technician think that the green university standard on waste management has the influence to the potential to adoption the zero-waste system in the university. Meanwhile, the other groups do not much agree on this aspects as indicated by the lower mean rank value on this aspect for the other stakeholder groups.

Table 26 Ranking opinions about the importance of technology factors and consumer characteristics in four sample groups

Factors	Stakeholders	N	Mean Rank
Quality of treated water	Students	18	55.89
	Staff/Technician/Engineer	20	63.30
	Management	6	49.50
	Lecturer/Researcher	68	55.28
	Total	112	
Footprint require	Students	18	59.75
	Staff/Technician/Engineer	19	74.18
	Management	6	59.75
	Lecturer/Researcher	68	49.60
	Total	111	
Investment cost	Students	18	52.64
	Staff/Technician/Engineer	20	79.52
	Management	6	63.83
	Lecturer/Researcher	68	50.10
	Total	112	
Easy to use	Students	18	60.44
	Staff/Technician/Engineer	20	57.65
	Management	6	72.17
	Lecturer/Researcher	68	53.74
	Total	112	

Factors	Stakeholders	N	Mean Rank
Stability of the system	Students	18	56.61
	Staff/Technician/Engineer	20	51.52
	Management	6	54.33
	Lecturer/Researcher	68	58.12
	Total	112	
Nuisance (smell)	Students	18	61.53
	Staff/Technician/Engineer	20	54.55
	Management	6	52.75
	Lecturer/Researcher	68	56.07
	Total	112	
Water recycle efficiency	Students	18	57.08
	Staff/Technician/Engineer	20	52.48
	Management	6	50.83
	Lecturer/Researcher	67	57.22
	Total	111	
Biogas recovery efficiency	Students	18	51.36
	Staff/Technician/Engineer	19	68.29
	Management	6	54.67
	Lecturer/Researcher	68	53.91
	Total	111	
Liquid fertilizer efficiency	Students	18	53.42
	Staff/Technician/Engineer	20	64.90
	Management	6	48.25
	Lecturer/Researcher	68	55.57
	Total	112	
University Image	Students	18	56.31
	Staff/Technician/Engineer	20	73.32
	Management	6	79.25
	Lecturer/Researcher	68	49.60

Factors	Stakeholders	N	Mean Rank
	Total	112	
University policy	Students	18	51.69
	Staff/Technician/Engineer	20	64.02
	Management	6	68.75
	Lecturer/Researcher	68	54.48
	Total	112	
Management attitude	Students	18	59.83
	Staff/Technician/Engineer	20	61.20
	Management	6	67.00
	Lecturer/Researcher	68	53.31
	Total	112	
Community attitude	Students	18	61.72
	Staff/Technician/Engineer	20	61.32
	Management	6	40.00
	Lecturer/Researcher	68	55.15
	Total	112	
Government Policy on BCG	Students	18	62.44
	Staff/Technician/Engineer	20	53.32
	Management	6	58.83
	Lecturer/Researcher	67	54.81
	Total	111	
Green University Standard	Students	18	46.92
	Staff/Technician/Engineer	20	72.15
	Management	6	54.25
	Lecturer/Researcher	68	54.63
	Total	112	

4.6 Statistical testing whether the four groups have different factors in the decision to use the zero waste technology

Since each sample group has different opinions and weight for each of the factors above, the study, therefore, tested whether the above four groups overall opinions on each factor were statistically consistent. The hypotheses for testing are as follows:

H_0: Mean Rank in the four groups no difference

H_1: Mean Rank in the four groups is the difference

Table 27 showed the statistical analysis results by Kruskal Wallis Test.

Table 27 Statistical Analysis by Kruskal Wallis Test

Test Statistics[a,b]

	Interest_Zero Waste	Quality of treated water	Footprint require	Investment cost	Easy to use	Stability of the system
Chi-Square	2.890	1.472	10.412	14.897	2.554	.855
df	3	3	3	3	3	3
Asymp. Sig.	.409	.689	.015	.002	.466	.836

a. Kruskal Wallis Test

b. Grouping Variable: Stakeholders

Test Statistics[a,b]

	Nuisance (smell)	Water recycle efficientcy	Biogas recovery efficiency	Liquid fertilizer efficiency	University Image	Univeristy policy
Chi-Square	.685	.576	3.920	2.242	13.084	2.935
df	3	3	3	3	3	3
Asymp. Sig.	.877	.902	.270	.524	.004	.402

a. Kruskal Wallis Test

b. Grouping Variable: Stakeholders

Test Statistics[a,b]

	Management Policy	Community attitude	Government Policy on BCG	Green University Standard
Chi-Square	2.157	2.892	1.109	7.255
df	3	3	3	3
Asymp. Sig.	.540	.409	.775	.064

a. Kruskal Wallis Test

b. Grouping Variable: Stakeholders

Focusing on the Asymp Sig. values, the Asymp Sig. values greater than 0.05 implied that almost all of them had no significant differences in opinions of interest and each factor. The results revealed that some issues such as footprint required, investment cost and university image that had the Asymp Sig. values were about

0.015, 0.002 and 0.04 respectively. Since the values were less than 0.05, it is implied that the Mean Rank about the opinion of those three issues by the four sample groups has the statistical differences (i.e., H1 accepted) at 95% confidence. Following to the survey data analysis as shown in Table 4.8, the factor regarding “footprint requirement” for installing the zero-waste was much gaining interest as the decisive factor for the group of engineer/technician people. Meanwhile, the factors regarding the “investment cost” and “university image” are significantly interest by the group of management and the group of engineer/technician too.

CHAPTER 5
INNOVATIVE ZERO-WASTE SYSTEM AND TESTING RESULTS

5.1 Innovative zero-waste system and testing results The chapter shows the detailed zero-waste system that was installed and used for the experiment in the study. The zero-waste system has been installed and operated at the Chulachakrabonse building for wastewater and food waste treatment to treat and utilize the benefits of the treated wastes. The system consists of three major processes, i.e. (1) the shredder and screw conveyor unit to convey the food waste into the anaerobic digester; (2) the anaerobic digester for treating the shredded food waste along with the biogas production, and (3) the Moving Bed Biofilm Reaction–Membrane Bioreactor (MBBR-MBR) process for wastewater treatment and reuse. The waste are all circulated inside the system.

5.2 The innovative zero-waste system

The zero-waste system has been operating by starting from (1) collecting food waste, (2) feeding the food waste into the shredder and the shredded waste is conveyed to the anaerobic digester by the screw conveyor (during this step) water is also added to the shredder for helping the shredding process, (3) the stirrer inside the digester has been starting at the same time during food waste feeding, (4) samples are collected in the experiment to monitoring the process and (5) biogas is collected by the gas towers.

5.2.1 Food waste management system using the food shredder and anaerobic digester

The zero-waste system has been operating as shown in Figures 15–17. Figure 15 shows the overview of the system that consists of different units i.e. shredder, screw conveyor, the single-stage anaerobic digester and gas holding tanks. The food shredder is installed to prepare the food waste to be the substrates (size between 5-10 mm). The shredded food waste is fed by the screw conveyor to pass it to the digester. A controller unit is developed for controlling the food waste treatment system operations. The single-stage anaerobic digester has the volume about 2500 L with working volume around 1250 L. A paddle type mixer is installed inside the digester to provide the slow mixing at short period during the food-waste feeding (Figure 17). The biogas generated from the anaerobic digester is kept in the biogas holding tank and sent through the gas pipeline for further utilization in canteen.

Figure 15 Overview of the food waste treatment system using in the zero-waste

Figure 16 Controller unit of the food waste treatment system

Figure 17 Digester unit (inside)

To start operation the food waste treatment system, the swine manure is used as the slurry for feeding into the anaerobic digestion system with energy recovery is the diesel consumption. In the study, the swine slurry transport from swine farm outside the Bangkok (Ratchaburi province) to Chulalongkorn University (Figures 18-20).

Figure 18 Collecting the swine manure from Ratchaburi province to use as the feed of food waste

Figure 19 Swine manure is loaded into the digester

Figure 20 The anaerobic digester that is filled by the swine manure at the beginning stage of the zero-waste system

Food waste is collected from the canteen of Chulachakrabonse building in order to feed into the anaerobic digester. Figure 21 shows the example of food waste used in the system. Figure 22 shows how to feed the food waste into the shredder. Water is added during this step to help the shredding and transferring the food waste.

Food waste (FW)

Vegetable and Fruit Waste (VFW)

Figure 21 Example of food waste and vegetable waste used in the study

Figure 22 Food waste feeding method

Figure 23 shows the biogas holding tank with floating drum to indicate the availability of biogas. The volume of biogas is measured by gas flow meter connected with the anaerobic digester. The compressed pressure tank is also installed to increase pressure to 2 bar for sending it to the canteen.

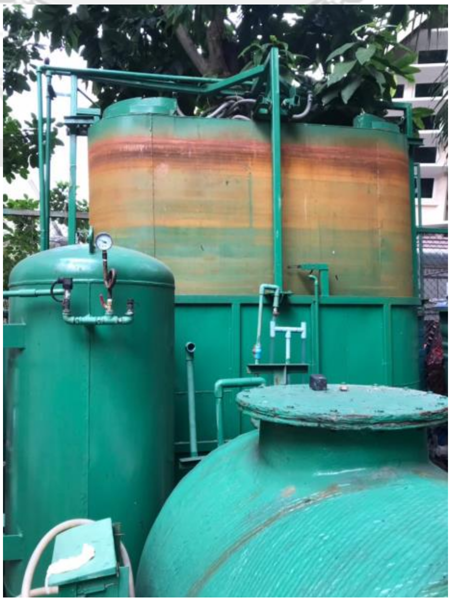


Figure 23 Biogas holding tank and compressed pressure tank

5.2.2 MBBR-MBR for wastewater management and recycle

For wastewater treatment, MBBR is the biofilm wastewater treatment technology that combining biological contact oxidation and biological fluidized bed in order to improve wastewater treatment efficiency (Di Trapani et al., 2014). The MBBR-MBR system is the activated sludge system with attached biofilm growth media that uses membrane filtration to replace a sedimentation tank (Figure 24). The microfilter (MF) membrane with a pore size of 0.4 microns is installed in the aerobic zone as well. The membrane permeation rate was kept at 2 cubic meters per day. The wastewater from the building will be fed in the anaerobic zone. The small pore of the membrane can capture the bacteria in the system to prevent it discharged together with the discharged water. Also, the system can use to substitute the bacteria and virus disinfection systems. The viruses that are larger than the porosity of membrane will not allow to pass the membrane and contaminate into the discharged water after the treatment of wastewater in the building. This membrane system is thus gaining attraction for treating and recycling the wastewater of building

The moving bed biofilm carrier is installed inside the aerobic zone. The biofilm carrier will cover the volume of nearly 20% of the total volume of the aerobic zone. In the study, the moving bed biofilm reactor media (round shape type) used in the system is made from polyethylene, and the active surface area is around 3,000 m^2/m^3 (Figure 25). The outlet water from the MBBR unit will go to the membrane bioreactor process (MBR) process. The MBR is gaining interest as the wastewater treatment technology that can help reduce the footprint required. Nevertheless, the membrane needs to be cleaned regularly. Figures 26 – 27 show the step of cleaning the membrane using Sodium hypochlorite. The samples are collected and analyzed via both on-site. The objectives of sampling and monitoring of wastewater are to assess the COD, N, and P removal efficiency for long-term operation of the system and the potential for liquid bio-fertilizer production. Figure 28 shows the example of on-site monitoring and Figure 29 shows the wastewater samples for the laboratory. The treated water after the MBR process is sent to the treated water tank and further use for watering the plants (Figure 30).

Figure 24 Oxidation ditch shape

Figure 25 Biofilm carrier (MBBR media) comparing the new MBBR media and the active MBBR media

Figure 26 Moving the MBR for cleaning

Figure 27 MBR cleaning

Figure 28 Onsite measurement of wastewater samples

Figure 29 Wastewater samples

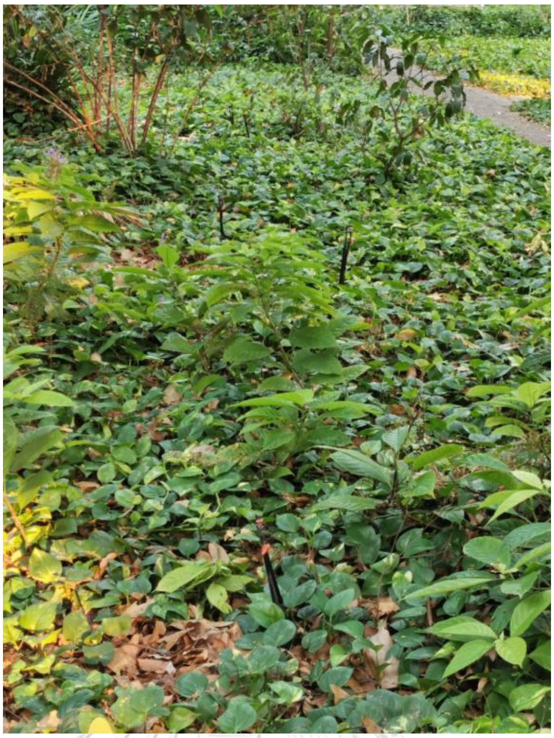


Figure 30 Recycled water for watering the garden

5.3 Testing results for the anaerobic digestion process of zero-waste system

5.3.1 Characteristics of food waste feedstock

The anaerobic digestion process is evaluated by measuring the following parameters: total solids, total suspended solids, volatile solids, COD, VFA, pH, Alkalinity, total phosphorus (TP), total Kjehldahl nitrogen (TKN), and biogas production. Table 28 shows the characteristics of food waste and the co-substrate feed, i.e., food waste (FW) mixed with the vegetable and fruit waste (VFW) and the waste sludge (WS) from the wastewater plant. The high variation of characteristics of feedstock is due to the variation of food waste from the canteen. The variations of enough and the variety of food waste sources were collected for feeding into the system. The ratio of volatile solid to total solid content (VS/TS) was 89.35%; this implied that the feedstock has organic content suitable for bacteria growth.

Table 28 Characteristics of food waste and fruit and vegetable waste in the study

Feedstock	Food waste feedstock		
	100% FW	80%FW20%WS	60% FW20% FVW20%WS
pH	5.6 ±0.2	6.5 ±0.4	4.7 ±0.6
COD (mg/L)	146,164 ±35,482	173,333 ±13,796	195,488 ±62,438
TS (mg/L)	108,486 ±31,372	101,133 ±56,305	77,441 ±48,672
TVS (mg/L)	85,779 ±28,500	93,400 ±56,052	54,394 ±57,279
TKN (mg/L N)	2,424 ±840	1,653 ±1,511	17,060 ±17,271
Ammonia (mg/L N)	169 ±72	140 ±48	135±75
Nitrate (mg/L N)	42 ±66	7 ±5	52.5±31.1
Alkalinity (mg/L $CaCO_3$)	4,606 ±3,610	200 ±115	356 ±130
Phosphate, Total (mg/L P)	952 ±846	501 ±103	123±28
Phosphate, Ortho (mg/L P)	401 ±286	380 ±58	65±17
VFA (mg/L $CaCO_3$)	27,566 ±15,115	12,600 ±2,425	9,830 ±934

5.3.2 Monitoring parameters of the anaerobic digester

Table 29 shows the monitoring results of the digestate from the anaerobic digester for different three testing runs i.e. 100% food waste (100%FW), 80% food waste with 20% waste sludge (80%FW20%WS) and 60% food waste mixed with 20% fruit and vegetables and 20% waste sludge (60%FW20%FVW20%WS).

Table 29 Parameters analyzed in the digester system

Parameters	Digestate		
	100% FW	80%FW20%WS	60% FW20% FVW20%WS
pH	7.3 ± 0.1	7.4 ± 0.1	7.4 ± 0.0
COD (mg/L)	47,825 ± 10,351	33,325 ± 1,053	21,875 ± 11,350
TS (mg/L)	41,239 ± 10,422	27,270 ± 9,605	17,503 ± 14,867
TVS (mg/L)	28,263 ± 7,756	18,105 ± 6,818	11,016 ± 10,538

Parameters	Digestate		
	100% FW	80%FW20%WS	60% FW20% FVW20%WS
TKN (mg/L N)	2,859 ± 1,024	1,828 ± 430	14,620 ± 14,005
Ammonia (mg/L N)	952 ± 286	1,150 ± 42	1,580 ± 76
Nitrate (mg/L N)	5.8 ± 2.6	4.5 ± 0.5	104 ± 29
Alkalinity (mg/L $CaCO_3$)	5,048 ± 791	5,358 ± 47	6,215 ± 5,785
Phosphate, Total (mg/L P)	2,155 ± 1,422	781 ± 99	531 ± 84
Phosphate, Ortho (mg/L P)	324 ± 143	161 ± 64	82 ± 46
VFA (mg/L $CaCO_3$)	1,675 ± 1,548	722 ± 45	864± 878

5.3.3 pH variations in an anaerobic digester

The digester's pH value is considered the function of volatile fatty acid (VFA) concentration, alkalinity, and bicarbonate concentration of the system as well as the fraction of CO_2. Figure 31 showed the pH variations of input food waste comparing to the pH in the anaerobic digestion system. The average pH in the anaerobic digester was 7.3 ± 0.1 for 100% food waste, 7.4 ± 0.1 for 80%FW20%WS and 7.4 for 60%FW20% FVW20%WS as shown in Table 29. Although the optimal pH range for methanogenic bacteria to obtain maximum biogas yield in anaerobic digestion is about 6.5-7.8 (Liu, Yuan, Zeng, Li, & Li, 2008) and the obtained pH value in the digester was still comply with the range. However, it was slightly high because the high variation rich in proteins and ammonia of food waste organic material.

5.3.4 VFA variations in an anaerobic digester

Figure 32 shows the VFA values of the digestate for the different feedstocks i.e. 100%FW, 80%FW20%WS and 60%FW20%FVW20%WS. Volatile fatty acid (VFA) is an important parameter predicted digester failure because it is linked to the pH of the digester. The VFA is an intermediate substrate for producing methane; therefore, it plays an important role in indicating the stability and performance of the digester that need to be monitored. The VFA is produced in the anaerobic digestion process through hydrolysis and acidogenesis, and the high amount of VFA can lead to a decrease in pH. The system can fail if there is an increased accumulation of VFA. Table 27 showed that the average VFA concentration resulted from the anaerobic digesters was 906 mg/L. The value was lower than 1500 mg/L, commonly considered the upper limit for allowing the biogas digester's stable operation.

5.3.5 Alkalinity variations in an anaerobic digester

Alkalinity prevents the fluctuations of pH in the anaerobic digester therefore it is an indicator to be measured in the study. Figure 33 shows the alkalinity values of the digestate for the different feedstocks i.e. 100%FW, 80%FW20%WS and 60%FW20%FVW20%WS. The values are higher than 1,500 mg/L, which is considered for allowing stable operation of biogas digester.

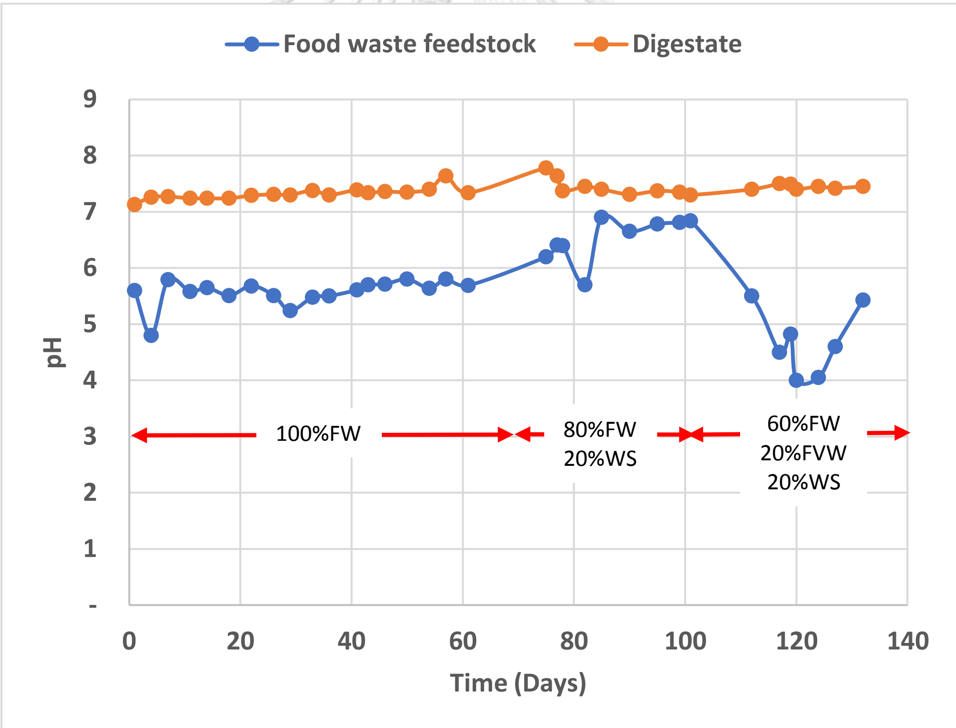


Figure 31 pH variations of input food waste and the digestate

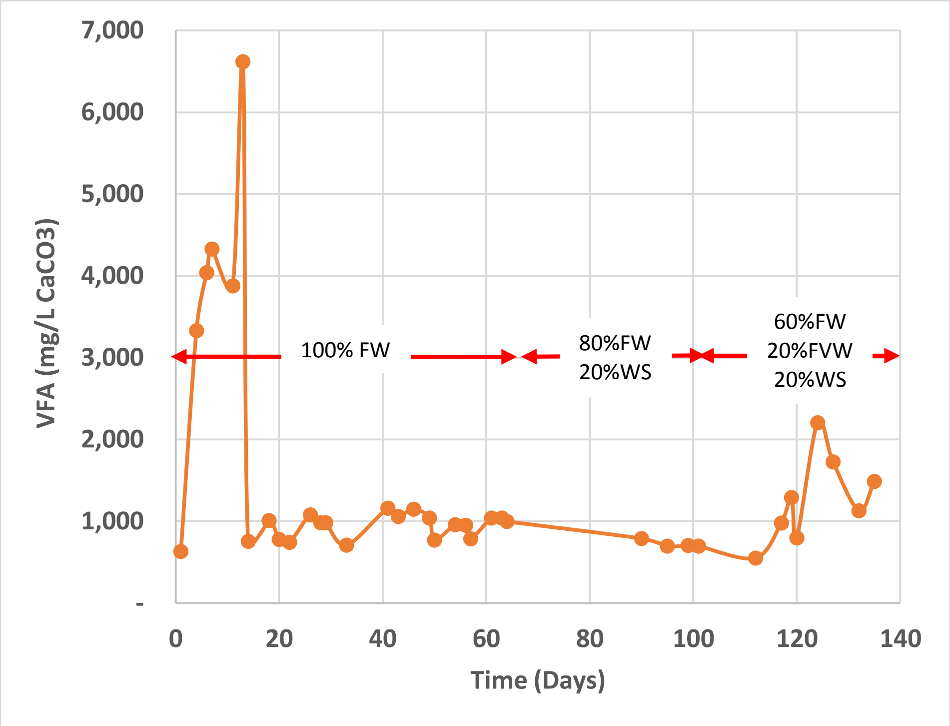


Figure 32 VFA variations in the anaerobic digester

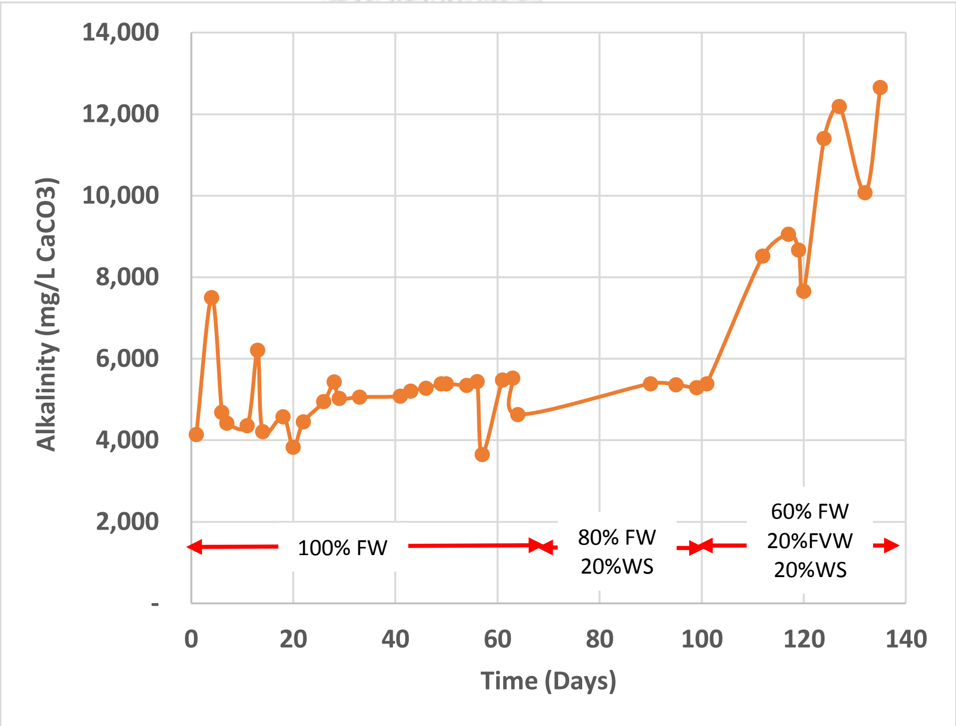


Figure 33 Alkalinity variations in the anaerobic digester

5.3.6 VFA/Alkalinity in an anaerobic digester

Figure 34 shows the VFA/Alkalinity variations in the anaerobic digester. The buffering capacity measured as the ratio of VFA/Alkalinity was about 0.17 implied the strong buffering capacity as the value of VFA/Alkalinity ratio lower than 0.4. If the value of close to 0.8, the system could fail due to the weak buffering capacity. The appendix shows the detailed analytical results of samples collected over the past experiment.

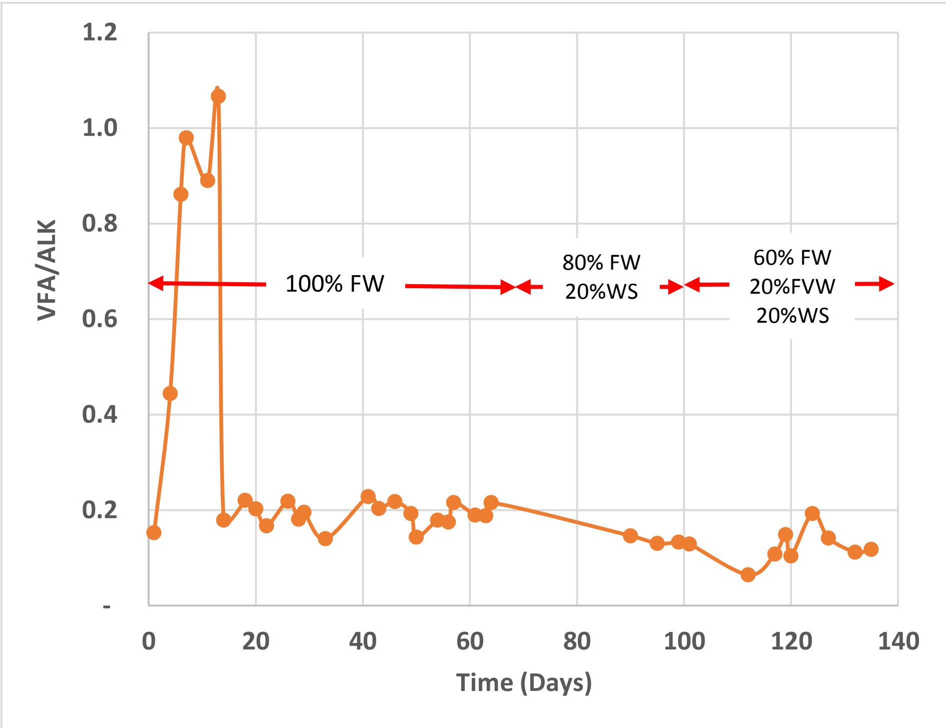


Figure 34 VFA/Alkalinity in the anaerobic digester

5.3.7 Total Solids (TS) and Total Volatile Solids (TVS) variations

Figure 34 shows the total solids of feedstock for the 100%FW, 80%FW20%WS and 60%FW20%FVW20%WS. By the average value, the total solids are reduced by the anaerobic digestion process. From the Tables 28 and 29, the TS is reduced from 108,486 to 41,239 mg/L (for 100%FW) and 77,441 to 17,503 mg/L (for 60%FW20%FVW20%WS). While, the Figure 35 also shows total volatile solids of feedstock for the 100%FW and 60%FW20%FVW20%WS. From the Tables 28 and 29, the TVS is reduced from 85,779 to 28,263 mg/L (for 100%FW) and 54,394 to 11,016 mg/L (for 60%FW20%FVW20%WS).

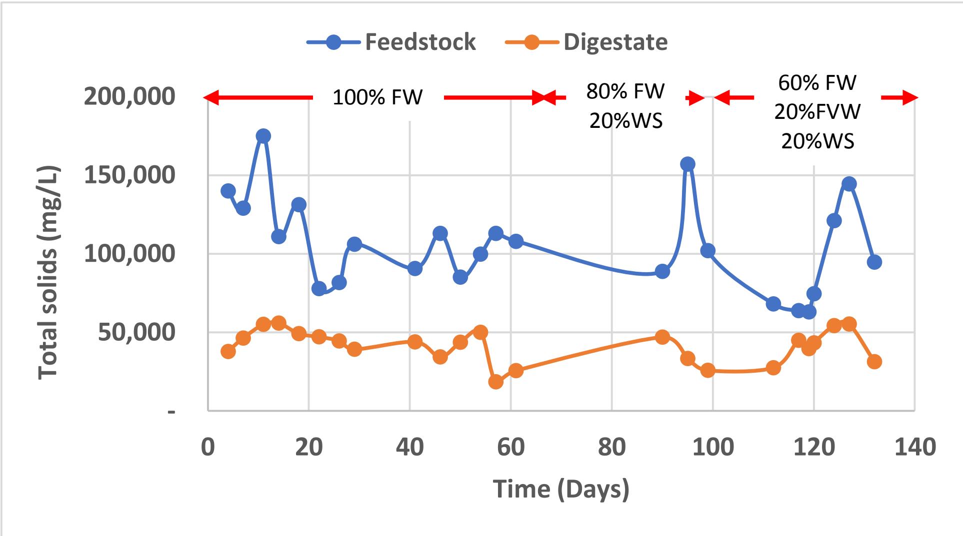


Figure 35 Total solids of feedstock and digestate of the anaerobic digester

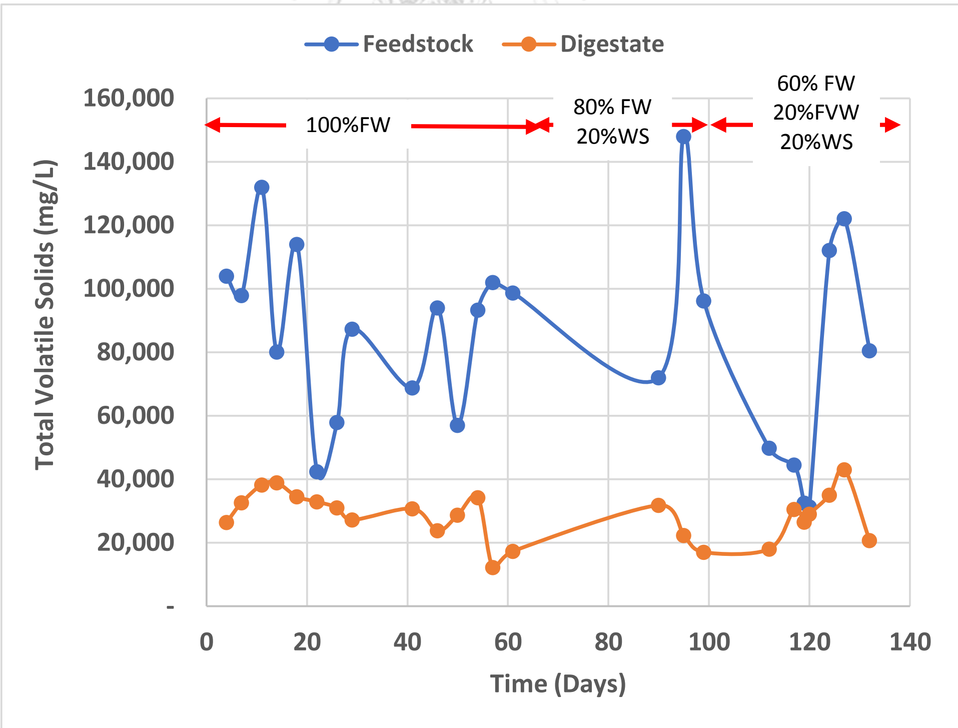


Figure 36 Total solids of feedstock and digestate of the anaerobic digester

5.3.8 COD removal and biogas generation

The food waste and vegetable & fruit waste added in the digester was prepared by the shredder to mix and homogenize the feedstock. The COD of feedstock and digestate are measured as Figure 36. The average COD of feedstock and liquid digestate from the single-stage anaerobic digestion process (as Tables 28 and 29) indicated that the system's COD removal efficiency was about 75%, or the COD could be removal around 125,857 mg/L.

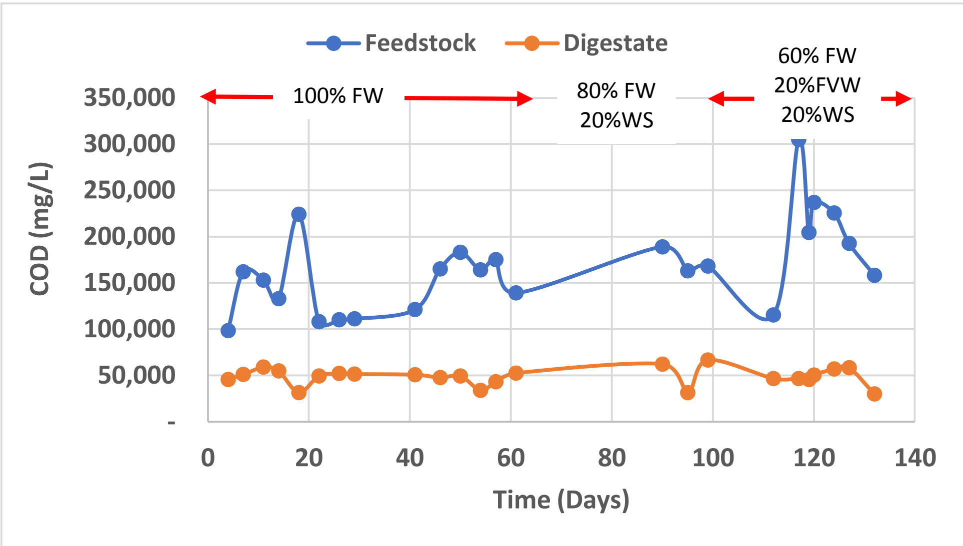


Figure 37 COD variations of feedstock and digestate of the anaerobic digester

Figure 38 shows the accumulation of biogas generation. The daily biogas production was observed from the meter along with the food waste input and the COD removal information; the results revealed that the biogas production is about 0.1265 m^3/g COD removed. However, the high variation of the % methane in biogas depended on the performance, operation control, and system period. The percentages of methane were varied from 21% - 65%. However, it must be noted that the low percentage of methane reported here occurred during the startup period of the plant, there was some effect from the food waste and pH value in the digester. However, after running the system for a few week, the system was more stable and the averaged percentage of methane in the biogas were ranged from 56 – 65%. The analysis has also done by comparing the amount of biogas production in different feedstock scenarios as shown in Figure 39. The results show that the case "60%FW20%FVW20%WS" has the highest averaged biogas production i.e. 0.43 Nm^3/day. The range of the biogas generation was about 0.15 – 0.8 Nm^3/day.

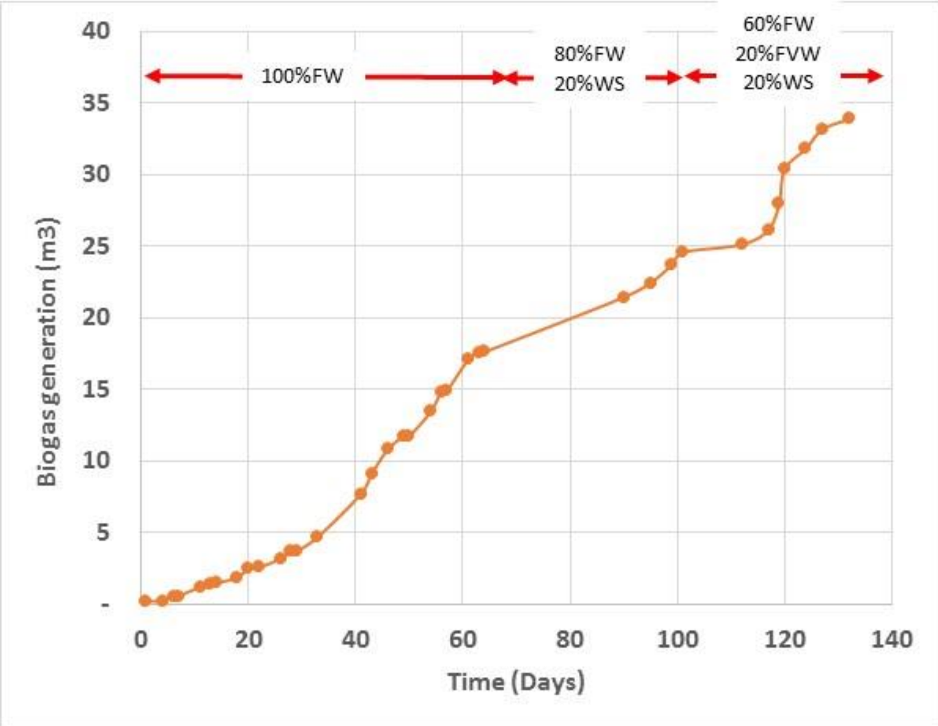


Figure 38 Accumulate biogas generation during the testing of system

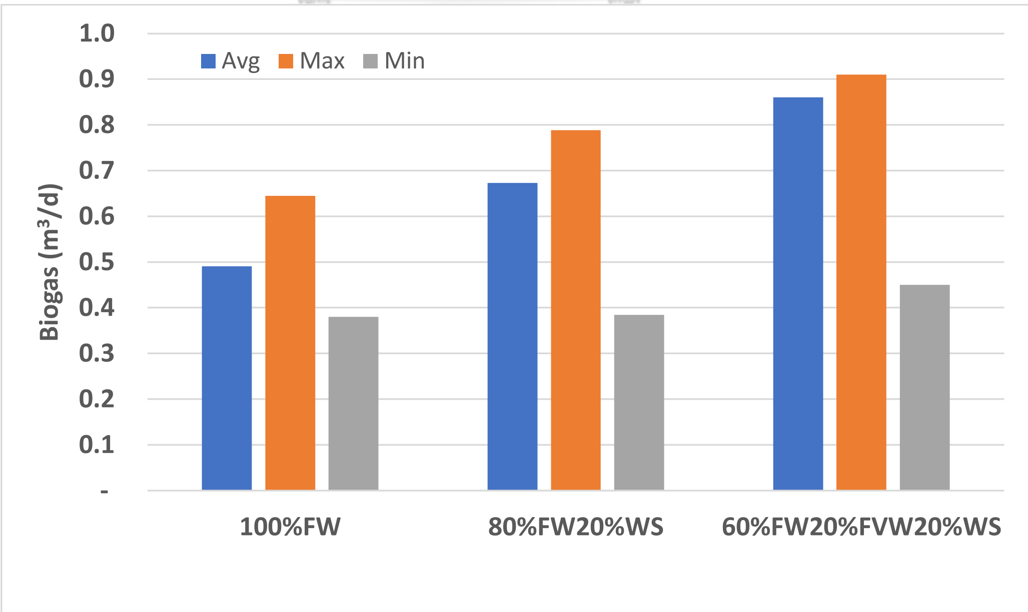


Figure 39 Biogas generation for different food waste feedstock scenarios

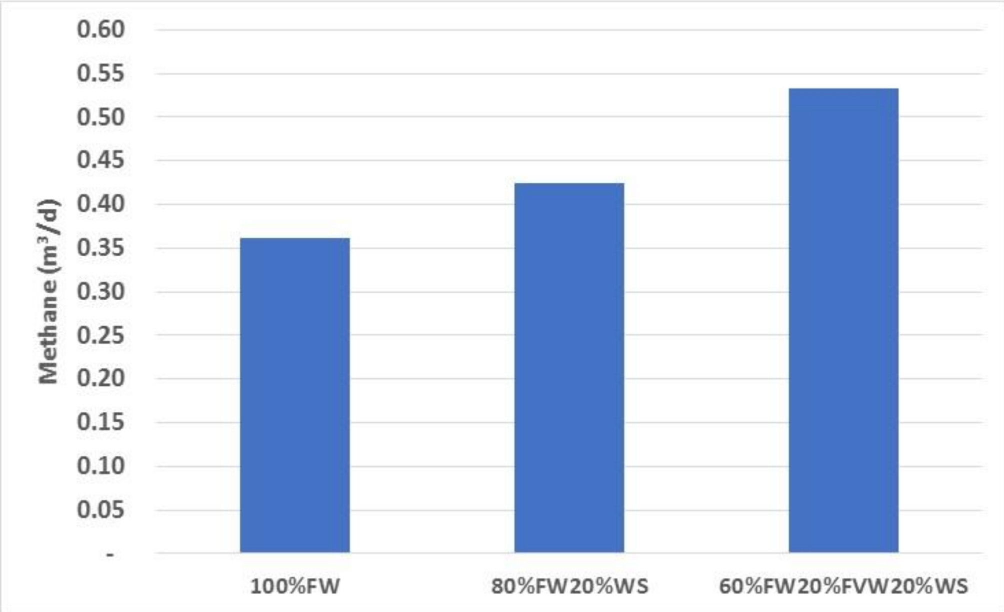


Figure 40 Methane gas production for different food waste feedstock scenarios

The amount of methane gas generation can be analyzed and shown in Figure 40. The results show that the case "60%FW20%FVW20%WS" has the highest averaged methane generation according to the biogas production and the higher percentage of methane. The results shown that for cases 2 and 3 which are the anaerobic co-digestion between the food waste and wastewater sludge result in the improved yield of methane. This consistent to the several studies that have shown that using co-substrates in anaerobic digestion systems lead to the positive synergisms in the digestion medium (Chow et al., 2020).

The co-digestion of food waste and sewage sludge can help improve the system stability and enhance the volumetric biogas production as comparing to the mono digestion because the addition of sludge could reduce Na+ concentration which in turn help maintain the stability during conversion of food waste to biogas (Dai, Duan, Dong, & Dai, 2013). Food waste general contains higher concentration of dissolved salts e.g. sodium which can inhibit microbial growth and decrease the methane yield (Mehariya, Patel, Obulisamy, Punniyakotti, & Wong, 2018). In addition, the degradation of protein-rich FW such as meat which contains high ammonia, will release ammonium ions. However, if the ammonium ion is too higher i.e.

concentration more than 1500 mg/L, it will moderate inhibitory effects on methane production (Mehariya et al., 2018). The sludge can help increase the nutrients like nitrogen and phosphorus. Nitrogen is essential to the growth and phosphorus is required to accelerate the metabolic rate of microbes associated with the anaerobic digestion process (Zhang, Wu, Guo, Zhou, & Dong, 2015).

The removal efficiency for the volatile solid and COD by the anaerobic digestion process of the zero-waste system was about 64-73% and 65-86%, respectively as shown in Figure 41. The case "60%FW20%FVW20%WS" has the slightly higher percentage of VS and COD removal efficiency.

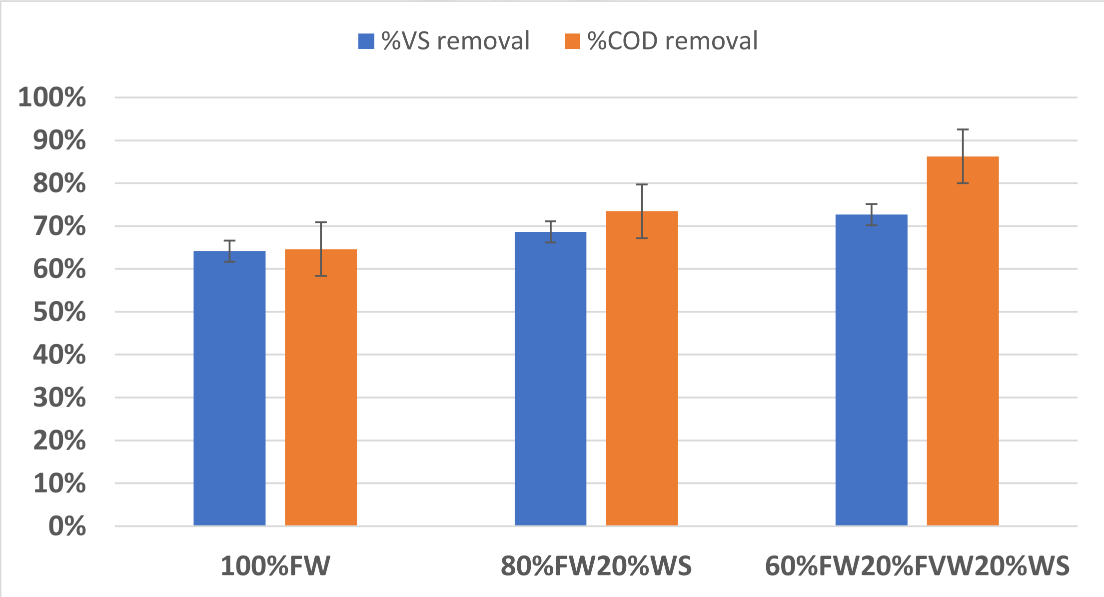


Figure 41 *VS and COD removals efficiency of digester for different feedstock*

5.3.9 Temperature

Figure 42 shows the average temperature of the anaerobic digester that was about 30.2 °C and 27.0 °C for the case of 100% food waste and 60%FW20%FVW20%WS, respectively. The optimal temperature for microorganism to grow in mesophilic temperature range (25.9-32.6 °C). The seasonal effect e.g. summer and/or winter might be effect to the operating temperature inside the digester.

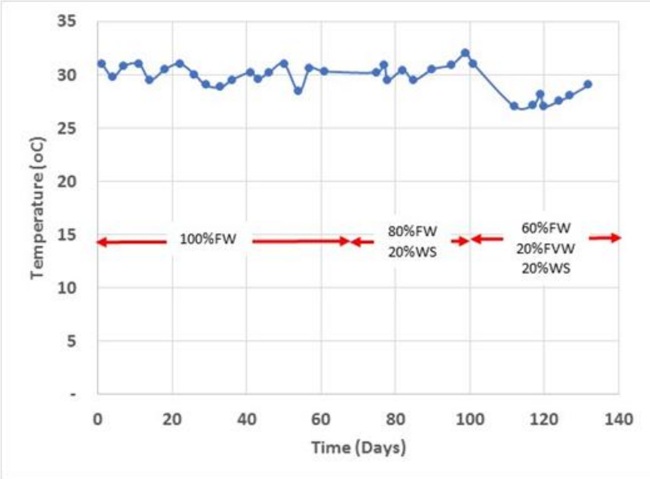


Figure 42 Temperature variations in the anaerobic digester

5.4 Testing results for the MBBR-MBR process of zero-waste system

5.4.1 Wastewater sample collection

Figure 43 shows the wastewater samples collected from the wastewater treatment plant classified into three sampling points i.e. wastewater inlet, water in the reactor and treated water outlet as shown by no.1, 2 and 3, respectively. It can be seen that the no.3 which is the treated wastewater after the MBBR-MBR, there is the significant clear color of water as compared to the inlet wastewater (no.1).

No.1 No.2 No.3

Figure 43 Wastewater and treated water samples

5.4.2 COD variation of wastewater and the treated water

Figure 44 shows the COD results of inlet wastewater to the MBBR-MBR and the outlet water after the treatment system to see their variations. The average COD of inlet wastewater is around 223 mg/L (Range 135-400); meanwhile, the average COD of the treated water is about 22 mg/L (Range 20-45). Figure 45 shows the NH_4 variations results. The average NH_4 of the treated wastewater is about 25 mg/L.

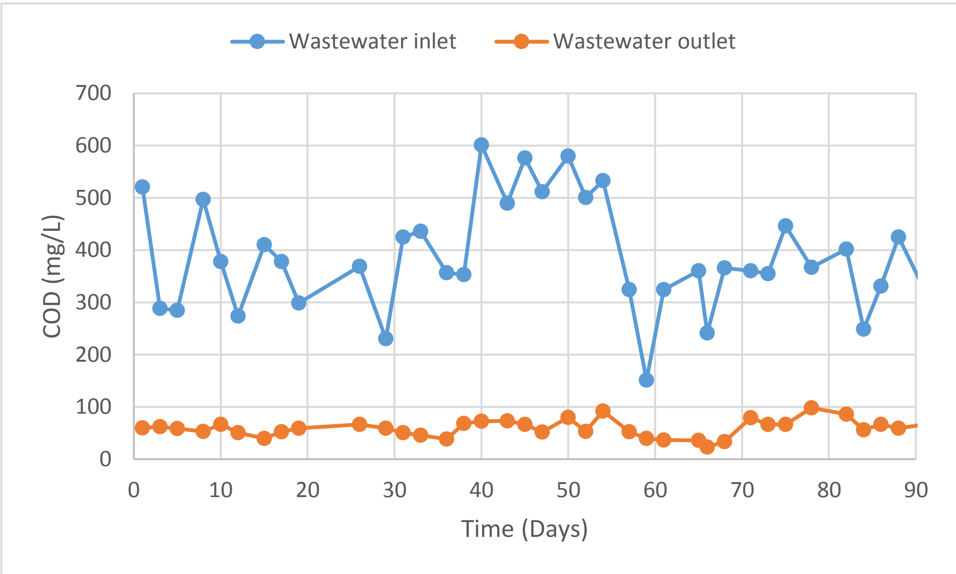


Figure 44 COD of wastewater and treated water after passing MBBR-MBR

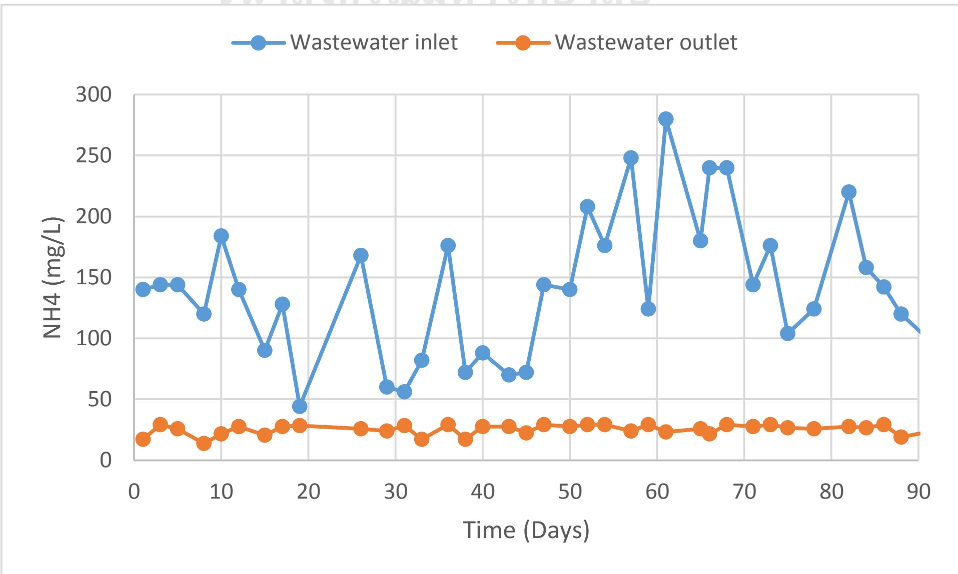


Figure 45 NH_4 variations of wastewater and treated water after passing MBBR-MBR

Table 30 shows the average water quality parameter of treated wastewater by MBBR-MBR. The results are compared to the US EPA Guideline for water reuse (2012) (US-EPA, 2012). The results show that the treated water have passed the standard of landscaper irrigation as well as the nonfood crop irrigation. This implies that there is the potential to be used of the water for landscape in the university.

Table 30 Water quality parameters of the treated wastewater by MBBR-MBR and the standard for water reclamation as agricultural reuse

Water quality parameters	Treated WW from MBBR-MBR	Agricultural reuse (US-EPA, 2012)	
		Landscape Irrigation	Nonfood crops
pH	7.3	6-9	6-9
TS (mg/L)	<0.2	-	-
BOD (mg/L)	2.05	≤ 30	≤ 30
Turbidity (NTU)	0.76	≤ 2 NTU	≤ 30 (SS)
COD (mg/L)	22	-	-
Ammonia (mg/L as N)	16.9	-	-
Nitrate (mg/L as NO_3)	28.9	-	-
Ortho Phosphate (mg/L as PO_4)	1.9	-	-
Fecal coliform (No./100 mL)	No detectable	No detectable	≤ 200

The results show that the treated wastewater by the MBBR-MBR unit in the zero-waste system is able to be used for watering the garden in the university as proposed. The results are compared to the US EPA Guideline for water reuse (2012) and it can be seen that the treated water have passed the standard and it has the potential to be used as agricultural reuse for nonfood crops in the university.

5.5 COD balance analysis of the zero-waste system

The overall zero-waste system can be explained by the mass balance concept. The study has thus assessed the COD balance of the zero-waste system and simplifying the results into Figure 46. A zero-waste system's mass balance can be done by assuming the steady-state condition. The following equations are the mass balance equation for the anaerobic digester and the MBBR-MBR.

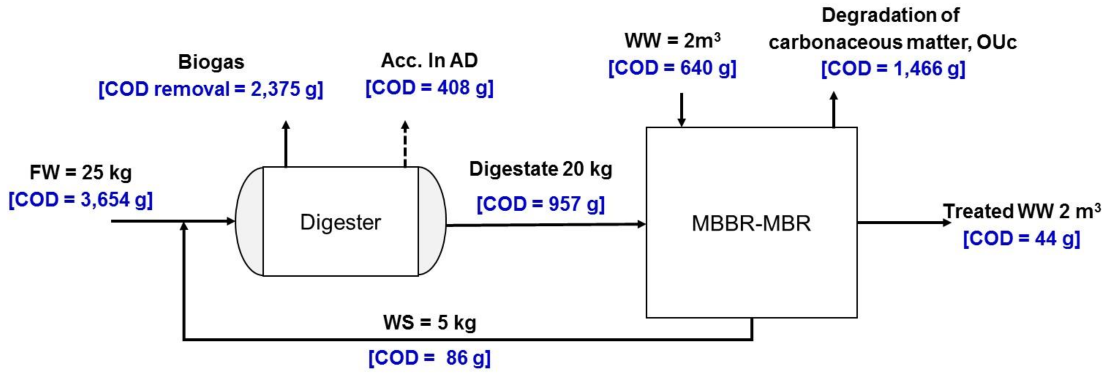


Figure 46 COD balance of the zero-waste system

(1) Single stage anaerobic co-digestion

From Figure 46, the material balance based on the COD for an anaerobic digester can be determined by using Equation (1). The steady state condition is assumed at the digester. The calculation is based on the food waste and wastewater input to the system per day.

$$FW_{COD} + WS_{COD} = BIOGAS_{COD} + DIGESTATE_{COD} + ACC \qquad \text{Equation (1)}$$

Where

- FW_{COD} represents the amount of COD input from the food waste input (g/day)
- WS_{COD} represents the amount of COD input from the sludge of MBBR-MBR (g/day)
- $BIOGAS_{COD}$ represents the amount of COD that is removed and converted to be the biogas (CH_4) (g/day)
- $DIGESTATE_{COD}$ represents the amount of COD output with the digestate sent to the MBBR-MBR (g/day)
- ACC represents the unbalance with is considered as the amount of accumulate COD in the anaerobic digester in terms of digestate (g/day)

The results show that the COD input about 3,654 g is obtained from 25 kg food waste and the COD concentration of about 146,164 mg/L. The COD removal from the digester and converted to be the CH_4 in biogas and the rate of COD removal is about 65%. The digestate about 20 kg is sent to the MBBR-MBR, the COD concentrate of digestate is about 47,825 mg/L. The ACC is obtained from the mass balance calculation which will show the unbalance amount of the all stream i.e. 408 g. It is considered as the amount of COD that accumulate in the digester in form of digestate.

(2) MBBR-MBR

From Figure 46, the material balance based on the COD for an MBBR-MBR can be determined by using Equation (2). The steady state condition is assumed at the MBBR-MBR.

$$WW_{COD} + DIGESTATE_{COD} = TWW_{COD} + WS_{COD} + OU_C \qquad \text{Equation (2)}$$

Where

- WW_{COD} represents the amount of COD input from the wastewater (g/day)
- $DIGESTATE_{COD}$ represents the amount of COD output with the digestate sent to the MBBR-MBR (g/day)
- TWW_{COD} represents the amount of treated wastewater that is sent out for watering the garden (g/day)
- WS_{COD} represents the amount of COD output from the sludge of MBBR-MBR that sent to the AD system (g/day)
- OU_C represents the degradation of the carbonaceous matter due to the organic matters take places with oxygen (g/day)

The results show that the COD input from wastewater is 640 g based on 2 m^3 of wastewater per day from the building and the COD concentration of about 320 mg/L. The digestate about 5 kg is sent to the MBBR-MBR, the COD concentrate of digestate is about 47,825 mg/L. The treated water around 2 m^3/d is sent to watering the garden and the COD of the treated water is about 22 mg/L. The OU_C is thus obtained from the mass balance calculation which will show the unbalance amount of the all stream. It is considered as the amount of degraded COD i.e. around 1,466 g. The system is considered as the balance system for the zero-waste system.

5.6 Life-cycle energy and GHG emissions assessment of the zero-waste system

The study aims to assess the cumulative energy demand and GHG emissions of a zero-waste system for building wastewater recycling and food waste management using the life cycle assessment (LCA). The study goal is to evaluate life-cycle energy use and GHG emissions of the operating zero-waste system at the Chulachakrabonse building for reusing wastewater and producing the biogas from food waste by comparing to the conventional food waste and wastewater treatment techniques, i.e., landfill of organic waste and the treatment of wastewater using the activated sludge system. The functional unit is set to treat about 60 kilogram of food waste and 2 m^3 of wastewater, which is the average daily waste input into the system.

5.6.1 System boundary and functional unit of assessment

Figure 47 shows the simplified system boundary of the zero-waste system for conducting the life cycle analysis.

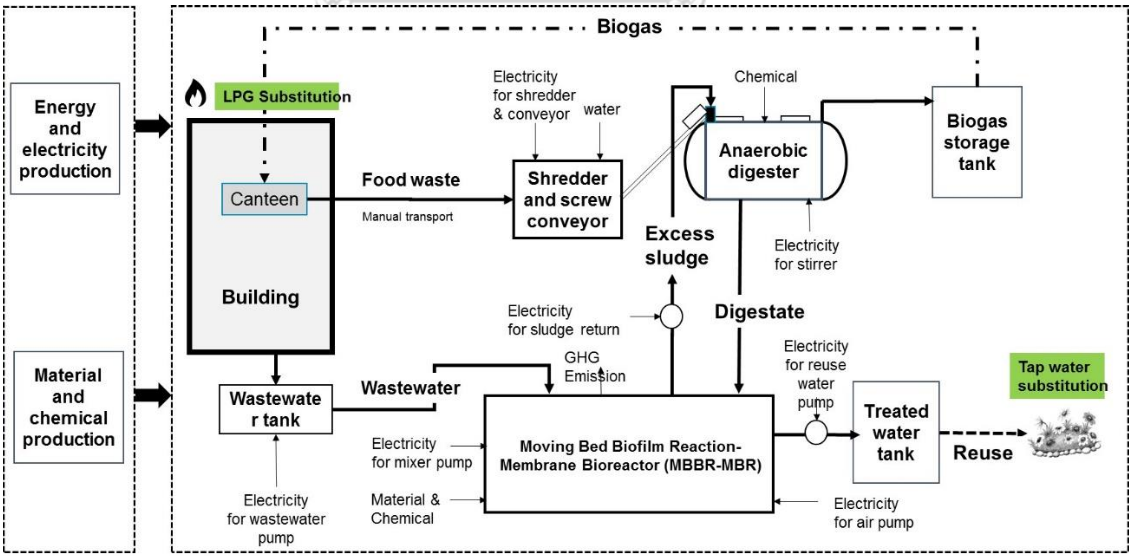


Figure 47 System boundary of the studied zero-waste system

The scope of assessment covers the “cradle-to-grave” which can be separated into five main life-cycle stages, i.e.

(1) Production of materials/fuel/energy/electricity used;

(2) Wastewater treatment and recycling;

(3) Food waste treatment;

(4) Use of biogas and treated water reuse; and

(5) Environmental credits from the biogas and treated wastewater reuse.

The environmental credits from the biogas and treated water reuse are accounted for as the substitution of LPG used for cooking in the canteen and the replacement of tap water used for watering the plants.

5.6.2 Life cycle inventory analysis

The key environmental interventions considered are the resources used, materials, and chemicals used for the zero-waste system operation. Table 31 shows the LCI data sources used in the study.

Table 31 LCI data sources

Life cycle stage	Inventory	Sources
Material and chemical production	Lime, Polyethylene, Tap water, Sodium hypochlorite, LPG	(Ecoinvent3.0, 2012)
Utility	Grid-mixed electricity Tap water	(MTEC, 2014) (Ecoinvent3.0, 2012)
Transport of pig slurry	Municipal waste collection service	(Ecoinvent3.0, 2012)

To operate the zero-waste system, electricity is one of the key input required for the operation. Table 32 shows the lists of pump and motor used in the zero-waste system which the electricity consumption for those all machine is necessary to determine in LCA.

Table 32 Pump and motor used in the zero-waste system

No	Unit operation	Machine	Picture	Description
1	Shredder	Motor for screw conveyer		1.5 kW, 2 hp 1390 rpm, 6.43 A
2	Anaerobic digester	Motor for stirrer		1.5 kW, 2 hp 1390 rpm, 6.43 A
3	MBBR-MBR	Motor for sludge suction		0.75 kW, 1 hp 2850 rpm, 5.20 A
		Motor for outlet treated water		0.37 kW, 0.5 hp 1400 rpm, 2.81 A
		Moroe for inlet wastewater		0.75 kW, 1 hp 2850 rpm, 3.80 A
		Aeration unit		0.115 kW

Table 33 shows the inventory data primarily collected from the operating zero-waste system at the Chulachakrabonse building based on the functional unit. The SimaPro software and the Ecoinvent database inside the SimaPro Software used for the data compilation and analysis.

Table 33 Environmental impact factors based on the inventory, impact assessment

Inventory	**unit**	**Environmental impact factors** Climate change (CC Factor) kg CO_2eq/unit	Cumulative Energy Demand (CED Factor) MJeq/unit	**Source**
Electricity	kWh	0.609	2.26	(MTEC, 2014)
Lime, hydrate, packed (GLO)	kg	0.88	5.92	(Ecoinvent3.0, 2012)
Municipal waste collection service by 21 t lorry (GLO)	t.km	1.3	19.4	(Ecoinvent3.0, 2012)
Polyethylene, high density, granulate (GLO)	kg	2.04	73.2	(Ecoinvent3.0, 2012)
Sodium hypochlorite, without water, in 15% solution state (GLO)	kg	1.1	11.8	(Ecoinvent3.0, 2012)
Liquefied petroleum gas (LPG) market	kg	0.72	57.1	(Ecoinvent3.0, 2012)
Tap water, at user (RoW) market	m^3	0.474	4.95	(Ecoinvent3.0, 2012)

*GLO = Global, RoW = Rest of the World

Table 34 shows the environmental impact factors of key material, chemical and energy used in the zero-waste system. The environmental impact factors are calculated by using the software to run the two impact assessment per unit of material i.e. climate change (using the ReCipe Impact assessment method which referring the IPCC 2013) and the cumulative energy demand factor (CED factors)

Table 34 Life cycle inventory of the studied zero-waste system as per functional unit (Waste input: 60 kg of food waste and 2 m^3 wastewater)

Life cycle stage	Inventory	Unit	Value
Food waste treatment	Food waste input	kg	60
	Electricity (shredder, conveyor, and stirrer)	kWh	1.95
	Water (during shredding)	L	6
	Lime	kg	0.6
	Pig slurry	m^3	0.01
	Transport distance for pig slurry	km	100
	Biogas produced	Nm^3	5.6
Wastewater treatment	Inlet wastewater	m^3	2
	Electricity (inlet wastewater pump)	kWh	0.32
	Electricity (MBBR-MBR e.g., mixer, air pump, and sludge return)	kWh	1.76
	Polyethylene (media material)	kg	0.003
	Tap water (membrane cleaning)	L	3.4
	Sodium hypochlorite (membrane cleaning)	kg	0.34
Use of biogas	LPG substitution[1]	kg LPG	0.03
Use of treated wastewater for watering plants	Electricity (water pump)	kWh	0.24
	Tap water substitution	m^3	1.9

[1]Calculated based on the heating value of LPG =49 MJ/kg and the heating value of biogas = 23 MJ/Nm^3

5.6.3 Comparative CED and Life-cycle GHG emission results

Table 35 shows the cumulative energy demand and the life-cycle GHG emissions of the zero-waste system based on the management of 60 kg of food waste and 2 m^3 wastewater/day.

Table 35 Cumulative energy demand (Fossil energy) and Life-cycle GHG emissions of the zero-waste system (Waste input: 60kg of food waste and 2 m^3 wastewater)

Cumulative energy demand	Unit	Anaerobic digester	MBBR-MBR	Total system
Electricity	MJ-eq	16	20	36
Lime	MJ-eq	5		5
Transport (pig slurry)	MJ-eq	20		200
Polyethylene	MJ-eq		0.2	0.2
Sodium hypochlorite	MJ-eq		4	4
LPG (substitution credit)	MJ-eq	-151		-151
Tap water (substitution credit)	MJ-eq		-10	-10
Total CED	MJ-eq	- 110	14	-96.2
GHG emissions				
Electricity	kg CO_2-eq	1.2	1.6	2.8
Lime	kg CO_2-eq	0.8		0.8
Transport (pig slurry)	kg CO_2-eq	1.4		1.4
Fugitive methane	kg CO_2-eq	1.1		1.1
Polyethylene	kg CO_2-eq		0.0	0.0
Sodium hypochlorite	kg CO_2-eq		0.4	0.4
Fugitive N_2O	kg CO_2-eq		0.2	0.2
LPG (substitution credit)	kg CO_2-eq	-10.0		-10.0
Tap water (substitution credit)	kg CO_2-eq		-0.5	-0.5
Total GHG emissions	kg CO_2-eq	- 5.6	1.2	-4.4

The results revealed that the zero-waste system could reduce fossil energy use by around 96.2 MJ-eq. The main credit came from fossil energy use reduction due to the substitution of LPG with biogas. The total life-cycle GHG emissions would also be negative value i.e., -4.4 kg CO_2-eq/functional unit. The credits mainly originated from the biogas as well. The main contributor to the energy use and GHG emissions of the anaerobic digestion system with energy recovery is the diesel consumption for pig slurry transport from farm in Ratchaburi to use as the seed sludge. The other contributors followed by the electricity use for the stirrer in the digester and the food waste shredder, consecutively.

For the MBBR-MBR system, the primary fossil energy use is electricity consumption for the air pump, contributing around 52% and 51% of the total fossil energy use and GHG emission. Based on the analytical results of the anaerobic digester, the influent COD of the feeding substrates (food waste) was about 162,000 mg/L, and the effluent COD was 54,900 mg/L; the COD removal of the system was about 107,100 mg/L, and the biogas generation was 0.00013 Nm3/mg COD removal. This is based on the hydraulic retention time (HRT) of about 30 days. Nevertheless, it must be noted that the HRT, i.e. could significantly vary the biogas production rate; the longer HRT would have less amount of total biogas production; the percentage of methane in biogas would be higher (Ratanatamskul et al., 2014).

Although the zero-waste system's total results indicated the negative values for both cumulative fossil energy consumption and life-cycle GHG emissions; however, the main benefit is mainly from the credit of biogas. Focusing on the MBBR-MBR, the life-cycle GHG emission value was about 0.6 kg CO_2-eq/m^3 of wastewater management. This value is higher than the GHG emission of the municipal wastewater treatment used for the carbon footprint of product calculation in Thailand, about 0.14 kg CO_2-eq/m^3 of wastewater (TGO, 2020). This comparison is just to look at the GHG emission result; however, it does not imply that the MBBR-MBR system is a lower performance in terms of GHG emissions because the two systems' functions are different. The GHG emission factor of TGO is also lack enough background information of the system to analyze.

The zero-waste system aims at wastewater reuse, sludge recovery, and energy recovery; the conventional municipal wastewater treatment is only to treat the wastewater. There are several environmental advantages of MBBR-MBR, e.g., low space requirement, high efficiency of wastewater treatment and recycling, resource depletion reduction that needs to be considered. It can be concluded that the innovative zero-waste system developed in the study can deliver the biogas and treated wastewater reuse from food waste and wastewater management with the net fossil energy use and GHG emission credits. The study shows the initial stage of implementing the zero-waste system, which there still has the potential to improve operational efficiency. Nevertheless, there can also be uncertainty of the environmental performance especially due to variations in the amount and composition of food waste and wastewater throughput into the system.

In summary, the innovative zero-waste system developed in the project is the process innovation that will be the integration of (1) anaerobic digester for biogas production from food waste and (2) MBBR-MBR process for wastewater treatment and recycle. The excess wastewater sludge from MBBR-MBR process can be returned to the digester for biogas production to save the disposal cost. The digestate from anaerobic digester can be used as the substrate for co-digestion which will enhance the performance of the biogas production. Finally, the waste will be prevented to send out from the system and the by-products such as biogas and treated wastewater can be reused.

CHAPTER 6
POTENTIAL COMMERCIALIZATION MODEL

The research and development of an innovative zero-waste system is ongoing in the phase that the system has been installing and commissioning at the Chulachakrabonse building, Chulalongkorn University. This chapter aims to present the preliminary analysis for the commercialization plan of the zero-waste system after the research has been accomplished and the system were completely tested. The technology commercialization process that is analyzed and discussed consisting of (1) Value proposition, (2) Competitive advantage, (3) Market opportunity and (4) Commercialization strategy and plan. Details are as following.

6.1 Value proposition of "innovative zero-waste system"

Over the past decades, the trends on environment is rising globally especially the climate change, water scarcity and resource depletion. Innovative zero-waste system can be introduced as one of the *"innovative"* and *"green"* technology for food waste and wastewater management in various buildings and it is applicable to the university. The study establishes the role of the innovative zero-waste system from our project on *"green value proposition"* i.e. circulating and creating values of waste than before. The way of energy transition into the renewable resources from food waste and recycling the water to be valuable for end consumers has enabled. Figure 48 shows the technology positioning of the innovative zero-waste system comparing to the conventional food waste and wastewater treatment in the university in two perspectives i.e. waste treatment focus and resource recovery focus. The zero-waste system is shown both positive to waste treatment performance and resource recovery performance.

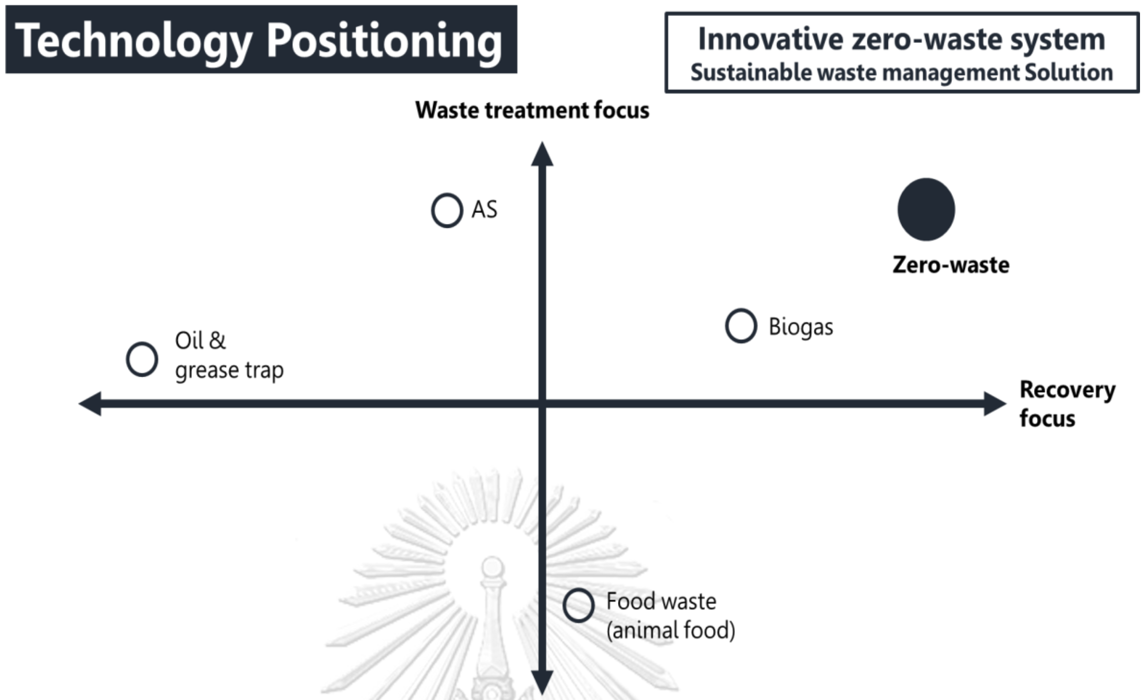


Figure 48 Technology positioning of the innovative zero-waste system

6.1.1 Green value proposition and "Sustainable development goals"

Why does green value proposition? The green value is essential and align with the global trend on sustainable development. This can be seen by the United Nations Sustainable Development Goals (SDGs) that is set ambitious priorities for governments and businesses to drive the implementation of sustainable development up to 2030. There are 17 goals with 169 targets. The 17 goals of SDG are shown in Figure 49 including no poverty, zero hunger, good health and well-being, quality education, gender equality, clean water and sanitation, affordable and clean energy, decent work and economic growth, industry, innovation and infrastructure, reduced inequalities, sustainable cities and communities, responsible consumption and production, climate action, life below water, life on land, peace and strong institutions, and partnerships for the goals.

Figure 49 United Nations Sustainable Development Goals (SDGs)

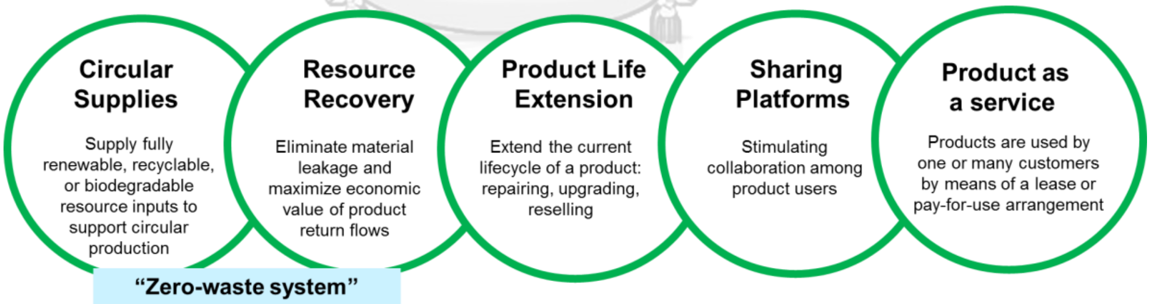
Figure 50 shows the relevant SDGs that would be contributed by the core value proposition of the “zero-waste system” for building’s wastewater and food waste management (in the university). The promotion and implementation of “innovative zero-waste system” can help the university, companies as well as government as a step forward to the successful of many SDGs for an organization e.g. SDG6, SDG 7, SDG 12 and SDG13.

Figure 50 Innovative zero-waste and relation to SDGs

The advantage of achievement on SDGs will provide benefits to the customers not only the tangible benefit like cost saving but also the intangible benefits to society such as environmental protection due to zero-waste discharge to the environment which in turn will not affect to the ecosystem quality. In addition, the benefits such as social education to students and community on the university development is much more important to the society.

6.1.2 Green value proposition and Circular economy

Another core value of the innovative zero-waste system is the promotion of circular economy. In recent years, the concept of circular economy is considered as the promising business model so called "circular business model" for generating profit in new and environmentally conscious ways (Guldmann, 2014). The circular economy is "a continuous positive development cycle that preserves and enhances natural capital, optimize resource yields, and minimizes system risks."(MacArthur, 2013). Lacy, Keeble, and McNamara (2014) has defined the circular business models into five types including circular supplies, resource recovery, product life extension, sharing platforms and product as a service (Figure 51).



Source: Lacy et al. (2014)

Figure 51 Five circular business models and position of the "zero-waste system" in the circular economy models

Figure 51 also revealed the innovative zero-waste system and it's relevant to the circular business models. The circular use of food waste and wastewater is consistent to the *"circular supplies model"* i.e. supplying renewable energy (biogas or electricity) from the biobased resources or waste. The recycle wastewater is consistent to the *“Resource Recovery”* model. Innovative zero-waste system is thus the green technology in context of recovers useful resources or energy out of disposed product or by-products and thus transform waste into value. The biggest successful example the Walt Disney World Resort sends food waste for biogas and power generation.

6.1.3 Green value proposition for Global University Ranking

University is confronting the global challenges and competition. Global University Rankings (GURs) are therefore developed intend to measure the performance of universities. At present, there are several global university ranking schemes available. For the GURs, the Academic Ranking of World Universities (ARWU), the *Times Higher Education* World University Ranking Standard and the *QS World University Ranking* Standard are the three schemes that worldwide recognition. The ARWU is known as “Shanghai Ranking’s Academic Ranking” is established since 2003. The Quacquarelli Symonds (QS) World University Rankings and the Times Higher Education (THE) World University Rankings are established since 2004 and 2010, respectively. Those three standards might have different assessment methodology, criteria and parameters; however, the focus is still the same i.e. performance or academic-based ranking of the universities (Muñoz-Suárez, Guadalajara, & Osca, 2020).

For example, Times Higher Education World University Ranking Standard (THE World University Rankings, 2020) has set the performance indicators by grouping into five areas i.e. (1) Teaching (the learning environment); (2) Research (volume, income and reputation); (3) Citations (research influence); (5) International outlook (staff, students and research); and (5) Industry Income (knowledge transfer). Meanwhile, the QS World University Ranking standard has defined five basic criteria including (1) Research impact and productivity, (2) Teaching commitment, (3) Employability, (4) Online impact and (5) Internationalization (Quacquarelli-Symonds, 2020). The ranking of university is somehow essential to the long-term sustainability of the university in terms of attractiveness to the students as well as the researchers around the world to come and work for increasing research values of the university themselves.

However, over the past ten years, there is another world ranking standards recognized worldwide including Thailand is the UI GreenMetric World University Ranking Standard (UI-GreenMetric, 2018) which developed in Universitas Indonesia in 2010. This standard differs from the THE World University Rankings and QS World University Rankings in the sense that the ranking of UI GreenMetric World University Ranking is focused on the corporate social responsibility (CSR) or campus sustainability of the universities (Muñoz-Suárez et al., 2020). **Figure 52** shows the results of the 2019 UI GreenMetric World University Ranking that Chulalongkorn University was ranked 84th in the world and 3rd in Thailand for sustainable and green campus. Chula is the top Thai university list in three major categories, including Energy and Climate Change, Waste Management and Education and Research. One of the key success factors is the project on “Chula Zero Waste” projects in the university (Chula, 2020)

Figure 52 UI GreenMetric World University Ranking in 2019 for Chulalongkorn University

The UI GreenMetric ranking classifies 780 universities from 83 countries and adopts the environmental sustainability concept that has three elements (environmental, economic, and social) with six indicators and their weighting i.e. Infrastructure (15%), Energy and Climate Change (21%), Waste (18%), Water (10%), Transportation (18%), Education and Research (18%) (Muñoz-Suárez et al., 2020). Those criteria are used for the universities because the universities have significant impacts on greenhouse gas emissions, water and energy use, and waste generation (Suwartha & Berawi, 2019). This indicates how the “innovative zero-waste system” aligning with the global trends of the green university and this can be considered as the external factor or opportunity to the zero-waste technology to be implemented for the other universities in Thailand.

6.2 Competitive advantage of “innovative zero-waste system”

Competitive advantages of the zero-waste system for food waste and wastewater management in the universities can be evaluated by the simple question that *“What make the zero-waste system superior to all other choices that customers have?”* This can be explained by the benefits obtained from the zero-waste adoption comparing to the competition in the market. Following to the survey of food waste management methods as well as the wastewater treatment technologies used in the university in Thailand (Table 23), the conventional practices from 20 universities showed that all universities have the septic tank and grease trap (100%) as the basic technology for wastewater treatment. There are around 20% that have the extra wastewater treatment process i.e. Activated sludge and stabilized pond (15%), Aerated lagoon system (5%) and Dissolved Air Floatation system (5%). Almost the wastewater is discharged after treated. For food waste, all universities have sent the food waste out as animal feed (100%). Only 10% of the universities that have the anaerobic digestion for biogas production. There are no integration of food waste and wastewater management found from the surveyed universities.

6.2.1 Advantages/benefits of zero-waste system

The key advantages of zero-waste system comparing to the conventional food waste and wastewater treatment technologies are as follows:

- Zero-waste system developed from the project can simultaneously treat both wastewater and food waste generated from buildings
- Economic benefits from biogas and recycled wastewater for substituting LPG in canteen and for watering garden, respectively.
- Do not have the sludge, digestate as well as leachate to be sent out the system that can cause the nuisance or impact to the ecosystem and reduce costs for further treatment of those final waste sludge
- There is no integrated system for both food waste and wastewater management of building available in the market specially in the university
- Environmental benefits form GHG mitigation and reduce fossil fuel consumption

The specific characteristics and performances of the zero-waste system comparing to the conventional food waste and wastewater treatment practices in the Thai universities is shown in Table 36.

Table 36 Zero-waste system performance comparing to the conventional practices

Features/criteria	Zero-waste system	Activated Sludge + Food waste left away
Quality of waste after treatment	Reclaimed water standard	General standard
Energy consumption	Medium	Medium
Land requirement	Less	Moderate
Investment cost of the system	High	Moderate
Operation and maintenance cost	Moderate to high	Moderate
Maintenance requirement	Moderate	Moderate
Ease of use	Moderate	AS is difficult to control
Stability of the system	High	Moderate (Difficult to control sludge)
Water recycle efficiency	High	Less to None
Biogas recovery	Medium-High	None

*Green highlight means the best option comparing to the alternatives in other column
Source: Modified from STeP. (2016).

6.2.2 Tangible benefits of zero-waste system

Tangible benefits of zero-waste stems from the resource recovery from the food waste and wastewater. It is contrary to the other food waste treatment system in the university nowadays that generally being the end-of-pipe treatment which generate only the cost of waste treatment. The estimated benefits are as follows:

- Water cost saving about 2-8 m^3/day due to the recycle of treated water from the zero-waste system
- LPG cost saving due to the substation by biogas generated from zero-waste system
- Waste treatment cost reduction e.g. excess sludge treatment based on the WWT plant due to the recovery of it for biogas production
- Carbon credits from the project
- Sludge treatment cost reduction
- Land cost saving

6.2.3 Intangible benefits of zero-waste system

Intangible benefits of zero-waste system implies to the benefits that are not shown by the prices e.g. environmental and social benefits, education and awareness enhancement. Details are as follows:

- Ecosystem quality protection due to the none of food waste, wastewater as well as the sludge from the system leaks to the environment
- Water resource saving to help the problem of water scarcity of the society
- Societal education i.e. teaching via practicing to students and community on how the university enhance society via sustainable waste management
- Leverage university rankings following to the global university ranking standard such as the Green UI university rankings.
- Climate change mitigation due to reduce the life-cycle GHG emissions

6.2.4 Economic analysis of the zero-waste system

The business model selected for commercialization of the zero-waste is the “Outsource OM & SM vendor” type. The approach will be the collaboration with the established sewage treatment plant providers that currently working in the market. The university’s researchers provide only the knowledge about the design, manufacturing and commission of the zero-waste system. For the manufacturing of the zero-waste system will also responsible by the partners in order to keep the lowest investment cost on infrastructure as small as possible at the beginning stage.

The study has thus conducted the economic analysis to evaluate the economic viability of the innovative zero-waste system. The cost-benefit analysis method is applied for the analysis by assuming the conditions of “with” and “without” using the zero-waste system. The analysis is conducted by using indicators of the Economic Internal Rate of Return (EIRR), Net Present Value (NPV), and Benefit/Cost Ratio (B/C). Basic assumptions used for the economy analysis are as follows:

- The evaluation period is set for 15 years lifetime of the zero-waste system which includes 1 year of design and manufacturing of the system.
- The cost of initial construction and O&M of the project is estimated based on the price of the zero-waste system excluding any tax.
- The economic analysis is based on the prototype zero-waste system for treating about 60 kg food waste/day and 8 m^3/day of wastewater (capacity basis).

6.2.4.1 Economic cost

- **Initial Investment Cost**

The investment cost for manufacturing the zero-waste system prototype is about 1.4 Million Thai Baht (THB) which can be classified into a set of MBBR-MBR system about 600,000 THB and a set of anaerobic digester with food waste shredder about 800,000 THB as shown in Table 37.

Table 37 Initial investment cost of the zero-waste system

Initial investment cost	Unit	Value
Membrane Module	THB	200,000
MBBR media	THB	50,000
Reactor tank	THB	200,000
Aeration system	THB	10,000
Controller & accessories	THB	40,000
Installation & others	THB	100,000
Digester + Shredder	THB	800,000
Total investment cost of zero-waste system	THB	1,400,000

- **Operation and Maintenance (O&M)**

The O&M cost of the zero-waste system, the cost is calculated from the O&M cost of MBBR-MBR system and the O&M Cost of the digester system for food waste. The total O&M costs of the zero-waste system is estimated to be 84,049 THB/year (Based on the wastewater about 2,880 m^3/year and food waste about 21.6 tonnes/year). Details information for the specific units i.e. MBBR-MBR and the digester are as follows:

- The average O&M unit cost for the MBBR-MBR is estimated to be about 14 THB/m^3, and multiplying this average cost with the annual treatment amount of wastewater i.e. 2,880 m^3/year to get the annual O&M cost of the MBBR-MBR system for wastewater treatment and water recycle.
- The average O&M unit cost for the anaerobic digester is estimated to be about 2.0 THB/kg FW, and multiplying this average cost with the annual treatment amount of wastewater i.e. 21,600 kg food waste/year to get the annual O&M cost of the anaerobic digestion process for food waste treatment and biogas production.
- The amount of wastewater and food waste are assumed to be fixed along the time of the project for the benefit calculation. Detailed information is shown in Table 38.

- The zero-waste system is assumed to operate 360 days/year. The left 5 days are for during the university close and maintenance of MBBR-MBR. However, actually, there still have biogas generation from anaerobic digester although the university has closed because there still have the food waste remaining in the digester and the gas will continue generate. All the gas generated will be collected in the biogas tank and further use in the kitchen when the university start operation.

Table 38 O&M cost of the zero-waste system

Operation and Maintenance cost (O&M)	Unit	Value
Anaerobic digester for food waste		
Electricity consumption	kWh/d	1.95
Electricity price	THB/kWh	3.8
Electricity (cost) (@360 days/year)	THB/year	2,668
Other O&M cost (assumed 5% of machine cost)	THB/year	40,000
Total O&M cost of digester	*THB/year*	*42,668*
MBBR-MBR		
Electricity consumption	kWh/d	8.3
Electricity (cost) (@360 days/year)	THB/year	11,382
Other O&M cost (assumed 5% of machine cost)	THB/year	30,000
Total O&M cost of MBBR-MBR	*THB/year*	*41,382*

6.2.4.2 Economic Benefits of the zero-waste system

The potential economic benefits apart from the food waste and wastewater treatment by the zero-waste system can be summarized as following.

a) Biogas recovery for LPG substitution
b) Reusing of the treated water
c) Carbon credits from renewable energy like biogas
d) Cost reduction for sludge treatment
e) Land saving as comparing to the conventional wastewater treatment

Table 39 summarized the benefits of the zero-waste system based on the treatment of wastewater 8 m^3/day and 60 kg of food waste/day. The total economic benefits of zero-waste is around 256,215 THB/year. Descriptions are as follows:

- Biogas recovery lead to save the LPG cost in canteen around 65,610 THB/year. The calculation is based on LPG price in year 2020 which is about 22.5 THB/kg (https://www.bot.or.th/App/BTWS_STAT/statistics/).
- MBBR-MBR that help treat and improve the quality of treated water for reusing in the garden lead to the saving of water price about 43,200 THB/year. The water price is referred from the Municipal Water Authority (MWA) which is about 15 THB/m^3 (https://www.mwa.co.th/ewt_news.php?nid=303).
- The life-cycle GHG reduction of the zero-waste system based on the LCA lead to the benefit in terms of carbon credit from the renewable energy like biogas. The carbon price is referred from the Thailand Greenhouse Gases Management Offices (TGO) and the average price for biogas in 2020 is about 189 THB/t CO_2eq (Carbon Market, 2020). This leads to the carbon credits gain by the zero-waste system around 299 THB/year.
- The innovative zero-waste can also help reduce the excess sludge that will need further properly manage. The estimated cost for sludge treatment cost of the conventional wastewater treatment system is about 100 THB/m^3. This brings about the cost saving around 3,105 THB/year.
- Lastly, the land required for wastewater treatment using the zero-waste system that installed the MBBR-MBR will be lesser than the traditional wastewater treatment system like the activated sludge. This is significantly important to the building in the city where the space is very important and expensive. The study therefore assessed the benefit of zero-waste system on the land use reduction. The rental cost of land is referred from the average rental price in the city of Bangkok like Pathumwan district which is about 36,000 THB/m^2/year. This leads to the benefits around 144.000 THB/year.

Table 39 Economic benefits of the zero-waste system

Economic benefits description	Unit	Value
Biogas recovery		
Biogas production (0.3m^3/kg FW × 60kg FW/d)	m^3/day	18
Biogas conversion to LPG	kg LPG/day	8
(1m^3 biogas =0.45 kg LPG)		
	kg/year	2,916
LPG price	THB/kg	22.5
LPG saving from biogas	THB/year	65,610
Reusing of the treated water		
Water recycle	m^3/day	8
Tap water price	THB/ m^3	15
Tap water saving	THB/year	43,200
Carbon credits from biogas		
Net GHG credits of zero-waste system	kg CO_2eq/yr	1,584
Carbon price[1]	THB/kgCO_2	0.189
Carbon credit obtained	THB/year	299
Reduce sludge treatment cost		
Excess sludge to be removed from conventional	m^3sludge/m^3WW	0.01
wastewater treatment (Activated Sludge)	m^3/yr	31
Sludge treatment cost	THB/m^3	100
Sludge treatment saving	THB/year	3,105
Land saving		
Land required for AS	m^2/m^3 WW/d	1.0
Land required for zero-waste system	m^2/m^3 WW/d	0.5
Land saving	m^2/yr	4.0
Assume land rental price	THB/m^2/yr	36,000
Land saving cost	THB/yr	144,000

Note: [1] http://carbonmarket.tgo.or.th

6.2.4.3 Results of economic analysis

The discounted rate is set by expectation at 8% to overcome the inflation rate and the interest rate if the money is used general investment. The zero-waste project lifetime is about 15 years. The EIRR, NPV and B/C of the zero-waste system can be summarized in Table 40. The results revealed that for the base case, the innovative zero-waste system can be viable in economic due to the EIRR became higher than 8% as expected. The EIRR, NPV and B/C for the base case are about 8.83%, 66,646 THB and 1.44 respectively.

The sensitivity analysis is also conducted by varying into 4 different conditions i.e. the benefit decreased 10%, the benefit increased 10%, the cost increased 10%, and the cost decreased 10, respectively. The results as Table 40 indicate that the benefit-to-cost ratio of the zero-waste system in all conditions are more than 1. However, if the benefits decrease by 10% or the cost increases by 10%, the EIRR of the project would be 6.23 and 6.48%, respectively which would be lower than the expected discounted rate that we set at 8%. Nevertheless, if the benefits are increased by 10% or the cost are decreased by 10%, the innovative zero-waste system would bring the EIRR more than 10% and it is viable in economic view. The positive net present value indicates that the zero-waste system's rate of return exceeds the discount rate. Importantly, it must be noted that, there is the potential to increase the cost efficiency of the zero-waste system because of the return to scale principle will be applied. The prototype zero-waste system is still small scale and if the system were scaled up, the cost per unit of wastewater and food waste must be decreased.

Table 40 EIRR, NPV and B/C of the zero-waste system in different conditions

Conditions	EIRR	NPV	B/C
Base case (discount rate 8%)	8.83%	66,646 THB	1.44
Benefit -10%	6.23%	-134,416 THB	1.30
Benefit +10%	11.27%	269,708 THB	1.59
Cost + 10%	6.48%	-129,751 THB	1.31
Cost – 10%	11.53%	263,043 THB	1.60

In addition to the environmental benefits as assessed before, there still have the other externalities like the policy support by the government on BCG and the achievement the commitment on SDG contribution of the users the are the intangible benefits of the zero-waste system implementation in buildings. Especially for the universities, to be the green university achievement as well as to raise awareness and to educate students and society from their actual practices are the most important external benefits obtained from the zero-waste system.

6.2.5 Patent review and mapping

The study has reviewed the patents related to the key technologies used in the zero-waste system i.e. anaerobic digester and MBBR-MBR. Since the anaerobic digester is the conventional technology that widely used in the market, the patent research therefore is focused on "MBBR-MBR" for wastewater treatment. The exploration has been done by using "The Lens". The Lens is an open public resource for patent searching and mapping (https://www.lens.org/lens/). The searching criteria are set from year "2000-2019" and the key word is "MBBR-MBR".

The results revealed that the MBBR-MBR that we used for the zero-waste system is one of the new technologies for sewage treatment and there is an increasing researches and patents since year 2016 (Figure 53). The high number of patents were found in the United States and Republic of China (Figure 54).

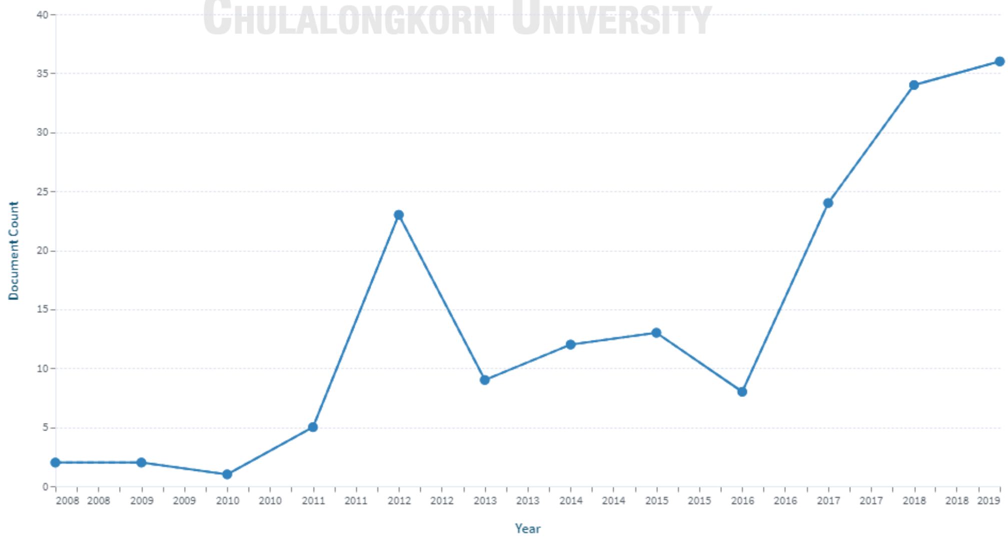


Figure 53 Patent publication of "MBBR-MBR" from year 2000-2019

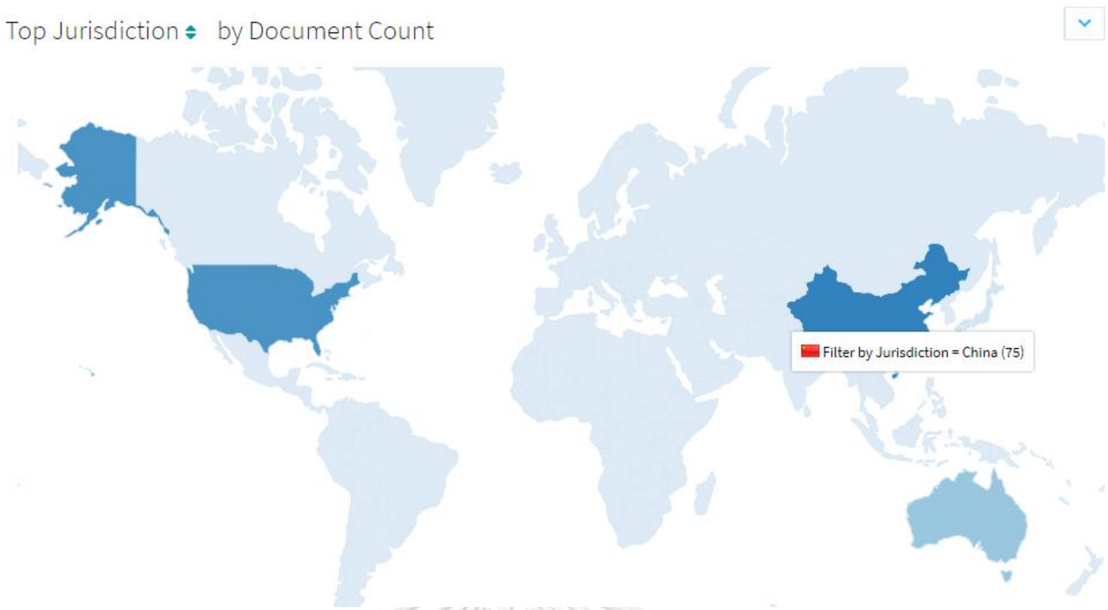


Figure 54 Distribution of patents of “MBBR-MBR” by countries

The major companies that is working and apply the MBBR-MBR for sewage treatment are the Palo Alto Research Center Inc. and General Electric (GE) as the list of company shown in Table 41.

Table 41 Top patent applicants for “MBBR-MBR”

Patent applicants	**No. of documents**
Palo Alto Research Center Inc	20
General Electric	9
Dalian Gelanqing Water Environment Engineering Co., Ltd.	9
Yunnan Aoyuan Environmental Protection Technology Co., Ltd.	8
Easter Scott F.	8
Early Daniel M.	8
Lean Meng H.	7
Melde Kai	7
Chang Norine	5
University TianJin Chengjian	5

Meanwhile, Figure 55 and Figure 56 show the top inventors and top owners for the MBBR-MBR There also have some researches in Japan and Australia. It can be concluded that the technology used in our zero-waste system is new to the market and less competition in Thailand.

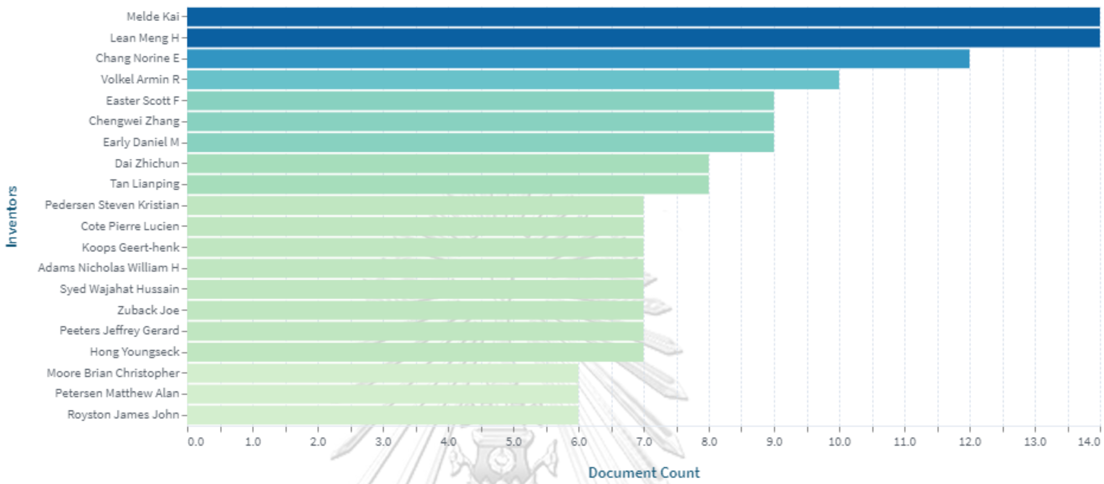


Figure 55 Top inventors in MBBR-MBR

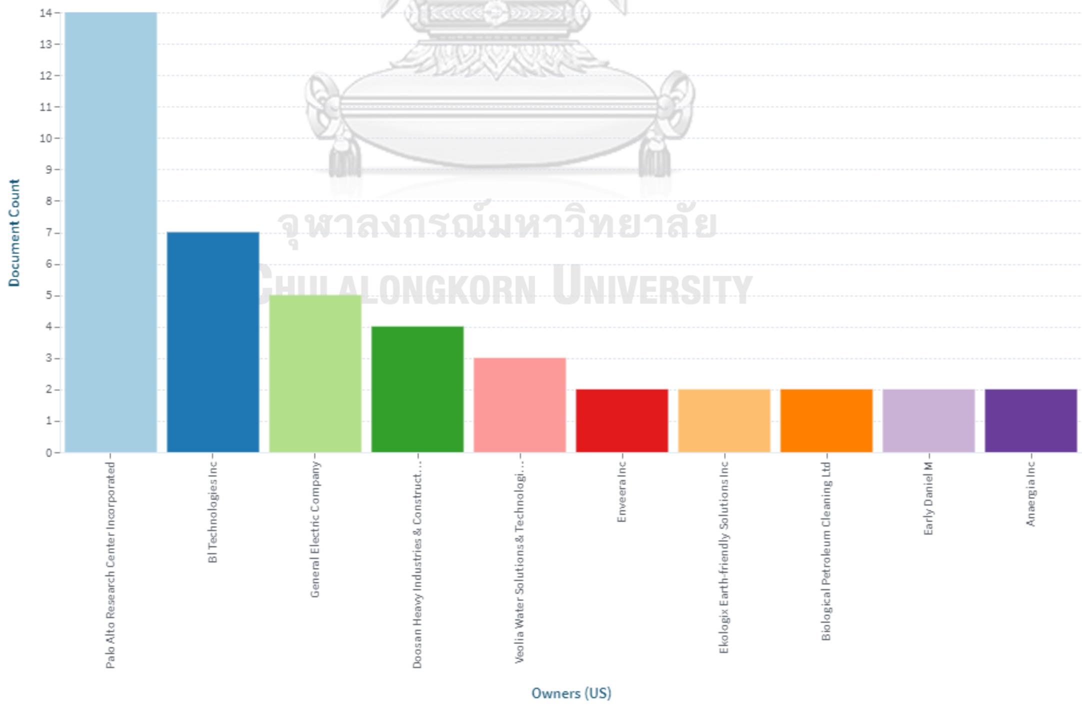


Figure 56 Top owners in MBBR-MBR patents

6.3 Market opportunity of "innovative zero-waste system" (Market assessment)

6.3.1 Market opportunity analysis

Success can be determined by how good you are in making the benefit to the target market and convince them that the benefit is better than the competition. Table 42 shows the analyzed market opportunity and the benefits of zero-waste system.

Table 42 Market opportunity analysis and the benefits of zero-waste system

Aspects	Benefits
Market opportunity	• Beginning stage: Can be used for buildings in all universities • Next stage: Buildings in other institutions as well as the office buildings
Technical feasibility of zero-waste system	• High feasibility because the system has been installed and operated as the pilot scale in the Chulalongkorn University
Technology impacts on society and morality	• Consistent to the Sustainable Development Goals (SDGs) • Societal education i.e. teaching via practicing to students and community on how the university enhance society via sustainable waste management • Can help leverage university rankings
Technology impacts to environment	• Ecosystem quality protection due to the none of food waste, wastewater leaks to the environment • Water resource conservation • Renewable energy supply • Climate change mitigation

6.3.2 SWOT analysis of the innovative zero-waste system

Table 43 shows the SWOT analysis of the innovative zero-waste system. The zero-waste system has the strengths and opportunities due to its performances on waste treatment and recovery. However, the weaknesses are also reviewed e.g. the requirement of appropriate design and commission of the system specifically to each customers, the skilled operators are necessary, and especially its high investment and operation costs as comparing to the conventional food waste and wastewater treatment practices in the universities.

Table 43 SWOT analysis of the innovative zero-waste system

Strength	Weakness
• Recycle of wastewater and produce biogas from food waste and fruit waste • High performance of food waste and wastewater treatment • Use less space than conventional waste water treatment plant • Easy to use and maintenance • Material to construct can buy in Thailand • The system is durable and resistance even install in outdoor	• Higher investment costs comparing to the other system • Require the appropriate design of the system for specific conditions of the customers • Training is necessary at the beginning of the operation to increase the skill of operators
Opportunities	**Threat**
• Climate change is an important issue at the present. The customer now concerns the environmental technology to mitigate climate change problem. • Circular economy is gaining attractive globally as the important business models for the future (Ellen MacArthur Foundation, 2013).	• The existing competitors already have their own customers

• Government policy promotion of BCG • Supporting SDGs move of the organization and the country • Supporting the UI GreenMetric World University Rankings	

6.3.3 Five Forces analysis

The Porter's Five Forces is thus applied to analyze the zero-waste benefits and the risks on market competition. The summary of the five forces analysis is shown in Table 44. The results show that the market opportunity of the innovative zero-waste system in the university is high because of the low risks from threat of new entrants and bargaining power of suppliers. However, there will have the moderate risks for the bargaining power with buyers, threat of substitution and competition rivalry.

Table 44 Five forces analysis of the innovative zero-waste system

Elements	Description
Threat of new entrants	• Treat from competitor is low because MBBR-MBR is the new research and development that not widely available. This indicated by the Patent search by the Lens (https://www.lens.org/lens/), the results show that the MBBR-MBR has been developed in recent years and no patent available in Thailand. The integration of food waste and wastewater treatment system for building is also not much available in the market and the installation and commission of the zero-waste system sometimes it is required the pilot plant and laboratory to test the feedstock, substrate and the efficiency of the zero-waste system to optimize the operation need the knowledge to do innovative zero-waste system and it is difficult to copy.

Elements	Description
Bargaining power of suppliers	• Supplier bargaining power is low due to there are many suppliers and engineering shop that can produce the zero-waste system according to the design. • Suppliers of MBBR media can be widely found in the market as well as in the online market like Alibaba. • Suppliers of MBR is also increase in the market as comparing to the past five years due to its prices decrease. • Suppliers of substrate for anaerobic digester e.g. manure from swine farm is easy to contact and access for the collaboration.
Bargaining power of buyers	• Customer bargaining power is moderate to high because there is no law/regulation that the customers have to treat and recycle the waste like the zero-waste system. • The customers who concern on environmental willing to pay for innovative zero-waste system to PR their company image and already have awareness on environmental issues.
Threat of substitute products or services	• Treat from substitute goods is moderate risk because, although, there is no technology such as zero-waste system that can both recycle waste water and produce biogas from food waste and fruit waste; however, the standalone system is available and there is the potential that customers will use the standalone system instead of the combining system like zero-waste system
Rivalry among existing competitors	• Competition from existing companies is moderate because the existing competitors have used the conventional technology e.g. the activated sludge for wastewater treatment and they generally already have their own customers. For zero-waste system, there is no competitors because there still lack of the integrated food

Elements	Description
	waste and wastewater treatment system in the market. However, we need to have that collaboration with the companies that they already have their own customer that they are good in selling and marking for applying our zero-waste system to the customers by using our engineering knowledge and zero-waste technology model to renovate the conventional waste treatment plant or to install the new waste treatment system for the customers.

6.4 Commercialization strategy for "innovative zero-waste system"

Technology commercialization is the process of transferring a technology-based innovation from the developer of the technology to an organization utilizing and applying the technology for marketable products. To commercialize the zero-waste system, a consulting company for zero-waste engineering and management is expected to establish for providing the solutions on integrated waste management to customers.

6.4.1 Type of our product and services

The company missions are to provide the knowledge, consult, and technical solutions about solid waste and wastewater management to government, business and industry. The role of the company is to give the consultation as well as engineering design, construction and installation of the zero-waste system for food waste and wastewater management in buildings of various sectors. The product and services of the company can be categorized into three types following to the nature of waste treatment business operation as follows:

(1) Zero-waste system design and manufacturing

Provide the design, manufacture, and install of the appropriated zero-waste system for the customers using our core competency in environmental engineering. The work includes since the analyzed the characteristics of food waste and wastewater of customers, design the appropriated zero-waste scale, manufacturing/construction of the zero-waste system, on-site installation and commissioning of the system.

(2) Zero-waste system consultant, project management & construction supervision (PMS)

Provide services about the technical consultation, zero-waste project management and zero-waste system construction management to the partners or zero-waste project owners who lack personnel or have no expertise in management and construction of the zero-waste system. Entrepreneurs or project owners, it is necessary to hire an experienced engineer and consultant with expertise in zero-waste project management and control to represent the management and control of activities and results at every stage of the project. The service activities of zero-waste project management and construction control into 3 main activities which are 1) project management, 2) construction control and 3) review of work results for delivery. This is to cover since the planning process of the project that it is necessary to recruiting contractors to work in the detailed design process system, the construction until the process after delivery of construction i.e. personnel training, testing the system, review the results and work checks during the guarantee period.

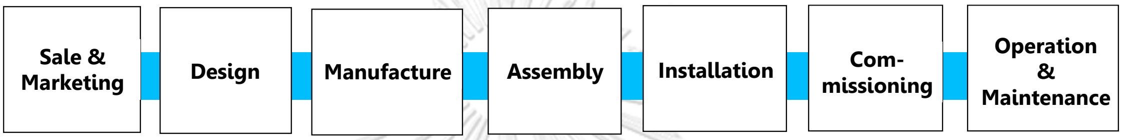
(3) Zero-waste education and training

The company provides education services including demonstrating the zero-waste system for food waste and wastewater management using the pilot plant. The target group of training is for the government, academic institutions, local government e.g. municipalities and private sectors who are interested on food waste and wastewater recycling technologies. This work will enhance the visibility of the company and zero-waste system to nationwide and will help support the selling and marking of the developed zero-waste system.

6.4.2 Value chain and potential business model

To commercialize the zero-waste system to the target market, the value chain of a waste treatment plant project can be categorized in to six types of business activities as shown in Figure 57. The value chain includes since (1) Sale and

Marketing (SM) that will interface with end customers/buyers; (2) Design which implies to emerging design of the waste treatment system; (3) Manufacturing of the equipment/system; (4) Assembly i.e. integrating component parts to be the zero-waste system; (5) Installation which is the physical delivery of system at the customer's site; (6) Commissioning which is responsible for testing to verify if the zero-waste system functions can work in accordance with the design objectives and specifications; and (7) Operation and Maintenance (O&M) which will upkeep the installed zero-waste system working properly via the annual maintenance contract.



Source: Modified from STeP (2016)

Figure 57 Value chain of the zero-waste system commercialization to the market

The detailed role of each implementer type in the waste treatment system implementation project is shown in Table 45.

Table 45 Categories of waste/sewage treatment plant implementer

Types of implementers	Roles in the value chain of waste/sewage treatment plant (STP) implementation
End-to-end vendors	Perform all functions from Sale & Marketing (SM), design to commission, and Operation and Maintenance (OM).
Outsource OM vendors	Perform functions from design to commission, but outsource OM.
Outsource SM vendors	Perform functions from design to commission, but outsource SM.
Outsource SM & OM vendors	Perform functions from design to commission, but outsource SM and OM.
Packaged system vendors	Design and manufacture, and sell to vendors that do the installation and maintenance

Presently, there are various business models for the waste/sewage treatment system implementation depending on the scope of works in the value chain. It can be categorized into five types of sewage/waste treatment system implementers as shown in Figure 58.

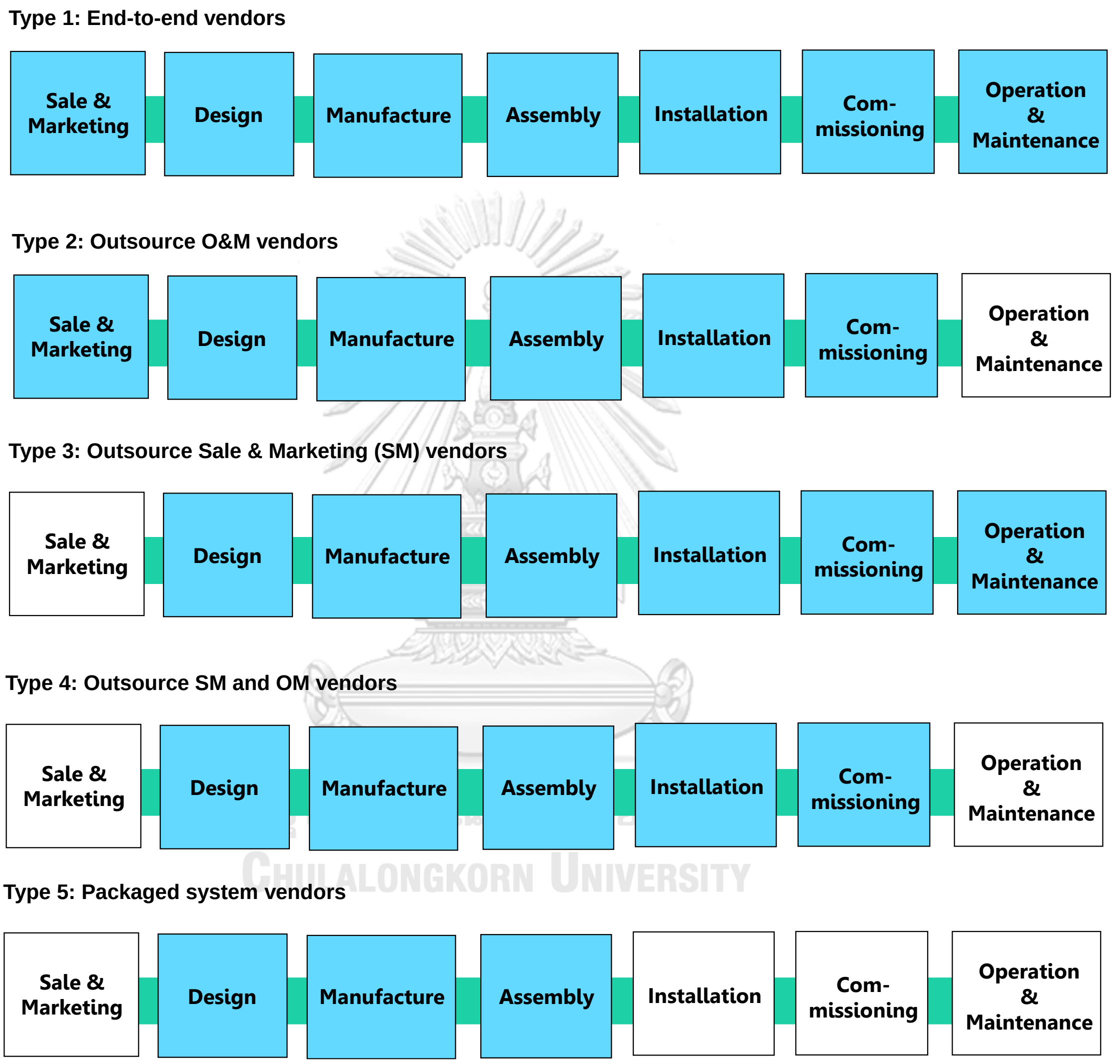


Figure 58 Types of STP system implementers and the value chain involvement for a sewage/waste treatment project implementation

Due to the "innovative zero-waste system" developed in the project need to be designed for specific case because the scale is upon the amount of food waste and wastewater generation in each site. In addition, our team strength is the design of the appropriate zero-waste system and the commissioning of the system until it can work properly following to the designed system. Hence, business models like *"outsource OM & SM vendor"* or *"packaged system vendor"* are the two potentially business models. This is because the important steps for the implementation of the zero-waste system are the design, manufacture, assembly and the commissioning the system.

However, the "outsource SM and OM vendors" is selected as the commercialization model for the zero-waste system because this model focused on the engineering and installation, and commissioning which are the strength of the team. The other activities in value chain such as sale and marking, manufacturing and installation, as well as maintenance, we can find the partners or change the competitor to be the partners for those all activities due to their strength in the existing market. The collaboration would be the part/unit operation manufacturers and the contractors and OM contractors that on one hand can help finding the customers; on the other hand, the contractors and OM contractors can help operate and maintenance the systems for the customers too.

6.4.3 Collaboration channels

Kirchberger and Pohl (2016) proposed the potential channels between the organizations as the developers of the technology and the organizations commercializing technology or integrating the developed technology into the products that can be sold in the market place so called "Market party" (Figure 59). We think that the collaboration channel with the established companies is the highest potential approach to commercialize the innovative zero-waste system to the customers. The strategy of commercialization from the research work to the market thus should be the "Market entry with own technology" of the innovative zero-waste technology.

		Market party		
		Established companies	**Technology startups**	**Universities and research institutes**
Technology party	**Universities and research institutes**	Joint research, selling or licensing	Spin-offs from academia	Governmental institutions developing
	Technology startups	Selling or licensing	Market entry with own technology	Spin-ins to governmental agencies
	Established companies	Market entry with own technology; Selling or licensing	Spin-outs from established companies	Research requests by governmental institutions

Figure 59 Potential channels with the established companies for commercialization of the innovative zero-waste system

6.4.4 Business Model Canvas for commercialization of zero-waste system

The commercialization strategy is analyzed and proposed based on the existing common business models used for the waste treatment plant implementation system, The Business Model Canvas for the *"outsource OM & SM vendor"* business model to commercialize the innovative zero-waste system into the marketplace is analyzed and shown in **Table 46**.

Table 46 Business model canvas of zero-waste system's commercialization model

Key Partners	Key Activities	Value Propositions	Customer Relationships	Customer Segments
• Part manufacturers and channel partners • STP company • Contractors and OM contractors	Design, manufacturing, assembly, installation and commissioning **Key Resources** • Intellectual capital • Pilot plant for testing the conditions • Laboratory for measuring parameters	• Engineering expertise • Pilot plant for testing • Buyer has flexibility to choose own OM	Through channel partner or project contractor **Channels** Subcontract or Tender process	Universities (government and private) Building sectors

Cost Structure	Revenue Streams
<u>Overhead</u> Human resources, labor, OM contract, and channel partner commission <u>Manufacturing</u> Material, processing, and parts; Outsource manufacturing expenses <u>Parameter testing</u> Sampling material, chemical, labor, lab equipment and maintenance	• Design and manufacturing of "zero-waste" system to buyers/target customers • Consultant, project management & construction supervision (PMS) • Education and Training

6.4.5 Marketing plan

The market target group can be categorized following to the three types of services by the company as following.

(1) Market target for the zero-waste system design and manufacturing

The groups for zero-waste system design and manufacturing at the beginning stage of three years will be promoted for the group of universities/academic institutes in Thailand as stated before that the zero-waste system is highly relevant to the government policy promotion and the environmental and waste management nowadays become the criteria for the global university rankings of the universities. Based on the information from The Office of the Higher Education Commission (OHEC), as of 2020, there are 155 institutions of higher education in Thailand, Ministry of Education in cooperation which can be classified into 26 Autonomous universities, 10 Public universities, 38 Rajabhat universities, 9 Rajamangala universities of technology, and 72 Private higher education institutions.

The second stage would be the office buildings as well as the other economic sectors especially the hotels where the food waste and wastewater will be the major environmental problems of the business. In addition, the environmental protection as well as the social responsibilities are very important issues to the business. In Thailand. Especially for the remote area resorts like island where they have the limitations of land available for waste management and the limitation of fresh water resource used in their business. The zero-waste system must be the very fit options to those hotels/resorts in the remote area.

(2) Market target for zero-waste system consultant, project management & construction supervision (PMS)

This group of customers would be the entrepreneurs or project owners, it is necessary to hire an experienced engineer and consultant with expertise in zero-waste project management and control to represent the management and control of activities and results at every stage of the project. This service will be work closely with the existing sewage treatment plant providers in the market where they already have the selling and marking unit for finding the project from the business sectors. We can provide the technical support and consultation for the projects as per requested.

(3) Market target for zero-waste system education and training

The target group for zero-waste system education and training will be the government management officers e.g. Ministry of Higher Education, Science, Research and Innovation (MHESI) who directly involves with the controlling of higher education in Thailand and the Ministry of Interior which will include the representatives (management level) from the local government e.g. municipalities in Thailand. The last group will be the interested people from private sectors, academia and students.

(4) 4P's of marketing

The four major marketing decisions are product, price, place (distribution) and promotion or known as the 4 P's of marketing have been analyzed for the company to promote the zero-waste system and services by the company.

- **Product and Service**

The company aims to provide the consultation and technical solutions about solid waste and wastewater management to government, business and industry especially the engineering design, construction and installation of the zero-waste system for food waste and wastewater management in buildings of various sectors. The products and services are different from the conventional consultation on waste treatment plant that focusing on the treatment technology. However, our aims are to bring the benefits of zero-waste system i.e. recycle wastewater, produce biogas from food waste and fruit waste to return to the customers. This novelty of the system is the integration of food waste and wastewater management. Using MBBR-MBR is the new technology that can use for lesser space than conventional waste water treatment plant. The system has the high performance of food waste and wastewater treatment, easy to use, and having the stability for the variations of food waste inputs.

- **Price**

The price is competitive to other conventional waste treatment system as shown by the EIRR, NPV and B/C of the zero-waste system, the installed zero-waste system has the EIRR, NPV and B/C for the base case are about 8.83%, 66,646 THB and 1.44 respectively. In contrary to the conventional waste treatment system that will be only the costs to the company for the long run. In addition, we will provide the period of payments to customer following to the installation progress of the system at site.

- **Place (distribution)**

For the channel to distribution our technology and services on zero-waste system design, engineering, manufacturing and commission to the target customers, the company will do for two approach i.e.

(1) Being the "Outsource Selling and Marketing (SM) and Operation and Maintenance (OM) vendor" by working with the other sewage treatment plant provider partners that they already have the customers and SM units in the existing market.

(2) Direct selling and marking via the work on education and training activities that the company has set the plan for the target groups like OHEC, Ministry of Interior, Universities and other target groups.

- **Promotion**

The consultation services of the company will not limited to direct physical consultation but the company will provide the online consultation services to the customers in case there is any abnormal situation to the system. In addition, regularly monitoring of the zero-waste system will be provided to all customers as the after sale services.

6.4.6 Organization and HR plan

The organization of the company is set as the flat organization for efficiently work and make decision. There are three units to cover the three types of product and services as shown in Figure 60 i.e. (1) Design & Engineering Unit, (2) Education, Training and Marketing Unit and (3) Financial & Administration. The design and manufacturing unit will responsible for the works regarding zero-waste system design and manufacturing and the consultation as well as the project management & construction supervision (PMS). The Education, Training and Marketing Unit will responsible for the works regarding training and marketing of zero-waste system to public and the supporting the design and engineering unit for the case of the testing of samples and commissioning of the zero-waste system. Financial and administration will be responsible for the all financial and administrative works between the university, partners, vendors/suppliers and customers.

Figure 60 Organization of the company

Key human resource of the company

- Manager of company: Require Master/Doctoral Degree of Environmental Engineering or Civil Engineering. The company manager must be the professional engineer with at least 8 year experience. The job description include the management of company and zero-waste system project development. The salary would be around 80,000 THB/month. However, for the case that company owner, the salary can be set to 30,000 THB/month.
- A senior engineer for the design and engineering unit: Require Bachelor/Master degree of environmental engineering with 5 year experience. The senior engineer must be Associate engineer or Professional engineer. The job description include the zero-waste system design and manufacturing as well as the zero-waste project consultation and management. The salary would be around 50,000-70,000 THB/month upon the experience.
- A scientist/engineer for the education, training, and marketing unit: Require Bachelor/Master degree of environmental engineering with 0-2 year experience. The job description includes the training and demonstrating the zero-waste

system to the interested people/parties, marketing of the research unit activities to public The salary would be around 18,000-30,000 THB/month upon the experience

- An officer for the financial and administration: Require Bachelor degree of administration or accounting with 0-2 year experience. The job description includes the financial activities and documents including report for all projects under the company. The salary would be around 15,000-30,000 THB/month upon the experience.

Table 47 Human resources of the company

Position	No of staff	Salary (THB/month)
Company manager (Assuming company owner)	1	30,000
Senior engineer	1	50,000
Scientist/engineer	1	20,000
Financial & administration officer	1	18,000
Total salary per year (THB/year)	1,416,000	

*Numbers of staff can be further increased depended on the projects available of the company. The hiring staff can be considered as the project staff for temporary.

6.4.7 Operational plan

(1) Equipment and facility required for the operation

The zero-waste system prototype has been already installed at the Chulachakrabonse building and it can be used for academic, supporting the research and development, and for future commercialize of the anaerobic digester system for food waste and wastewater sludge and the MBBR-MBR for wastewater treatment and recycling. The cost of the prototype is therefore not considered in the assessment because it is already available.

(2) The zero-waste system manufacturing and installation cost

For the design and production of the zero-waste system, the lump-sum manufacturing cost of the zero-waste system is around 1,000,000 THB/unit including installation. The net profit per unit of zero-waste system is set to be around 40% of the total cost of the zero-waste system.

(3) Laboratory facility and office space

At the beginning stage, the laboratory work can outsource to the partner e.g. environmental engineering lab for analysis of wastewater and food waste characteristics. The rental space and utility is mainly for the office work estimated to be around 20,000 THB/month. The total cost is around 240,000 THB/year.

(4) Chemical and consumables

Chemical and consumables used as well as the maintenance cost for the zero-waste system prototype and the laboratory equipment are estimated to be lump sum around 150,000 THB/year.

(5) Computer printer and internet network

A new computer set equipped with a printer and internet facility is required and it costs about 50.000 THB as the initial investment cost.

6.4.8 Financial plan

6.4.8.1 Estimated initial investment cost and operational costs

To operate the company, the initial budget is required should be enough to sustain for the initial investment cost (computer facility) at 0^{th} year and the operation cost for the 1^{st} year activities. Table 48 shows the estimated initial budget that is required for the company as this is assumed to be the initial investment cost of the company. The total initial budget required would be around 2,856,000 THB. Table 49 shows the estimated total operation costs occurred over the five years of the company. The financial estimation assumption is that the fixed operation costs e.g. salary, consumable materials, lab facility, utility that considered as lump sum costs per year will increase 3% annually due to the inflation rate.

Table 48 Investment cost required for initial stage (0th year) and 1st year operation

(Unit: Million THB)

Initial cost for investment and 1st year operation	Total amount (M.THB/year)
(1) A zero-waste system manufacturing and installation cost	1.000
(2) Human resource	1.416
(3) Chemical and consumables	0.150
(4) Laboratory facility and office space	0.240
(5) Computer printer and internet network	0.050
Total	**2.856**

Table 49 Estimated total operation costs of the company

(Unit: Million THB)

Total operation costs	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Total
(1) A zero-waste system manufacturing and installation cost	0.500	0.500	2.000	3.000	4.000	6.000	16.000
(2) Human resource		1.416	1.458	1.502	1.547	1.594	7.518
(3) Chemical and consumables		0.150	0.155	0.159	0.164	0.169	0.796
(3) Laboratory facility and office space		0.240	0.247	0.255	0.262	0.270	1.274
(5) Computer printer and internet network	0.050	0.000	0.000	0.000	0.000	0.000	0.050
Total cost	**0.550**	**2.306**	**3.860**	**4.916**	**5.973**	**8.033**	**25.638**

6.4.8.2 Income estimation

There are three sources of income according to the three types of product/services over the five years.

(1) Income from the zero-waste system design and manufacturing

Income from the design and manufacturing of the zero-waste is estimated with the conservative estimation i.e. one zero-waste system for the first year and increasing continuously. The income for a zero-waste system produced (Capacity about treatment recycling of 8 m^3 wastewater/day and 60 kg food waste per day), the selling price of the system including the design, engineering drawing, approval of the installation of the biogas system, installation and commissioning at the site is set to 1,400,000 THB/unit. However, it must be noted that the prices can be varied by the scale of the zero-waste system developed to the customers. This activities can be done by using the joint research with the partners in the markets because the technology is consistent to the government policy promotion on BCG and SDGs that some research funding can be granted for the installation of the technology. Table 50 shows the estimated income from the product and services of the company. The projection of increasing numbers of zero-waste system selling in the next 5 years is due to the assumption that the work is expanded to the other field not specifically to the university but also the other buildings e.g. hotels, school or office buildings.

Table 50 Income from the zero-waste system design and manufacturing

Income from design and manufacturing	No. of zero-waste system produced	Total income (THB)
Year 1	1	1,400,000
Year 2	2	2,800,000
Year 3	3	4,200,000
Year 4	4	5,600,000
Year 5	6	8,400,000
Total		**22,400,000**

(2) Income from zero-waste system consultant, project management & construction supervision (PMS)

The operation of the company will also provide the consultation to the partners/customers for the zero-waste project management and construction supervision. The partners would be the group of sewage treatment plant (STP) companies in the market that need the consultation and project construction supervision for the specific case like anaerobic digestion of food waste or the wastewater treatment plant like an MBBR-MBR. The income stream for this specific consultation case is the estimated to be around 20% of the STP project cost. Assumption if the project cost is 2,000,000 THB (based on a unit cost of zero-waste system plus the extra charge by the partners to customers), the charged for the consultation and project management would be around would be around 400,000 THB/project. However, it must be noted that the prices can be varied by the scale of the sewage treatment plant developed to the customers. Table **51** shows the estimated income from the consultation and project management activities of the company. The projection of high numbers of consultation projects due to the assumption that the network and partner would be expanded over the five years.

Table 51 Income from the zero-waste system consultation and project management

Income from consultation and project management	No. of consultation project	Total income (THB)
Year 1	4	1,600,000
Year 2	5	2,000,000
Year 3	6	2,400,000
Year 4	7	2,800,000
Year 5	8	3,200,000
Total	**15**	**12,000,000**

(3) Income from zero-waste system education and training

The aims of zero-waste education and training is to raise awareness and increase the visibility of the zero-waste system benefits to stakeholders e.g. the government management officers e.g. Ministry of Higher Education, Science, Research and Innovation, Ministry of Interior, local governments, and the interested people from private sectors e.g. hotel, academia and students. Table 52 shows the net income from training is expected to be around 60,000 THB/year at the first year and will increase 20% annually until the 5th year.

Table 52 Income from the zero-waste system consultation and project management

Income from education and training	Total income (THB)
Year 1	60,000
Year 2	72,000
Year 3	86,400
Year 4	103,680
Year 5	124,416
Total	**446,496**

Table 53 shows the estimated total income of the company for the next five years based on the market plan and the cost estimation. The total income would be around 34.846 Million THB over the five years of operation.

Table 53 Estimated total income of the company

(Unit: Million THB)

Revenue structure	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Total
(1) Income from zero-waste system design and manufacturing	-	1.4	2.8	4.2	5.6	8.4	**22.4**
(2) Income from zero-waste consultation and project management	-	1.6	2.0	2.4	2.8	3.2	**12.0**

Revenue structure	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Total
(3) Income from education and training	-	0.060	0.072	0.086	0.104	0.124	**0.446**
Total income	**0.000**	**3.060**	**4.872**	**6.686**	**8.504**	**11.724**	**34.846**

The financial feasibility can be analyzed based on the initial investment, human resource cost and operating costs of the company comparing to the income to the company. Table 54 shows that over the five years of operation and following the marketing plan, the company would have the net profit around 9.208 million THB. Based on the initial investment costs that set as 2.856 million THB, the payback period of the company would be around 3 years.

Table 54 Estimated financial feasibility of the company for five years period

(Unit: Million THB)

Financial feasibility	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Total
Total income	0.000	3.060	4.872	6.686	8.504	11.724	34.846
Total cost	0.550	2.306	3.860	4.916	5.973	8.033	25.638
Net profit/ (loss)	**(-0.550)**	**0.754**	**1.012**	**1.770**	**2.530**	**3.692**	**9.208**

As seen by the Figures shown in Table 54, the net loss is only for the 0^{th} year that is the initial investment. For the first year, the net profit would be around 0.754 THB but it will increase continuously. If the discount rate is set as 8%, the NPV over the five years of the company would be around 4.155 million THB and the IRR would be around 43%. This financial feasibility results reveal that if the marketing plan and costs can be controlled accordingly, the establishment of company for commercialization of zero-waste system to the target market is feasible.

CHAPTER 7
CONCLUSIONS & RECOMMENDATIONS

The study has shown a comprehensive analysis for the development of an innovative zero-waste system for food waste and wastewater management in building. The framework of the study has started since (1) the conceptual model to explaining the factors affecting the intention to use the “zero-waste system” for wastewater and food waste management of the target market group (universities); (2) the development of an zero-waste system and testing operation of the system prototype for actual food waste and wastewater management Chulachakrabonse building of the Chulalongkorn University; (3) Evaluate the zero-waste system performance using the zero-waste system using life-cycle energy and GHG emissions; and (4) the analysis of commercialization model of the zero-waste system as the “innovative” and “green” technology solution for waste management of building including the value proposition, competitive advantage, market opportunity, economic analysis of the technology and the potential commercialization plan. The discussions and conclusions each step of work is as follows:

7.1 Conclusion and Discussion

7.1.1 Factors affecting the decision to use the zero-waste technology for wastewater and food waste management in the universities

The conceptual model to explain the factors affecting the interest or the intention to use the “zero-waste system” for wastewater and food waste management in the university building has been conducted and tested. The extensive survey of 112 samples from 20 universities out of the total 29 targeted public universities was achieved. The statistical analysis (multiple regression analysis) of the survey data indicated that the factors affecting the interest and the decision to use the zero-waste technology are as follows: (1) <u>Technological factors</u> include the quality of treated water, investments and costs, ease of use, system stability, odor disturbances, efficiency of water recycling and efficiency of biogas production; and (2)

Consumer characteristics factors include the university's image, university policy, management attitudes on environmental issues and government policy. The factors that do not affect the interest or the decision to use of zero-waste technology in the university (as shown by the dotted arrows in Figure 5.1) are the size of area required, fertilizer production efficiency, and community pressure, and the green university standards.

The results showed that the technology performance is still be the key factor to predict the intention to adoption consistent to several studies (Chen et al., 2011; Ahn, Kang, and Hustvedt, 2016). However, not all the environmental aspects are essential to the intention to adoption of the technology. For example, the footprint required and fertilizer production efficiency are not significant to the interest of some populations. Figure 61 shows the acceptance and rejected hypothesis results following the conceptual model proposal. The questionnaire data and the statistical analysis have pointed out the issues for supporting the development and promotion of the zero-waste system to the university's building to improve the university's food waste and wastewater management. The key issues are as follows

- It was found that the sample was interested in the zero-waste technology. Factors affecting interest in deciding to use the zero-waste system were both the technology factors and the consumer characteristics factors as summarized.
- The water recycling efficiency is the most important factor affecting the interest in the zero-waste system, followed by the management attitude, biogas production efficiency, and water quality after treatment.
- Most of the opinions on zero-waste technology's interest among the four groups are in the same direction, and there is no significant differences except the factor on land required, investment cost and university image.
- Currently, the wastewater treatment used in the universities are mainly the septic tanks and grease traps, and only a few universities having the additional wastewater treatment systems. Meanwhile, every university has used some food waste for animal feed. This can be seen as an opportunity to introduce the zero-waste system technology

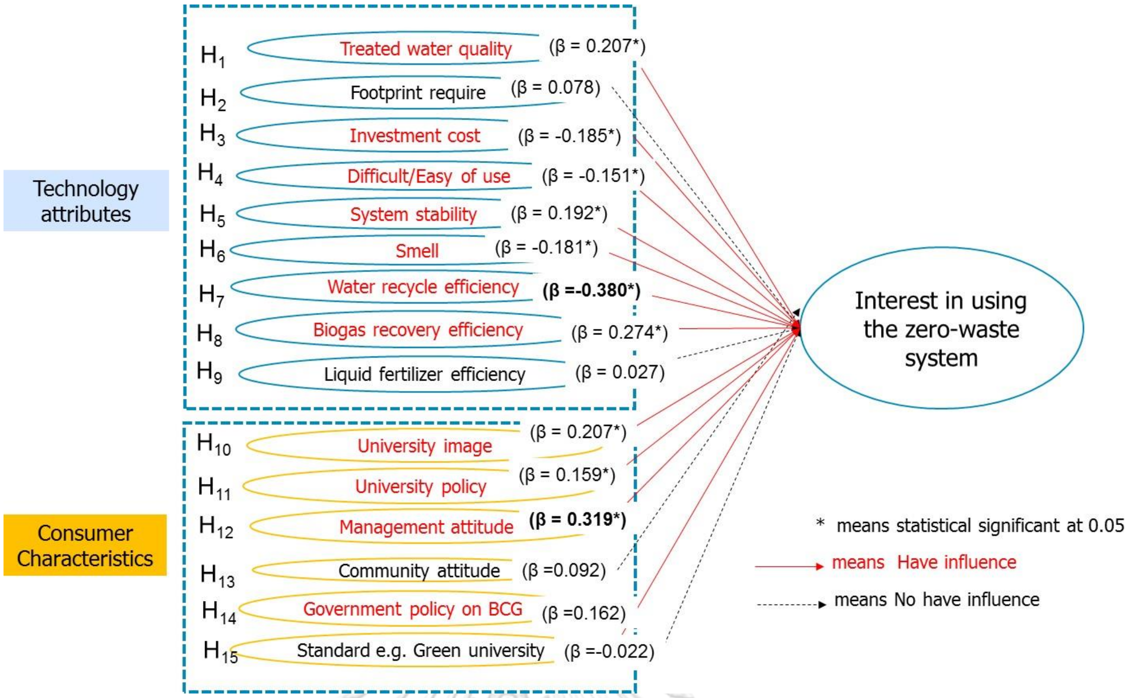


Figure 61 Summary hypothesis testing results of the proposed conceptual model

The research results have highlighted the factors that samples or people have attached to selecting the building's waste treatment system. This would be useful information for the waste treatment company and researchers to consider those issues in their ongoing research or waste treatment system, especially the zero-waste technology. The study also shows that the management's attitude and the university image on environmental protection also influence the decision to use the zero-waste system. To promote zero-waste technology to the target group, these consumer characteristic factors should be considered the benefits of zero-waste technology.

7.1.2 The zero-waste system and testing results

The innovative zero-waste system has been installed and operated for wastewater and food waste treatment to treat and use the benefits of the treated wastes. The zero-waste system consists of three major processes, i.e. (1) the shredder and screw conveyor unit to convey the food waste into the anaerobic digester; (2) the anaerobic digester for treating the shredded food waste along with the biogas production, and (3) the Moving Bed Biofilm Reaction–Membrane Bioreactor (MBBR-MBR) process for wastewater treatment and reuse. The system is installed but still on the process of testing in order to find the optimum condition in the future. For example, although the system still in line with the optimal pH range for methanogenic bacteria to obtain maximum biogas yield in anaerobic digestion is about 6.5-7.8. Especially, for the case of increase mixing of the vegetable & fruit wastes, the pH of feedstock would be decrease. The more acidity can fail the biogas system if they are not properly managed.

The key important for the zero-waste system is that the wastewater sludge and the leachate from the anaerobic digester would not be sent out the plant and they all will be return into the system as the Figure 62.

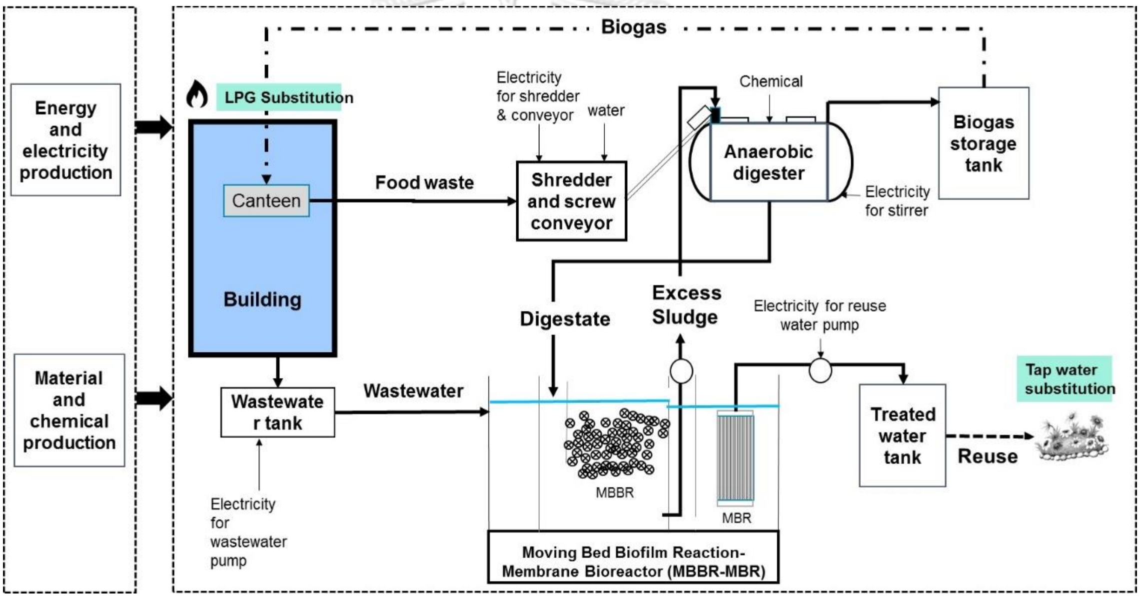


Figure 62 System boundary of the studied zero-waste system

(1) **Biogas production efficiency**

The range of the biogas generation was about 0.15 – 0.8 Nm^3/day. The averaged percentage of methane in the biogas were ranged from 56 – 65%. The anaerobic co-digestion between the food waste and wastewater sludge (case "60%FW20%FVW20%WS") result in the improved yield of methane. This consistent to the several studies that have shown that using co-substrates in anaerobic digestion systems lead to the positive synergisms in the digestion medium (Chow et al., 2020). The removal efficiency for the volatile solid and COD by the anaerobic digestion process of the zero-waste system was about 64-73% and 65-86%, respectively as shown.

(2) **Treated wastewater quality**

Table 55 shows the average water quality parameter of treated wastewater by MBBR-MBR that can pass the standard of landscape irrigation as well as the nonfood crop irrigation. This implies that there is the potential to be used of the water for landscape in the university.

Table 55 Key Water quality parameters of the treated wastewater by MBBR-MBR and the standard for water reclamation as agricultural reuse

Water quality parameters	Treated WW from MBBR-MBR	Agricultural reuse (**US EPA, 2012**)	
		Landscape Irrigation	Nonfood crops
pH	7.3	6-9	6-9
TS (mg/L)	<0.2	-	-
BOD (mg/L)	2.05	≤ 30	≤ 30
Turbidity (NTU)	0.76	≤ 2 NTU	≤ 30 (SS)
Fecal coliform (No./100 mL)	No detectable	No detectable	≤ 200

7.1.3 Environmental performance assessment of the zero-waste system using life-cycle energy and GHG emissions

LCA has been used as the tool to validate the zero-waste system performance for ensuring that the net environmental credits like GHG reduction would be obtained from the system when life-cycle stages are taken into account. The study assessed the cumulative energy demand and the life-cycle GHG emissions of the integrated system between the Moving Bed Biofilm Reaction–Membrane Bioreactor (MBBR-MBR) process anaerobic digester for treating food waste and wastewater management. The pilot system was developed and implemented under the zero-waste policy promotion at Chulalongkorn University, Thailand.

The system was called a “Zero-waste system” because the wastewater from the building could be treated and reused; the food waste from the canteen and the sludge from the wastewater treatment plant could be returned anaerobic digester to produce biogas. The assessment results showed that the zero-waste system could bring the net fossil energy reduction i.e. about -96.2 MJ-eq and GHG emissions reduction i.e. around -4.4 kg CO_2-eq as per the daily wastewater and food waste generation of the studied building. The main credit originated from the avoided fossil energy use and GHG emissions due to LPG substitution with biogas. Pig slurry transport from the pig farm as seed sludge, electricity consumption for the stirrer in the digester, and the air pump of the MBBR-MBR system are the significant sources of energy use and GHG emissions. The results were based on the initial stage of the system’s implementation. There are opportunities to improve the system efficiency via identifying the suitable condition of food and vegetable waste in operation and enhancing the benefits from treated wastewater and biogas.

7.1.4 Economic performance assessment of the zero-waste system

In terms of economic analysis, The EIRR, NPV and B/C of the zero-waste system are summarized in Table 56. The results revealed that for the base case, the innovative zero-waste system can be viable in economic due to the EIRR became higher than 8% as expected. The EIRR, NPV and B/C for the base case are about 8.83%, 66,646 THB and 1.44 respectively. The sensitivity analysis is also conducted by varying into 4 different conditions i.e. the benefit decreased 10%, the benefit increased 10%, the cost increased 10%, and the cost decreased 10%. The several economic benefits of the zero-waste system are as follows:

- Biogas recovery lead to save the LPG cost in canteen around 65,610 THB/year
- MBBR-MBR that help treat and improve the quality of treated water for reusing in the garden lead to the saving of water price about 43,200 THB/year.
- The zero-waste system leads to the carbon credits gain by the zero-waste system around 299 THB/year.

- Sludge treatment cost of saving when using the zero-waste comparing to the activated sludge system is about 3,105 THB/year.
- Land saving due to the less land required for wastewater treatment when using zero-waste system comparing to the activated sludge can bring the cost saving around 144,000 THB/year.

Table 56 EIRR, NPV and B/C of the zero-waste system in different conditions for discount rate 8%

Conditions	EIRR	NPV	B/C
Base case (discount rate 8%)	8.83%	66,646 THB	1.44
Benefit -10%	6.23%	-134,416 THB	1.30
Benefit +10%	11.27%	269,708 THB	1.59
Cost + 10%	6.48%	-129,751 THB	1.31
Cost – 10%	11.53%	263,043 THB	1.60

In addition to the environmental benefits as assessed before, there still have the other externalities like the policy support by the government on BCG and the achievement the commitment on SDG contribution of the users the are the intangible benefits of the zero-waste system implementation in buildings. Especially for the universities, to be the green university achievement as well as to raise awareness and to educate students and society from their actual practices are the most important external benefits obtained from the zero-waste system.

7.1.5 Commercialization plan for the zero-waste system

The environmental trends is rising globally especially the climate change, water scarcity and resource depletion. Innovative zero-waste system can be introduced as one of the "*innovative*" and "*green*" technology for food waste and wastewater management in various buildings and it is applicable to the university. This so called "*green value proposition*". The position of zero-waste system comparing to the conventional food waste and wastewater treatment in the university can be roughly seen in Figure 63.

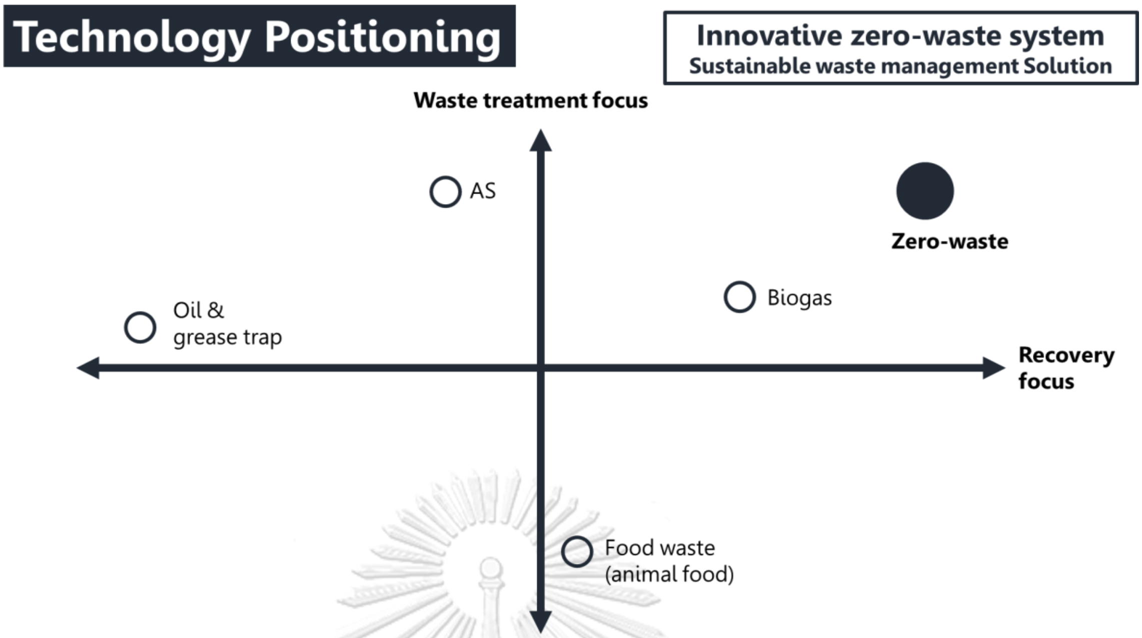


Figure 63 Technology positioning of the innovative zero-waste system

The external factors that benefit the zero-waste system are that the technology is developed in line with the global trends on "sustainable development goals (SDGs)" and "Bio-Circular-Green economy". In addition, implementing the zero-waste concept into the university should help the university fulfill the global ranking scheme like the UI GreenMetric World University Ranking. The study has also indicated several advantages/benefits of the zero-waste system comparing to the conventional waste treatment practices in Chapter 6. As well as, the patent review and mappings is shown in Figures 53 - 56.

(1) Commercialization plan

To commercialize the zero-waste system, a consulting company for zero-waste engineering and management is expected to establish for providing the solutions on integrated waste management to customers. The organization chart for the company is shown in Figure 60.

(2) Types of our product and services

Three types of product and/or services of the company are (1) Zero-waste system design and manufacturing, (2) Zero-waste system consultant, project management & construction supervision (PMS), and (3) Zero-waste education and training.

(3) Value chain and potential business model

The market assessment shows the zero-waste system's opportunity by commercializing it for buildings in universities and then further expanding to the other institutions or office buildings. The five forces analysis revealed the low risks from the threat of new entrants and suppliers' bargaining power if would like commercialize the technology to the universities. There will be moderate risks for bargaining power with buyers, threat of substitution, and competition rivalry. Based on the business chain of the sewage treatment plant implementation. Figure 64 shows the *"outsource OM & SM vendor"* business model that potentially viable for zero-waste system commercialization.

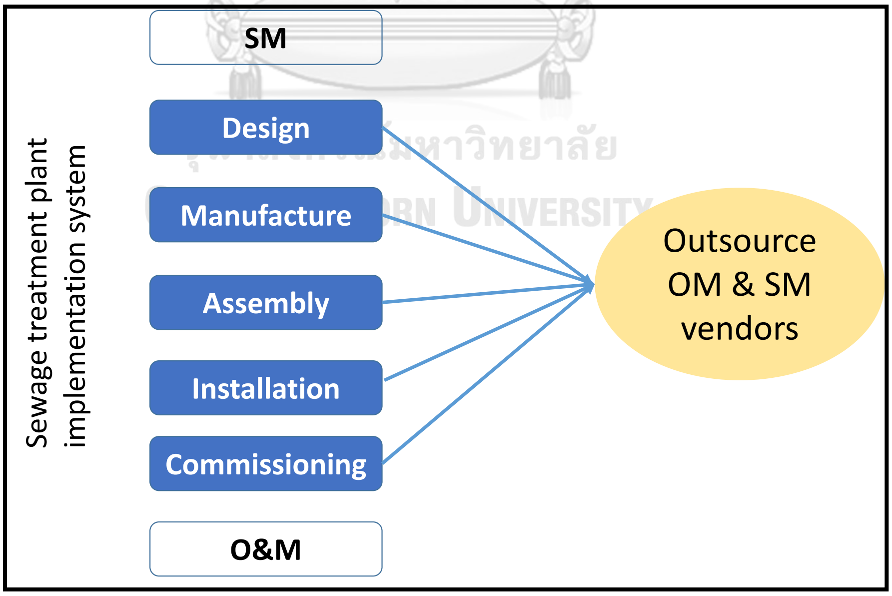


Figure 64 The outsource OM & SM vendor business model for zero-waste system

(4) Marketing plan

The market target group is classified following the three types of services by the company:

- **Market target for the zero-waste system design and manufacturing**

The groups for zero-waste system design and manufacturing at the beginning stage of three years will be promoted for universities/academic institutes in Thailand. There are 155 institutions in the country. The second stage would be the office buildings and the other economic sectors, especially the hotels where the food waste and wastewater will be the business's major environmental problems. Especially for the hotels in remote areas like islands, they have the limitations of land available for waste management and the limitation of fresh water resource used in their business. The zero-waste system must be the very fit option to those hotels/resorts in remote area.

- **Market target for zero-waste system consultant, project management & construction supervision (PMS)**

This group of customers would be the entrepreneurs or project owners, it is necessary to hire an experienced engineer and consultant with expertise in zero-waste project management and control to represent the management and control of activities and results at every stage of the project.

- **Market target for zero-waste system education and training**

The target group for zero-waste system education and training will be the government management officers e.g. Ministry of Higher Education, Science, Research and Innovation, Ministry of Interior, local government e.g. municipalities in Thailand. The last group will be interested people from the private sectors, academia, and students. The aims of zero-waste education and training are not for much profit, but the aims are to raise awareness and increase the visibility of the zero-waste system benefits to stakeholders.

(5) Financial plan

Based on the estimated incomes from three types of services and the investment and operational costs, the company's estimated financial feasibility is indicated in Table 57. Over the five years of operation and following the marketing plan, the company's net profits would be around 9.208 million THB. Based on the initial investment costs set as 2.856 million THB as shown in Table 52, the company's payback period would be around 3 years. At the discount rate set at about 8%, the NPV over the five years of the company would be approximately 4.155 million THB, and the IRR would be around 43%. These financial feasibility results show that if a company's establishment for the commercialization of zero-waste system to the target market is feasible.

Table 57 Estimated financial feasibility of the company for five years period

(Unit: Million THB)

Financial feasibility	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Total
Total income	0.000	3.060	4.872	6.686	8.504	11.724	34.846
Total cost	0.550	2.306	3.860	4.916	5.973	8.033	25.638
Net profit/ (loss)	**(-0.550)**	**0.754**	**1.012**	**1.770**	**2.530**	**3.692**	**9.208**

Nevertheless, due to the fact that there is no single company or individual has all the answers, we think that it is necessary to work together and build on each other's work. Partnership or the collaborative approach is essential in finding innovative solutions to overcome the challenge on green technology diffusion (Brant, 2014). To disseminate the zero-waste system to different places in Thailand, it is a complex and multi-dimensional process that need collaboration with stakeholders to ensure the deployment of appropriate and/or adapted technology solutions across countries over time.

7.2 Limitation

The survey and interview data for analyzing the results of factors affecting the intention to use the zero-waste system for wastewater and food waste management in the university is limited based on only 112 samples from 20 universities. The study principally surveyed by focusing on the public universities under the OHEC not yet covering for the whole 115 universities over the country. The extensive survey to all the universities therefore, may affect to the results. The study's sample size obtained was classified into 18 students, 20 technician/engineers, 6 management, and 48 lecturers/researchers (as shown in Table 21). Anyway, it was found that around 64 samples or 57.1% of the total sample hold the PhD degree which can be slightly expected that they all understand well the questions in the survey questionnaire and the responses are reliable.

7.3 Recommendations

7.3.1 Recommendations for zero-waste system adoption

The study revealed that the innovative zero-waste system had shown outstanding advantages as a sustainable waste treatment technology comparing to conventional food waste and wastewater treatment after considering sustainability dimensions. Its technical advantage is that the system integrates food waste and wastewater management, bringing benefits to water recycling and biogas production to save water and energy resources. The technology requires less land; it is recommended to use for the building, especially in the urban that land is an essential cost. Besides, for remote areas like hotels in islands where the freshwater resource is limited, and the land is not enough for waste landfilling, this zero-waste system must be the appropriate option. The scale of a zero-waste system can be designed for different customers. For example, in a retail store like Tesco Lotus and IKEA in Thailand, the food waste are around 150-200 and 300-400 kilograms/day, respectively (based on interview). Apart from technical feasibility, the LCA's environmental feasibility and the results have shown the system's net carbon credits.

In terms of economic perspective, the NPV is shown positive, and EIRR is more than 8% that demonstrated the possibility to use by the customers.

7.3.2 Future research recommendations

The zero-waste system proposed for building's food waste and wastewater management has shown the potential for commercialization. However, there still are areas of improvement in both the research and development of the zero-waste technology development and the commercialization process with they are not covered in this research's scope. The recommendations for future research are as follows.

(1) The food waste and wastewater properties in the different regions might have variations, although the current zero-waste system has the stability to accept the varieties of food waste loads. However, to have the best system design to the customers, the information regarding the food waste and wastewater properties of the customer is required for design the suitable scale and operating condition to the customers too.

(2) The societal benefits due to the zero-waste system implementation should be further investigated. Several advantages to society from the "green" and "environmental" technology that have not yet been taken into account in the market price e.g. ecosystem quality improvement, reduction of health impacts of the society, increasing the visibility of the organization brands and recognition. These all need economic research to determine the benefits to society. The policymakers/decision-makers can know the total benefits and use it to set the policy promotion and budget for implementing green technology like the zero-waste system.

(3) The commercialization process from R&D in the university to the market needs collaboration and support from various organizations. Therefore, the implementation step is necessary to have a professional unit or agency like the technology transfer office to support the researchers.

APPENDIX

Appendix A: Survey questionnaire

แบบสอบถามเพื่อการวิจัย

เรื่อง "ความต้องการและปัจจัยในการตัดสินใจเลือกเทคโนโลยีการจัดการน้ำเสีย และขยะเศษอาหาร ในอาคารของสถาบันการศึกษา (มหาวิทยาลัย)"

คำชี้แจงเบื้องต้นในการตอบแบบสอบถาม

การสำรวจแนวทางการจัดการขยะเศษอาหารและแนวทางการจัดการน้ำเสียที่เกิดขึ้นจากอาคารในสถาบันการศึกษาระดับอุดมศึกษา เช่น มหาวิทยาลัยรัฐและเอกชน สถาบันเทคโนโลยีราชมงคล และอื่นๆ รวมถึงสอบถามความคิดต่อต่อการตัดสินใจเลือกใช้เทคโนโลยีเพื่อการจัดการน้ำเสียและขยะเศษอาหารในของอาคาร (โรงอาหารกลาง) ของสถาบัน เพื่อการศึกษาวิจัยถึงความต้องการและปัจจัยในการตัดสินใจเลือกเทคโนโลยีการจัดการน้ำเสียและขยะเศษอาหารเพื่อไปใช้ในอาคารของสถาบันการศึกษาระดับอุดมศึกษาโดยแบบสอบถามดังกล่าวนี้แบ่งได้ออกเป็น 6 ส่วน จำนวน 11 หน้า

ส่วนที่ 1 ข้อมูลทั่วไปของสถาบันการศึกษา (จำนวน 4 คำถาม)

ส่วนที่ 2 ข้อมูลทั่วไปของผู้ตอบแบบสอบถาม (จำนวน 4 คำถาม)

ส่วนที่ 3 ข้อมูลการจัดการน้ำเสียและขยะเศษอาหารที่ดำเนินการอยู่ในปัจจุบัน (จำนวน 6 คำถาม)

ส่วนที่ 4 ข้อมูลสอบถามปัจจัยที่มีอิทธิพลต่อความเต็มใจจ่ายและการเลือกใช้เทคโนโลยีการจัดการของเสีย

ส่วนที่ 5 ทัศนคติที่มีต่อประเด็นการจัดการด้านสิ่งแวดล้อม และนวัตกรรมใหม่ๆ

ผู้วิจัยขอขอบพระคุณอย่างสูงกับผู้ตอบแบบสอบถามที่สละเวลาดังกล่าว ผลการสำรวจและผลการวิจัยที่ได้นี้ผู้วิจัยมุ่งหวังจะให้เกิดการหาแนวทางเพื่อเพิ่มประสิทธิภาพและแนวทางในการส่งเสริมเพื่อให้เกิดการใช้เทคโนโลยีการจัดการน้ำเสียและขยะเศษอาหารในอาคารได้อย่างกว้างขวางต่อไปในอนาคต ทั้งนี้หากมีข้อสงสัยกับแบบสอบถามประการใดสามารถติดต่อสอบถาม และส่งกลับแบบสอบถามได้ดังนี้

ส่วนที่ 1 ข้อมูลทั่วไปของสถาบันการศึกษา (จำนวน 4 คำถาม)

ประเภทของสถาบันการศึกษา

○ สถาบันการศึกษาในกำกับของรัฐ ○ สถาบันอุดมศึกษาของรัฐ

○ สถาบันการศึกษาไม่จำกัดรับ (ม.เปิด) ○ มหาวิทยาลัยเทคโนโลยีราชมงคล

○ มหาวิทยาลัยเทคโนโลยีราชภัฏ ○ มหาวิทยาลัยเอกชน

○ วิทยาลัยชุมชน ○ วิทยาลัยเอกชน ○ สถาบันเอกชน ○อื่นๆ

สถานที่ตั้ง

○ ภาคเหนือ ○ ภาคกลาง (รวมกรุงเทพมหานคร)

○ ภาคตะวันออกเฉียงเหนือ

○ ภาคตะวันออก ○ ภาคตะวันตก ○ ภาคใต้

จำนวนนักศึกษารวมทั้งหมด (คิดเฉพาะในวิทยาเขตที่ผู้กรอกแบบสอบถามทำงานอยู่)

○ น้อยกว่า 1,000 คน ○ 1,001 – 3,000 คน ○ 3,001- 5,000 คน ○ 5,001- 7,000 คน

○ 7,001- 9,000 คน ○ 9,001 – 11,000 คน ○ 11,001- 13,000 คน

○ 13,001- 15,000 คน ○ มากกว่า 15,000 คน โปรดประมาณจำนวนคน ....

ส่วนที่ 2 ข้อมูลทั่วไปขอบผู้ตอบแบบสอบถาม (จำนวน 4 คำถาม)

เพศ ○ ชาย ○ หญิง ○ อื่นๆ

อายุ

○ ต่ำกว่า 30 ○ 31-35 ปี ○ 36-40 ปี ○ 41-45 ปี

○ 46-50 ปี ○ 51-55 ปี ○ 56-60 ปี ○ มากกว่า 60 ปี

ตำแหน่ง

○ ผู้บริหารสถาบัน ○ เจ้าหน้าที่ฝ่ายอาคารสถานที่ ○ ผู้ออกแบบอาคาร

○ ที่ปรึกษา ○ ช่างที่ดูแลอาคาร ○ ผู้ดูแลระบบจัดการของเสีย

○ ผู้รับเหมา ○ อาจารย์ ○ นักศึกษา

○ นักวิจัย ○ อื่นๆ โปรดระบุ..................................

ระดับการศึกษา

○ ต่ำกว่าปริญญาตรี ○ ปริญญาตรี ○ ปริญญาโท ○ ปริญญาเอก

ส่วนที่ 3 ข้อมูลการจัดการน้ำเสียและขยะเศษอาหารที่ดำเนินการอยู่ในปัจจุบัน (จำนวน 6 คำถาม)

ระบบบำบัดน้ำเสียในอาคาร (โรงอาหารกลาง) ปัจจุบันของท่านเป็นแบบใด (ตอบได้มากกว่า 1 ข้อ กรณีที่มีหลายระบบร่วมกัน)

○ ไม่มีการบำบัด

○ มีการบำบัด (เลือกได้มากกว่า 1)

○ ระบบบ่อเกรอะ (Septic Tank)

○ ระบบบ่อกรองไร้อากาศ (Anaerobic Filter)

○ บ่อดักไขมัน (Grease Trap)

○ ระบบบำบัดน้ำเสียแบบบ่อปรับเสถียร (Stabilization Pond)

○ ระบบบำบัดน้ำเสียแบบบ่อเติมอากาศ (Aerated Lagoon หรือ AL)

○ ระบบบำบัดน้ำเสียแบบแอกทิเวเต็ดสลัดจ์ (Activated Sludge Process)

○ ระบบบำบัดน้ำเสียแบบคลองวนเวียน (Oxidation Ditch ; OD)

○ ระบบบำบัดน้ำเสียแบบแผ่นจานหมุนชีวภาพ (Rotating Biological Contactor; RBC)

○ ระบบบำบัดน้ำเสียแบบเมมเบรนไบโอรีแอคเตอร์

○ แบบอื่นๆ โปรดระบุ..

ระบบบำบัดน้ำเสียปัจจุบันมีการรีไซเคิลน้ำเสียกลับมาใช้ได้หรือไม่

○ ไม่มี ○ มี นำกลับมาใช้ทำอะไร (โปรดระบุ) ....

ท่านมีค่าใช้จ่ายในการจัดการน้ำเสีย เฉลี่ยต่อเดือน เป็นจำนวนเงิน .... บาทต่อเดือน

ท่านจัดการขยะเศษอาหารปัจจุบันด้วยวิธีการใด

○ ไม่มีการคัดแยก ○ มีการคัดแยก (เลือกได้มากกว่า 1)

○ ทิ้ง ○ ขายหรือให้เป็นอาหารสัตว์

○ หมักทำปุ๋ย ○ ผลิตก๊าซชีวภาพ ○ อื่นๆ โปรดระบุ.........

ท่านมีค่าใช้จ่ายหรือรายได้ในการจัดการขยะเศษอาหารหรือไม่

○ มีค่าใช้จ่ายในการจัดการขยะเศษอาหาร ประมาณ .... บาทต่อเดือน

○ มีรายได้จากการขายขยะเศษอาหาร ประมาณ .... บาทต่อเดือน

ท่านมีความสนใจกับแนวคิดการติดตั้งระบบซีโรเวสต์ (Zero waste) เพื่อรีไซเคิลน้ำเสียกลับมาใช้ใหม่และนำขยะเศษอาหารไปผลิตก๊าซชีวภาพและปุ๋ยน้ำเพื่อนำกลับมาใช้ประโยชน์ให้มากที่สุดหรือไม่

○ มีความสนใจเล็กน้อย ○ มีความสนใจปานกลาง ○ มีความสนใจมาก

○ มีความสนใจมากที่สุด ○ ไม่มีความสนใจเลย เพราะ ....

ส่วนที่ 4 ข้อมูลสอบถามปัจจัยที่มีอิทธิพลต่อการเลือกใช้เทคโนโลยีการจัดการของเสีย

ส่วนที่ 4 นี้เป็นการสอบถามถึงปัจจัยที่ท่านคิดว่ามีอิทธิพลต่อการที่ท่านจะใช้เพื่อเลือกซื้อหรือเลือกติดตั้งเทคโนโลยีการจัดการน้ำเสีย และการจัดการขยะเศษอาหารสำหรับอาคารในมหาวิทยาลัยของท่าน ซึ่งมีทั้งสิ้น 22 ปัจจัย ขอให้ท่านประเมินในทุกปัจจัยว่ามีความสำคัญมากหรือน้อยเพียงใด ขอให้ท่านทำเครื่องหมาย ✓ในแต่ละปัจจัยว่ามีความสำคัญมากหรือน้อยเพียงใดกับการตัดสินใจของท่าน

	ไม่มีความสำคัญ	สำคัญน้อย	ปานกลาง	สำคัญมาก	สำคัญมากที่สุด
คุณภาพของน้ำเสียหลังการบำบัด					
พลังงานที่ต้องใช้					
ขนาดพื้นที่ที่ใช้					
ต้นทุนของระบบบำบัด (เงินลงทุน)					
ค่าใช้จ่ายในการเดินระบบ และบำรุงรักษา					
ความต้องการการบำรุงรักษา					
ความยากง่ายของการใช้งานระบบ					
เสถียรภาพของระบบ					
กลิ่นโดยรอบระบบบำบัด					
ความสามารถในการรองรับปัญหากรณีที่มีของเสียเช่นน้ำเสียหรือขยะมีความแปรปรวนของปริมาณและภาระที่เข้าสู่ระบบ					
ประสิทธิภาพในการรีไซเคิลน้ำเสียกลับมาใช้ใหม่ได้					
ประสิทธิภาพในการนำขยะมาผลิตก๊าซชีวภาพ					
ประสิทธิภาพในการนำน้ำเสียไปทำปุ๋ย					
ประโยชน์ที่ได้รับจากการรีไซเคิล					
ความคุ้มค่าของการลงทุน					
ภาพลักษณ์องค์กรต่อความสามารถใน					

	ไม่มีความสำคัญ	สำคัญน้อย	ปานกลาง	สำคัญมาก	สำคัญมากที่สุด
การจัดการของเสียแบบซีโรเวสต์					
นโยบายของมหาวิทยาลัยหรือผู้บริหารต่อการจัดการด้านสิ่งแวดล้อมในแนวทาง ซีโรเวสต์ หรือการนำของเสียกลับมาให้อย่างคุ้มค่าที่สุด					
ทัศนคติด้านสิ่งแวดล้อมของผู้บริหารองค์กร					
ทัศนคติด้านสิ่งแวดล้อมของนักศึกษากับความต้องการให้เกิดการรีไซเคิลน้ำเสียและขยะเศษอาหารแบบซีโรเวสต์					
ทัศนคติด้านสิ่งแวดล้อมหรือแรงกดดันจากชุมชนโดยรอบต่อมหาวิทยาลัยในการจัดการน้ำเสียและขยะเศษอาหาร					
นโยบายของรัฐบาลต่อเรื่องของ ซีโรเวสต์, เศรษฐกิจหมุนเวียน, เศรษฐกิจชีวภาพในมหาวิทยาลัย					
เงื่อนไขจากมาตรฐานภายนอก เช่น มหาวิทยาลัยสีเขียว (Green university) ที่จะมีผลการต่อการเลือกใช้ระบบซีโรเวสต์เพื่อการรีไซเคิลน้ำเสียและขยะเศษอาหาร					
เงื่อนไขจากมาตรฐานด้านการจัดการสิ่งแวดล้อม ความปลอดภัย ที่ใช้ในการประเมินมหาวิทยาลัยและการจัดลำดับมหาวิทยาลัย					

ส่วนที่ 5 ทัศนคติที่มีต่อประเด็นการจัดการด้านสิ่งแวดล้อม และนวัตกรรมใหม่ๆ

ส่วนที่ 5 นี้เป็นการสอบถามถึงทัศนคติของท่านต่อประเด็นเรื่องของการจัดการด้านสิ่งแวดล้อมในมหาวิทยาลัย รวมถึงประเด็นความสนใจของท่านต่อนวัตกรรมใหม่ๆ ที่สามารถนำมาใช้เพื่อการจัดการด้านสิ่งแวดล้อมในมหาวิทยาลัยของท่าน ซึ่งมีทั้งสิ้น 9 คำถาม ขอให้ท่านประเมินในทุกคำถามว่ารู้สึกเห็นด้วยมากหรือน้อยเพียงใด

ขอให้ท่านทำเครื่องหมาย ✓ในแต่ละปัจจัยว่ามีความสำคัญมากหรือน้อยเพียงใดกับการตัดสินใจของท่าน

	ไม่เห็นด้วยอย่างยิ่ง	ไม่เห็นด้วย	ปานกลาง	เห็นด้วย	เห็นด้วยอย่างยิ่ง
ปัญหาด้านน้ำเสียจากอาคารที่ไม่ได้รับการบำบัดอย่างเหมาะสมเป็นปัญหาสำคัญ					
ปัญหาด้านเศษอาหารเป็นปัญหาที่มีแนวโน้มมากขึ้นและจัดการยากขึ้น					
มหาวิทยาลัยมีหน้าที่ต้องช่วยแก้ไขปัญหาด้านน้ำเสียและขยะเศษอาหาร					
การรีไซเคิลทรัพยากรกลับมาใช้ประโยชน์สูงสุดมีความจำเป็นอย่างยิ่งในอนาคต					
หากมีการใช้แนวทางการจัดการแบบซีโรเวสต์จะช่วยแก้ปัญหาน้ำเสียและขยะเศษอาหารได้ดีขึ้น					
มหาวิทยาลัยมีบทบาทสำคัญมากที่จะต้องไม่ก่อให้เกิดผลกระทบต่อสิ่งแวดล้อม					
ปัญหาการลดลงของทรัพยากรของโลกที่มีอยู่จำกัด เช่น น้ำจืด เป็นปัญหาที่สำคัญ					
เทคโนโลยีหรือนวัตกรรมที่ช่วยรีไซเคิลน้ำเสียและเศษอาหารกลับมาใช้มีความจำเป็นต่อการจัดการของเสีย					
การจะตัดสินใจติดตั้งหรือใช้งานระบบเพื่อจัดการของเสียคุณมักพิจารณาที่เงินลงทุน ค่าใช้จ่าย และระยะคืนทุนเป็นหลัก					

REFERENCES

Agarwal, R., & Prasad, J. (1998). A conceptual and operational definition of personal innovativeness in the domain of information technology. *Information systems research, 9*(2), 204-215.

Ahn, M., Kang, J., & Hustvedt, G. (2016). A model of sustainable household technology acceptance. *International Journal of Consumer Studies, 40*(1), 83-91.

Allison, P. D. (1999). *Logistic regression using the SAS system: Theory and Application*. New York: Cary, NC, SAS. institute Inc.

Arora, S., & Gangopadhyay, S. (1995). Toward a theoretical model of voluntary overcompliance. *Journal of economic behavior & organization, 28*(3), 289-309.

Australian-Government. (2003). *Mapping Australian Science and Innovation: Main report*. Australia: Australian Government

Awerbuch, S. (2000). Investing in photovoltaics: risk, accounting and the value of new technology. *Energy Policy, 28*(14), 1023-1035.

Balachandra, P., & Nathan, K. (2010). Commercialization of sustainable energy technologies. *Renewable Energy, 35*(8), 1842-1851.

Bering, S., Mazur, J., Tarnowski, K., Janus, M., Mozia, S., & Morawski, A. W. (2018). The application of moving bed bio-reactor (MBBR) in commercial laundry wastewater treatment. *Science of the total environment, 627*, 1638-1643.

Bouted, C., & Ratanatamskul, C. (2019). A novel prototype of integrated anaerobic filter-condenser (ANCO) system for application of waste heat from office building to improve performances of both air conditioner and wastewater treatment system. *Journal of environmental management, 231*, 66-72.

Carlson, R. C., & Rafinejad, D. (2008). Modeling sustainability in product development and commercialization. *Bulletin of Science, Technology & Society, 28*(6), 478-485.

Chen, C.-f., Xu, X., & Arpan, L. (2017). Between the technology acceptance model and sustainable energy technology acceptance model: Investigating smart meter acceptance in the United States. *Energy research & social science, 25*, 93-104.

Chen, C.-J., Chang, C.-C., & Hung, S.-W. (2011). Influences of technological attributes and environmental factors on technology commercialization. *Journal of Business Ethics, 104*(4), 525-535.

Chow, W. L., Chong, S., Lim, J. W., Chan, Y. J., Chong, M. F., Tiong, T. J., . . . Pan, G.-T. (2020). Anaerobic Co-Digestion of Wastewater Sludge: A Review of Potential Co-Substrates and Operating Factors for Improved Methane Yield. *Processes, 8*(1), 39.

Chula. (2020). UI GreenMetric World University Ranking 2019 Ranks Chula 3rd in Thailand. Retrieved from https://www.chula.ac.th/en/news/26448/

Clavreul, J., Guyonnet, D., & Christensen, T. H. (2012). Quantifying uncertainty in LCA-modelling of waste management systems. *Waste Management, 32*(12), 2482-2495.

Dai, X., Duan, N., Dong, B., & Dai, L. (2013). High-solids anaerobic co-digestion of sewage sludge and food waste in comparison with mono digestions: stability and performance. *Waste Management, 33*(2), 308-316.

Davis, F. D. (1989). Perceived usefulness, perceived ease of use, and user acceptance of information technology. *MIS quarterly*, 319-340.

De Clercq, D., Wen, Z., Fan, F., & Caicedo, L. (2016). Biomethane production potential from restaurant food waste in megacities and project level-bottlenecks: a case study in Beijing. *Renewable and Sustainable Energy Reviews, 59*, 1676-1685.

Di Trapani, D., Di Bella, G., Mannina, G., Torregrossa, M., & Viviani, G. (2014). Comparison between moving bed-membrane bioreactor (MB-MBR) and membrane bioreactor (MBR) systems: influence of wastewater salinity variation. *Bioresource technology, 162*, 60-69.

Digman, B., & Kim, D. S. (2008). Alternative energy from food processing wastes. *Environmental Progress, 27*(4), 524-537.

Duan, L., Li, S., Han, L., Song, Y., Zhou, B., & Zhang, J. (2015). Comparison between moving bed-membrane bioreactor and conventional membrane bioreactor systems. Part I: membrane fouling. *Environmental Earth Sciences, 73*(9), 4881-4890.

Ecoinvent3.0. (2012). *Swiss Center for Life Cycle Inventories*.

Everett, R. (1995). Diffusion of innovations. *New York, 12*.

FAO. (2011). *Global Food Losses and Food Waste, Extent, Causes and Prevention*. Retrieved from Rome:

Finkbeiner, M., Tan, R., & Reginald, M. (2011). *Life cycle assessment (ISO 14040/44) as basis for environmental declarations and carbon footprint of products.* Paper presented at the ISO Technical Committee 207 Workshop, Norway.

Fraj-Andrés, E., Martinez-Salinas, E., & Matute-Vallejo, J. (2009). A multidimensional approach to the influence of environmental marketing and orientation on the firm's organizational performance. *Journal of Business Ethics, 88*(2), 263.

Frischknecht, R., Jungbluth, N., Althaus, H.-J., Bauer, C., Doka, G., Dones, R., . . . Köllner, T. (2007). Implementation of life cycle impact assessment methods. In: Citeseer.

Guldmann, E. (2014). Best practice examples of circular business models. *World, 20*.

GWRC, F. J., Yuan, Z., Keller, J., Senante, E., Chandran, K., & Willis, J. (2011). *N 2 O and CH 4 emission from wastewater collection and treatment systems*. Retrieved from

Hasik, V., Anderson, N. E., Collinge, W. O., Thiel, C. L., Khanna, V., Wirick, J., . . . Bilec, M. M. (2017). Evaluating the life cycle environmental benefits and trade-offs of water reuse systems for net-zero buildings. *Environmental science & technology, 51*(3), 1110-1119.

Hendrickson, T. P., Nguyen, M. T., Sukardi, M., Miot, A., Horvath, A., & Nelson, K. L. (2015). Life-cycle energy use and greenhouse gas emissions of a building-scale wastewater treatment and nonpotable reuse system. *Environmental science & technology, 49*(17), 10303-10311.

Huijbregts, M., Steinmann, Z., Elshout, P., Stam, G., Verones, F., Vieira, M., . . . Van Zelm, R. (2016). ReCiPe 2016: a harmonized life cycle impact assessment method at midpoint and endpoint level report I: characterization.

Huiru, Z., Yunjun, Y., Liberti, F., Pietro, B., & Fantozzi, F. (2019). Technical and economic feasibility analysis of an anaerobic digestion plant fed with canteen food waste. *Energy conversion and management, 180*, 938-948.

Hundal, M. (2000). *Life cycle assessment and design for the environment.* Paper presented at the International Design Conference-Design.

Hustvedt, G., Ahn, M., & Emmel, J. (2013). The adoption of sustainable laundry technologies by US consumers. *International Journal of Consumer Studies, 37*(3), 291-298.

IIT. (2010). Sewage treatment in Class I towns: Recommendations and guidelines. Retrieved from http://www.moef.nic.in/sites/default/files/ngrba/003_EQP_S&R_02.pdf

Iorhemen, O. T., Hamza, R. A., & Tay, J. H. (2016). Membrane bioreactor (MBR) technology for wastewater treatment and reclamation: membrane fouling. *Membranes, 6*(2), 33.

Islas-Espinoza, M., De las Heras, A., Vázquez-Chagoyán, J., & Salem, A. (2017). Anaerobic cometabolism of fruit and vegetable wastes using mammalian fecal inoculums: fast assessment of biomethane production. *Journal of Cleaner Production, 141*, 1411-1418.

Isola, C., Sieverding, H. L., Asato, C. M., Gonzalez-Estrella, J., Litzen, D., Gilcrease, P. C., & Stone, J. J. (2018). Life cycle assessment of portable two-stage anaerobic digestion of mixed food waste and cardboard. *Resources, Conservation and Recycling, 139*, 114-121.

Kalbar, P. P., Karmakar, S., & Asolekar, S. R. (2012). Selection of an appropriate wastewater treatment technology: A scenario-based multiple-attribute decision-making approach. *Journal of environmental management, 113*, 158-169.

Khan, S. J., Ilyas, S., Javid, S., Visvanathan, C., & Jegatheesan, V. (2011). Performance of suspended and attached growth MBR systems in treating high strength synthetic wastewater. *Bioresource technology, 102*(9), 5331-5336.

Kirchberger, M. A., & Pohl, L. (2016). Technology commercialization: a literature review of success factors and antecedents across different contexts. *The Journal of Technology Transfer, 41*(5), 1077-1112.

Lacy, P., Keeble, J., & McNamara, R. (2014). Circular Advantage: Innovative Business Models and Technologies to Create Value in a World without Limits to Growth. Accenture Strategy. In.

Li, W., Loh, K.-C., Zhang, J., Tong, Y. W., & Dai, Y. (2018). Two-stage anaerobic digestion of food waste and horticultural waste in high-solid system. *Applied Energy, 209*, 400-408.

Liu, C.-f., Yuan, X.-z., Zeng, G.-m., Li, W.-w., & Li, J. (2008). Prediction of methane yield at optimum pH for anaerobic digestion of organic fraction of municipal solid waste. *Bioresource technology, 99*(4), 882-888.

Liwei, G., Shengkui, C., Xiaochang, C., Dan, Z., Xiaojie, L., Qi, Q., & Yao, L. (2013). An overview of the resources and environmental issues from wasted food in urban catering across China. *Journal of Resources and Ecology, 4*(4), 337-343.

MacArthur, E. (2013). Towards the circular economy, economic and business rationale for an accelerated transition. *Ellen MacArthur Foundation: Cowes, UK*, 21-34.

Manpetch, P. (2014). *Biogas production from co-digestion of food waste and rain tree leaf using single-stage and two-stage anaerobic digesters.* (Master's Degree). Chulalongkorn University, Bangkok.

Mehariya, S., Patel, A. K., Obulisamy, P. K., Punniyakotti, E., & Wong, J. W. (2018). Co-digestion of food waste and sewage sludge for methane production: Current status and perspective. *Bioresource technology, 265*, 519-531.

Mezzullo, W. G., McManus, M. C., & Hammond, G. P. (2013). Life cycle assessment of a small-scale anaerobic digestion plant from cattle waste. *Applied Energy, 102*, 657-664.

MichiganTech. (2020). Technology Commercialization Process. Retrieved from https://www.mtu.edu/research/innovation/commercialize-technology/process/

Morone, P., Koutinas, A., Gathergood, N., Arshadi, M., & Matharu, A. (2019). Food waste: challenges and opportunities for enhancing the emerging bio-economy. *Journal of Cleaner Production, 221*, 10-16.

MTEC. (2014). *Thailand national LCI database*.

Muñoz-Suárez, M., Guadalajara, N., & Osca, J. M. (2020). A Comparative Analysis between Global University Rankings and Environmental Sustainability of Universities. *Sustainability, 12*(14), 5759.

Nilthong, N. (2002). *Landfill Leachate treatment by submerged-type membrane bioreactor.* (Master's Degree). Chulalongkorn University, Bangkok.

OHEC (Writer). (2019). List of Accredited Thai Higher Education Institutions. In O. o. t. H. E. C. Bureau of International Cooperation Strategy (Producer). Thailand.

Pavi, S., Kramer, L. E., Gomes, L. P., & Miranda, L. A. S. (2017). Biogas production from co-digestion of organic fraction of municipal solid waste and fruit and vegetable waste. *Bioresource technology, 228*, 362-367.

PCD. (2018). *Thailand State of Pollution Report 2017*. Retrieved from Bangkok: http://www.pcd.go.th/file/AW-Pollution-Report2017.pdf

PCD. (2019). *Water Quality and Management*. Retrieved from http://www.pcd.go.th/info_serv/water_wt.html#s1

Pérez-Camacho, M. N., Curry, R., & Cromie, T. (2018). Life cycle environmental impacts of substituting food wastes for traditional anaerobic digestion feedstocks. *Waste Management, 73*, 140-155.

Poortinga, W., Steg, L., & Vlek, C. (2004). Values, environmental concern, and environmental behavior: A study into household energy use. *Environment and behavior, 36*(1), 70-93.

Quacquarelli-Symonds. (2020). QS Top University Rankings. Retrieved from https://www.topuniversities.com/qsworld-university-rankings/methodology

Ratanatamskul, C., & Kongwong, J. (2017). Impact of intermittent aeration mode on enhancement of biological nutrient removal by the novel prototype IT/OD-MBR (Inclined Tube/Oxidation-Ditch Membrane Bioreactor) for high-rise building's wastewater recycling. *International Biodeterioration & Biodegradation, 124*, 36-44.

Ratanatamskul, C., & Manpetch, P. (2016). Comparative assessment of prototype digester configuration for biogas recovery from anaerobic co-digestion of food waste and rain tree leaf as feedstock. *International Biodeterioration & Biodegradation, 113*, 367-374.

Ratanatamskul, C., Onnum, G., & Yamamoto, K. (2014). A prototype single-stage anaerobic digester for co-digestion of food waste and sewage sludge from high-rise building for on-site biogas production. *International Biodeterioration & Biodegradation, 95*, 176-180.

Ratanatamskul, C., Wattanayommanaporn, O., & Yamamoto, K. (2015). An on-site prototype two-stage anaerobic digester for co-digestion of food waste and sewage sludge for biogas production from high-rise building. *International*

Biodeterioration & Biodegradation, 102, 143-148.

Rogers, E. M. (2010). *Diffusion of innovations*: Simon and Schuster.

Romano, G., Rapposelli, A., & Marrucci, L. (2019). Improving waste production and recycling through zero-waste strategy and privatization: An empirical investigation. *Resources, Conservation and Recycling, 146*, 256-263.

Scano, E. A., Asquer, C., Pistis, A., Ortu, L., Demontis, V., & Cocco, D. (2014). Biogas from anaerobic digestion of fruit and vegetable wastes: experimental results on pilot-scale and preliminary performance evaluation of a full-scale power plant. *Energy conversion and management, 77*, 22-30.

Schaufeld, J. (2015). Technology Commercialization. In *Commercializing Innovation* (pp. 1-15): Springer.

Silalertruksa, T., & Gheewala, S. H. (2011). The environmental and socio-economic impacts of bio-ethanol production in Thailand. *Energy Procedia, 9*, 35-43.

Slorach, P. C., Jeswani, H. K., Cuéllar-Franca, R., & Azapagic, A. (2019). Environmental sustainability of anaerobic digestion of household food waste. *Journal of environmental management, 236*, 798-814.

Song, Q., Li, J., & Zeng, X. (2015). Minimizing the increasing solid waste through zero waste strategy. *Journal of Cleaner Production, 104*, 199-210.

STeP. (2016). Business model assessment of sewage treatment plants. In: Sanitation Technology Platform.

Suwartha, N., & Berawi, M. A. (2019). The role of UI GreenMetric as a global sustainable ranking for Higher Education Institutions. *Int. J. Technol, 10*, 862-865.

TGO. (2020). Emission Factors.

Tonini, D., Martinez-Sanchez, V., & Astrup, T. F. (2013). Material resources, energy, and nutrient recovery from waste: are waste refineries the solution for the future? *Environmental science & technology, 47*(15), 8962-8969.

Tornatzky, L. G., & Klein, K. J. (1982). Innovation characteristics and innovation adoption-implementation: A meta-analysis of findings. *IEEE Transactions on engineering management*(1), 28-45.

UI-GreenMetric. (2018). Guideline of UI GreenMetric World University Ranking, 2018. In. Depok, Indonesia: Universitas Indonesia.

US-EPA. (2012). *Guidelines for Water Reuse 2012* [EPA/600/R-12/618]. In EPA (Ed.).

Venkatesh, V., & Davis, F. D. (1996). A model of the antecedents of perceived ease of use: Development and test. *Decision sciences, 27*(3), 451-481.

Visvanathan, C., Aim, R. B., & Parameshwaran, K. (2000). Membrane separation bioreactors for wastewater treatment. *Critical reviews in environmental science and technology, 30*(1), 1-48.

WaCCliM. (2018). ECAM 2.2 Methodology: Energy performance and carbon emissions assessment and monitoring tool. *Water and Wastewater Companies for Climate Mitigation*.

Wang, L., Shen, F., Yuan, H., Zou, D., Liu, Y., Zhu, B., & Li, X. (2014). Anaerobic co-digestion of kitchen waste and fruit/vegetable waste: Lab-scale and pilot-scale studies. *Waste Management, 34*(12), 2627-2633.

Webster, J., & Martocchio, J. J. (1992). Microcomputer playfulness: Development of a measure with workplace implications. *MIS quarterly*, 201-226.

Williams, B. L., Suen, H. K., Rzasa, S. E., Heikkila, T., & Pennock-Roman, M. (2003). Diffusion of US army chemical weapons disposal technologies: public perception of technology attributes. *Journal of Environmental Planning and Management, 46*(4), 499-522.

Xu, C., Shi, W., Hong, J., Zhang, F., & Chen, W. (2015). Life cycle assessment of food waste-based biogas generation. *Renewable and Sustainable Energy Reviews, 49*, 169-177.

Zero-Waste, C. (2018). Solid waste database. Retrieved from http://www.chulazerowaste.chula.ac.th/waste-line-data/. Retrieved 20 August 2019 http://www.chulazerowaste.chula.ac.th/waste-line-data/

Zhang, W., Wu, S., Guo, J., Zhou, J., & Dong, R. (2015). Performance and kinetic evaluation of semi-continuously fed anaerobic digesters treating food waste: role of trace elements. *Bioresource technology, 178*, 297-305.

Zikmund, W. G., Carr, J. C., & Griffin, M. (2013). *Business Research Methods (Book Only)*: Cengage Learning.

Zinatizadeh, A., & Ghaytooli, E. (2015). Simultaneous nitrogen and carbon removal from wastewater at different operating conditions in a moving bed biofilm reactor

(MBBR): process modeling and optimization. *Journal of the Taiwan Institute of Chemical Engineers, 53*, 98-111.

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