Techno-Economic Analysis of the UASB Wastewater Treatment System in Fish Processing Industry in Indonesia

河野, 裕知
九州大学総合理工学府環境エネルギー工学専攻

https://hdl.handle.net/2324/4372232

出版情報：九州大学, 2020, 修士, 修士
バージョン：
権利関係：

TECHNO-ECONOMIC ANALYSIS OF THE UASB WASTEWATER TREATMENT SYSTEM IN FISH PROCESSING INDUSTRY IN INDONESIA

Hirotomo Kohno

Supervisor
Associate Professor. Hooman Farzaneh

February 2020

Energy and Environmental System Laboratory,
Department of Energy and Environmental Engineering
Interdisciplinary Graduate School of Engineering Sciences

KYUSHU UNIVERSITY
Japan

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

UASB (up-flow anaerobic sludge blanket) is an anaerobic treatment system that can treat organic wastewater with high efficiency and speed. The advantages are: "Energy saving and low running cost because aeration is not required. Industrial waste (dehydrated sludge) can be reduced. Energy can be generated from methane gas generated during the treatment process. In this study, A simulation model was developed to evaluate the detailed treatment process in a UASB reactor and its economic viability, considering climate and operating conditions in Indonesia.

Water pollution is a big challenge in Indonesia, and there is a need to introduce advanced wastewater treatment systems. In particular, the fish processing industry has a notably low reputation for wastewater treatment compared to other sectors. The UASB can be considered as the most effective technology for such a sewer, discharged from the fish-processing factories. Methane bacteria, a type of anaerobic bacteria used in the UASB, have an optimum temperature in the medium range (35°C), and in tropical regions such as Indonesia, there is little need for heating. It is also suitable for removing high concentrations of chemical oxygen demand (COD), which is consistent with the wastewater conditions in fish processing factories.

The UASB simulation was based on using a combination of the Monod and Mass Balance equations. The Monod equation is a kinetic model of biomass growth based on substrate concentration. The Mass Balance equation is a model that describes the advection and diffusion of the substrate in the fluid inside the UASB reactor. These two equations were combined and calculated using the numerical analysis software MATLAB, with the COD concentration and the rate of rising of the sewage flowing in from the bottom of the UASB as inputs, and the COD concentration and the amount of biogas produced after treatment as outputs.

Estimation of the technical parameters of the simulation model is a major issue in simulation calculations; the coefficients in the Monod equation were determined based on reference materials and taking into account the temperature. In this study, the diffusion coefficient was calculated by referring to the kinematic viscosity of water at different temperatures, and its validity was confirmed by comparing it with the reference data.

The treatment volume was calculated based on the difference in COD concentration between the inflow and outflow water and used to estimate biogas production. The amounts of substrate used for biomass growth and converted to sulfurous acid gas were subtracted to estimate methane gas production from the treated volume.

Based on the model results, the mass balance and energy balance were calculated by using the local wastewater data in Indonesia. As a result, the removal rate of COD was estimated at 68%, and about 1.27 kWh electricity was generated from 1m^3 of water treatment. Based on these results, an economic evaluation was conducted. In the economic evaluation, the LCOE, NPV, and IRR were calculated to confirm whether the introduction of biogas would be profitable. The NPV and IRR were negative in some scenarios. However, the introduction of biogas power generation generated significant profits and depending on the quality of the water, profits would be achieved.

ACKNOWLEDGMENT

First of all, I would like to express my greatest gratitude to my supervisor for my master's thesis, Associate Prof. Hooman Farzaneh. He spent a lot of time with me in my research and gave me a lot of advice and guidance. Without his support, I could not have proceeded with this research and thesis.

Secondly, I would like to thank my colleagues at the Energy and Environment System Lab. In particular, my two classmates shared a lot of information and discussed ideas with each other. We were also able to motivate each other by encouraging each other even during tough times. The international students gave me advice from new and diverse angles, and I gained new insights.

Finally, I would like to thank my family very much. They made it possible for me to attend graduate school and provided me with generous emotional and financial support.

Hirotomo Kohno

Chapter 1

INTRODUCTION

1.1 Global Water Environmental Issues and SDGs

Due to the lack of wastewater treatment, water pollution is a severe problem worldwide (especially in developing countries). Figure 1 below shows the wastewater treatment index (e.g., the percentage of wastewater treated normalized by connection rate). The indicators in North America and developed regions such as Europe show higher values. On the contrary, the indicators in Southeast Asia, Sub-Saharan Africa, and Latin America are low, indicating that wastewater treatment is not well developed. [1].

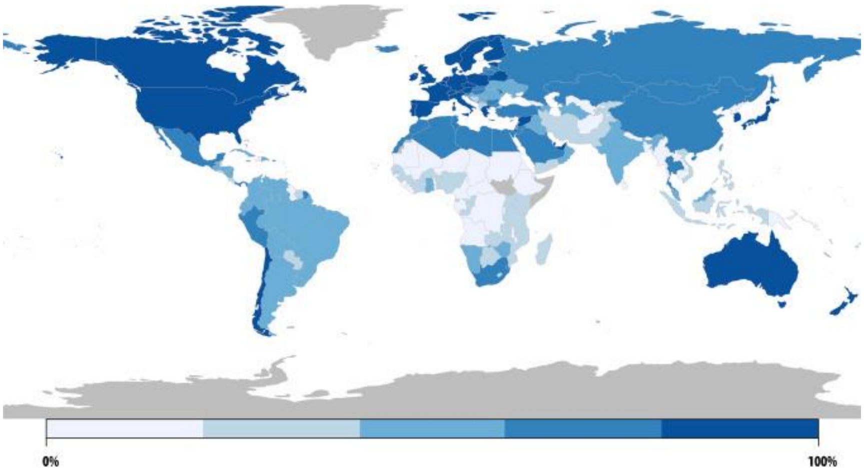


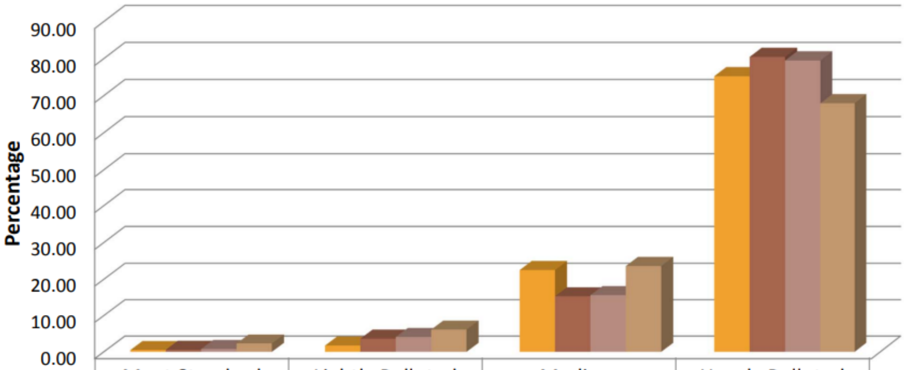
Fig. 1 The level of wastewater treatment normalized by connection rate as a proximity-to-target indicator for the 2014 EPI.

Sewage discharge causes human health problems due to water-borne diseases and other issues such as the destruction of river ecosystems and underground water resources. Diarrhea, dysentery, cholera, and other waterborne diseases kill 500,000 people a year, and about 660 million people do not have access to safe drinking water [2].

In order to solve this problem, the SDGs "Goal 6: Ensure availability and sustainable management of water and sanitation for all" describes wastewater treatment as "6.2: By 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations, "6.3: By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing the release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally, "6.A: By 2030, expand international cooperation and capacity-building support to developing countries in water- and sanitation-related activities and programs, including water harvesting, desalination, water efficiency, wastewater treatment, recycling, and reuse technologies" [3]. The world is currently working on solutions for the year 2030.

1.2 Water Environment Issues in Indonesia

Indonesia is an example of a region with severe water environment problems in Southeast Asia. As shown in Figure 2, there has been an improvement in the percentage of "severely contaminated", but the rate remains very high at 68%. The share of water that meets the standard also remains low. Therefore, to improve water quality, the treatment of "heavily contaminated" and "moderately contaminated" water needs to proceed with better water quality. [4]



	Meet Standard	Lightly Polluted	Medium Polluted	Heavly Polluted
2012	0.49	1.73	22.52	75.26
2013	0.57	3.64	15.33	80.46
2014	0.78	4.10	15.63	79.49
2015	2.30	6.13	23.62	67.94

Fig. 2 Trend of water quality state in Indonesia

Among the sources of sewage, contaminated water from the fish processing industry is the major one. It can be seen that nearly 90% of the management levels are rated low (black and red) in Indonesia's industry assessment in 2012, shown in Figure 3. The fish processing industry has ranked at the worst level compared to other sectors, and it needs to be improved, mainly due to the discharge of organic wastewater to the ground level water sources [5].

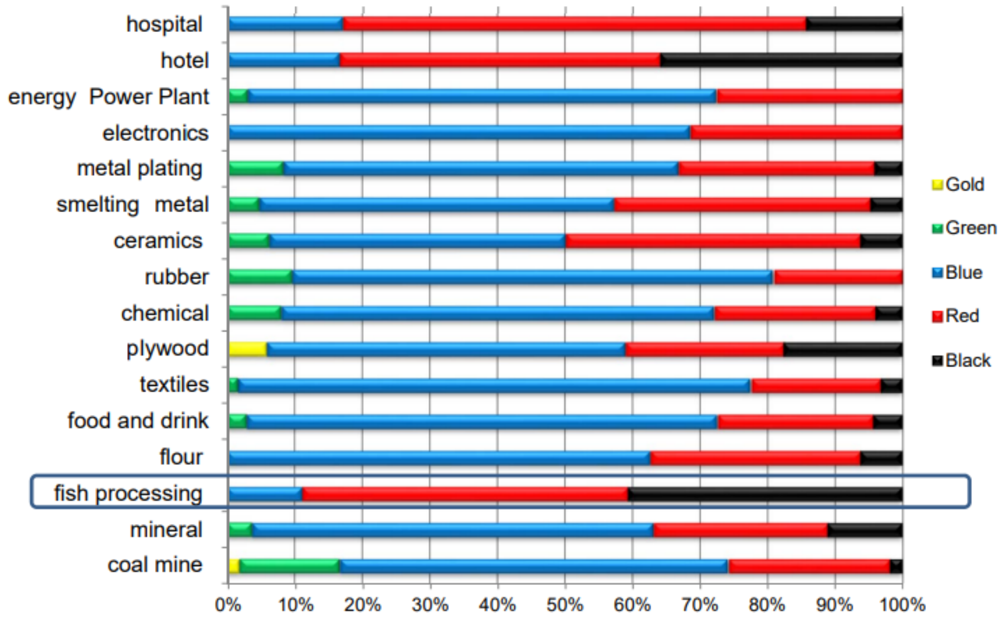


Fig. 3 Condition of environmental management

The chemical properties of various types of wastewater from actual fish processing plants in Indonesia are shown in Table 1.

Table 1 Wastewater characteristics by fishery processing process [6]

Type of industry	BOD (mg/L)	COD (mg/L)	TS (mg/L)	TSS (mg/L)	Oil (mg/L)	TKN (mg/L)
Fishery industry	3,500	326-1,423	4,721	918- 1,000	1,000	117
Canned food manufacturing	1,400	2,900		1,900	1200	82
Smoking Industry	1,700			400	200	77
Fish oil	11,500	91,000		25,900	25,000	268
Fish Powder	66,400	191,000		19,000	12,500	6,400

The effluent standards in Indonesia are also shown in Table 2 below.

Table 2 Wastewater Treatment Standards for Fish Processing Industry in Indonesia [7]

Type of industry	BOD (mg/L)	COD (mg/L)	TSS (mg/L)	Oil (mg/L)
Refrigeration Activities	100	200	100	15
Canned food manufacturing	75	150	100	15
Fish Powder	100	300	100	15

As can be seen in Table 1, the concentrations of both BOD and COD are very high. It is necessary to achieve a high removal rate to reach the effluent standard shown in Table 2.

Achieving this standard will protect the water environment and provide co-benefits in terms of effective use of resources (use as recycled water). In the case of the Jakarta fishing ports, there is a shortage of water resources and a demand for reclaimed water. The water supply is not yet developed, and the water is supplied by a desalination plant (RO), which costs a lot of money. There are also restrictions on groundwater extraction, and the demand for reclaimed water for cleaning is high. Treating the sewage generated by the plant and selling it as reclaimed water could be economically profitable.

By using anaerobic treatment using the UASB (up-flow anaerobic sludge blanket) method to treat this water, not only energy can be saved, but also both thermal and electrical energy can be generated simultaneously, thereby reducing GHG emissions. With these three co-benefits, the introduction of this system is now under consideration.

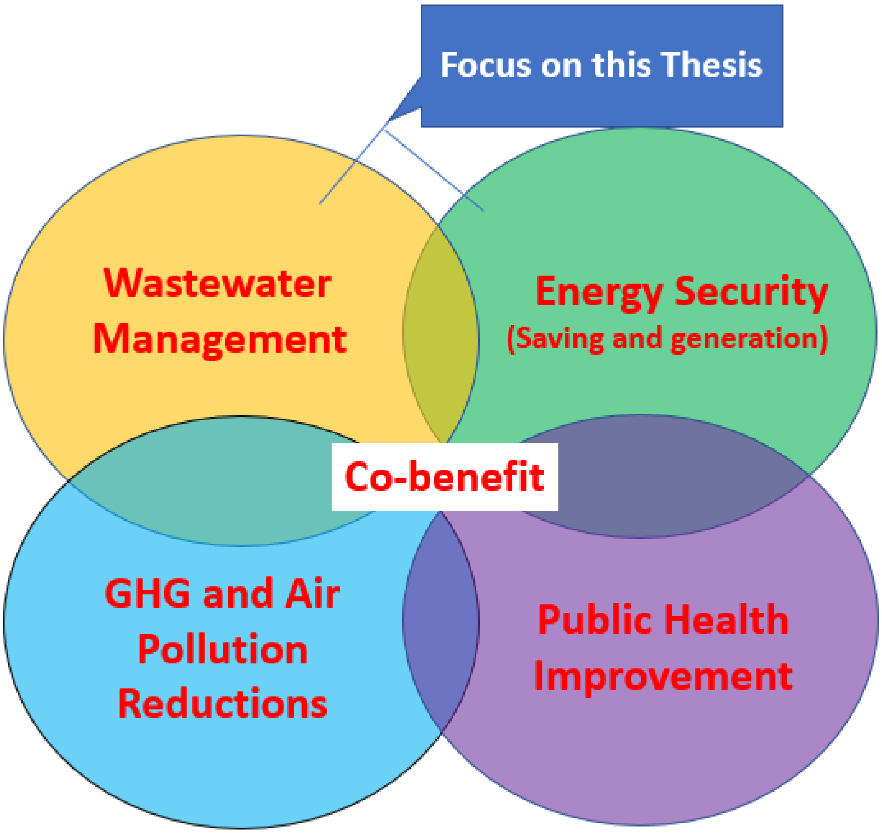


Fig. 4 Co-benefits in water treatment

The main treatment methods for organic wastewater are physicochemical treatment (separation of pollutants through coagulation and oxidation using physical-chemical reactions such as sedimentation, filtration, and adsorption), biological treatment (decomposition of contaminants in sewage by microorganisms such as bacteria), and the hybrid method, which combines these two methods [8].

1.3 Water Treatment by UASB method

This study focuses on the UASB method, which is a biological treatment method. The main advantages of the UASB method are 1) energy savings. 2) Low running costs. 3) Reduction of industrial waste (dewatered sludge), as no aeration is required for aerobic treatment. 4)The system is simple and does not require a large space. 5) Easy to maintain and manage.

The disadvantages of this system are: 1) heating to about 35 degrees Celsius, which is the optimal temperature for methane bacteria; 2) weakness to inhibitors due to the slow growth rate of methane bacteria; and 3) weakness to inhibitors due to the slow growth rate of methane bacteria. It is challenging to maintain methanogens when BOD (Biochemical Oxygen Demand) concentration and organic matter indicator is low. [9]

From these aspects, UASB is considered to have advantages to be implemented in developing countries in low latitude regions such as Southeast Asia. It is because the conditions for introducing UASBs are all in places, such as good economic efficiency and ensuring high water temperature, due to hot climate conditions in these regions.

UASB is a technology developed by Lettinga et al. in the Netherlands at the end of the 1970s, which uses the flocculation and agglomeration function of anaerobic bacteria to produce a superior particle size of 0.5-2.0[mm] without an adherent carrier. It is a method of holding the sludge as a granular sludge in a tank as a sludge layer. It is capable of treating high concentrations of organic sewage, producing methane gas and energy [10].

There are two types of anaerobes: absolute anaerobes, which cannot grow in the presence of oxygen, and passive anaerobes, which can grow in the presence of oxygen.
In the UASB method, methanogens, which are absolute anaerobes, are used for treatment.

Methane fermentation is a reaction in which biomass (organic matter) is decomposed by microbial activity under anaerobic conditions to produce biogas containing mainly methane and carbon dioxide eventually. For this reason, it has long been used for waste and wastewater treatment. In methane fermentation, various anaerobic microorganisms decompose high-molecular organic matter such as cellulose and protein into organic acids and hydrogen (hydrolysis process, acid formation process). Thereafter, methanogenic bacteria, which are anaerobic microorganisms, produce methane from acetic acid and hydrogen (methanogenesis process). Methane fermentation occurs in the absence of oxygen. In particular, the methanogenesis reaction is inhibited by the presence of oxygen. [11]

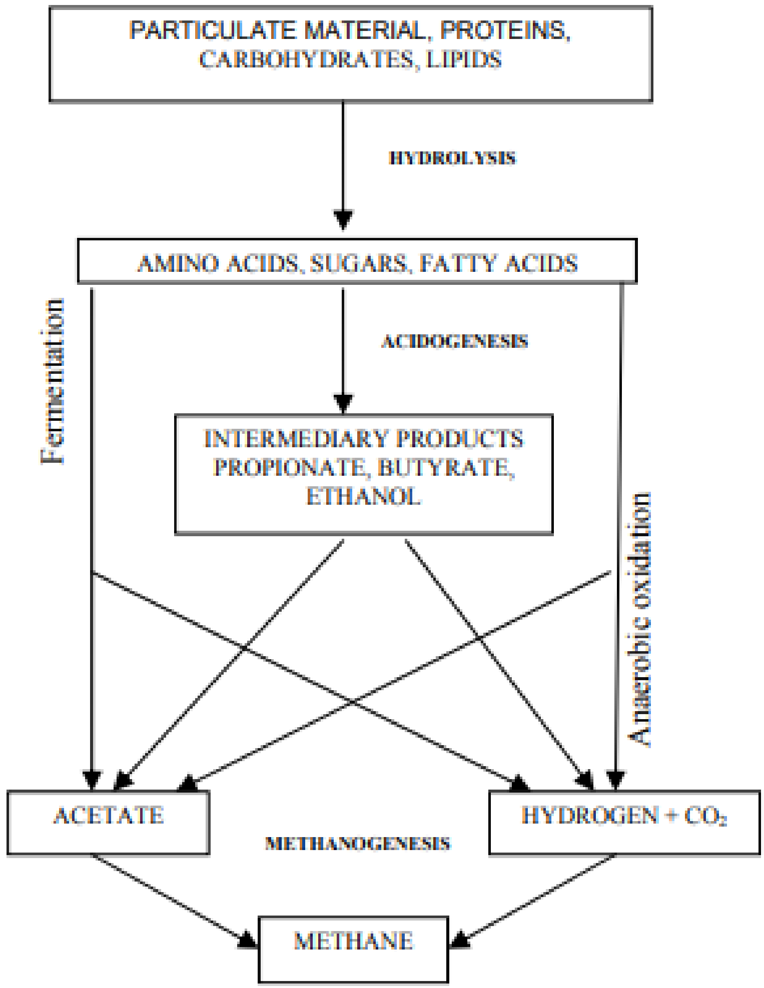


Fig. 5 Schematic diagram of carbon flow conversion in anaerobic digesters [12]

In methane fermentation, which is usually carried out by methanogens, 70% of the methane produced is from acetic acid. Most of the rest is considered to be produced by the reduction of carbon dioxide by hydrogen. Methane production from acetic acid is expressed by the following equation (1.1)

$$CH_3COOH \rightarrow CH_4 + CO_2 \tag{1.1}$$

Methane production from hydrogen and carbon dioxide is represented by the following equation(1.2).

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \tag{1.2}$$

Methanogens are known as Methanosarcina sp., Methanosaeta sp., Methanogeum sp. and others. Tables 3 to 5 below show the comparison of methanogens with other bacteria.

Table 3 Organism classification by nutrition acquisition format [11]

Nutrition acquisition format		Energy source	
		Light	Chemical compound oxidation
Carbon source	CO2	photo autotroph sulfur bacteria, algae	chemo autotroph methanogens
	Organic carbon	photo heterotroph sulfur bacteria	chemo heterotroph bacteria, fungi, animal

Autotroph- An organism that can grow using carbonic acid (CO2 or carbonate ions) as its sole carbon source.
Chemo- An organism seeking an energy source for the oxidation reaction of various compounds

Table 4 Classification of microorganisms by optimal temperature [11]

Microbial community	Optimum temperature(°C)	Example
psychrophile bacterium	10-20	Pseudomonas, Vibrio
mesophilic bacterium	20-40	Many bacteria, yeast, methanogen
thermophile	40-60	Bacillus, Clostridium, High temperature methanogen

Table 5 Classification by oxygen demand of microorganisms [11]

microbial community	Properties for oxygen	Example
strict aerobic bacteria	Does not grow without oxygen	Most mold, Pseudomonas, Bacillus
facultative anaerobe	Grows with or without oxygen	Most yeast, Lactic acid bacteria, E. coli
obligatory anaerobe	Does not grow in the presence of oxygen	Clostridium, methanogen

The structure of the UASB is shown in the following figure 6. The treatment flow includes:

1) allowing sewage water to flow through the bottom portion of the process. Generally, a sewage rise rate of 1.5 to 2.0 [mm/h] is allowed.
2) The water is mixed with granules, a collection of methane bacteria, and treated.
3) The treated water and biogas (mainly methane gas) are separated and collected.

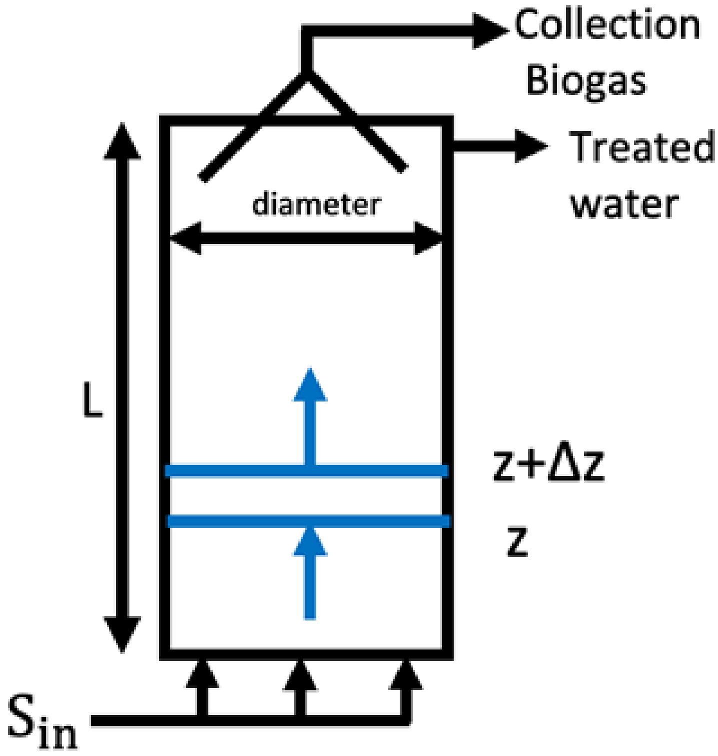


Fig. 6 Schematic view of UASB reactor [12]

Granules are a collection of active anaerobic microorganisms and are granular sludge with a diameter of 2 to 3 mm. The granules allow UASB to hold a large number of bacteria in the reaction tank and decompose organic matter. In UASB, dense biofilm particles (granules) containing millions of organisms per gram of biomass form. These agglomerates have settling velocities (20-80 m/h) much higher than the upwelling velocity (Vup=0.1-1 m/h), so that large amounts of biomass can accumulate at the bottom. In this way, high sludge loading rates (SLR) can be applied (up to 5 g COD gVSS/day).

The relationship between the size of the granules and the treatment factor will be discussed in detail in Chapter 2

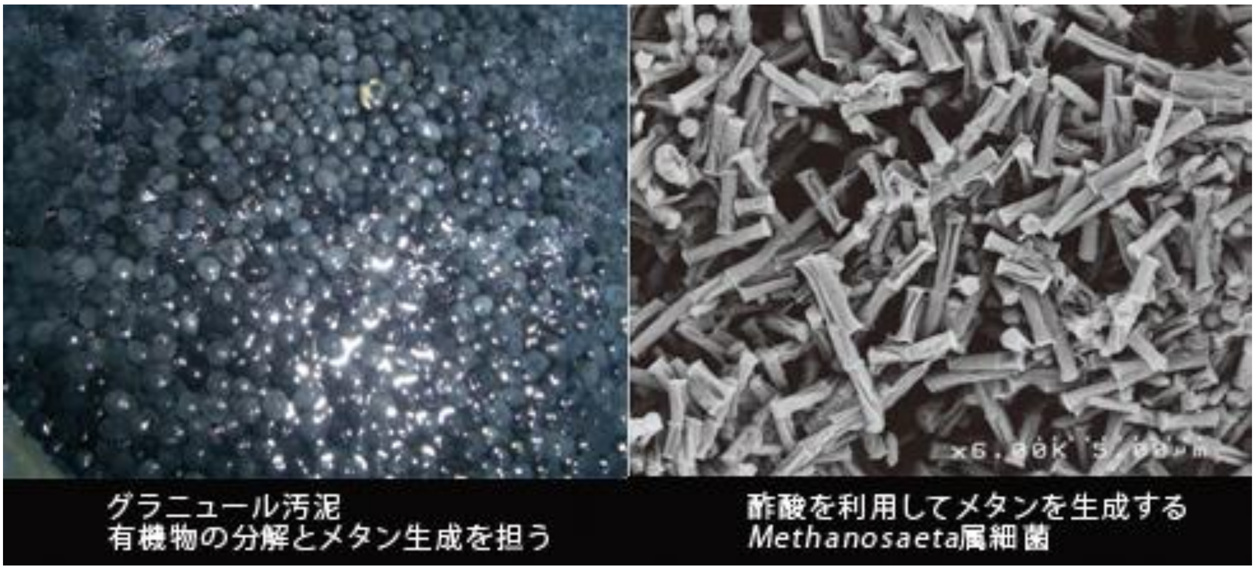


Fig. 7 Granulars and microscopic view of methanogens [12]

The bacteria in the granules decompose the organic matter into methane gas and carbon dioxide, etc. The granules with gas attached to their surface float with the treated water due to the air-lift effect, and the settler (gas-solid-liquid separator) installed at the top collects the gas and separates the treated water from the granules to extract only clean water.

The biogas creates hydraulic turbulence as it rises through the reactor, providing proper mixing in the system and eliminating the need for mechanical mixing. On the other hand, flotation and turbulence can cause loss of biomass. On the other hand, high upward flow velocities cause the wastewater to pass through the system faster, thus failing to achieve the expected reduction in organic matter. However, high flow velocities can increase the mass transfer coefficient in the membrane in such a way as to improve dispersion (mixing) in the reactor and enhance the final performance of the reactor.

Typically, three zones are distinguished (Figure 6). These are: a dense sludge bed consisting of biomass aggregates at the bottom, a sludge blanket containing finely suspended flocs or aggregates, and a zone of clarified water containing little or no solids in the internal settler.

A typical treatment process for UASBs is shown in Figure 8: pre-treatment, such as removing oil that is incompatible with UASB and adjusting the pH. The UASB then treats and separates the generated biogas from the treated water. However, UASB is specialized to treat high concentrations of sewage, they are not entirely removing contaminants, so it is common to add post-treatment to the process. The biogas produced removes sulfur and nitrogen oxides and uses the methane gas to generate electricity and heat through a generator.

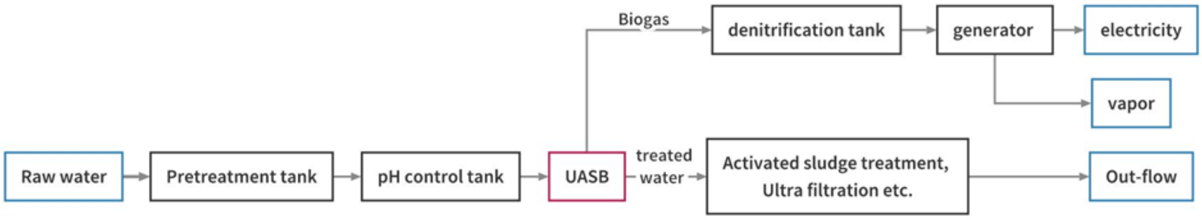


Fig. 8 A typical UASB-based water treatment process

1.4 What will be elucidated in this research:

The overall schematic of the proposed system in this research is shown in Figure 9 below.

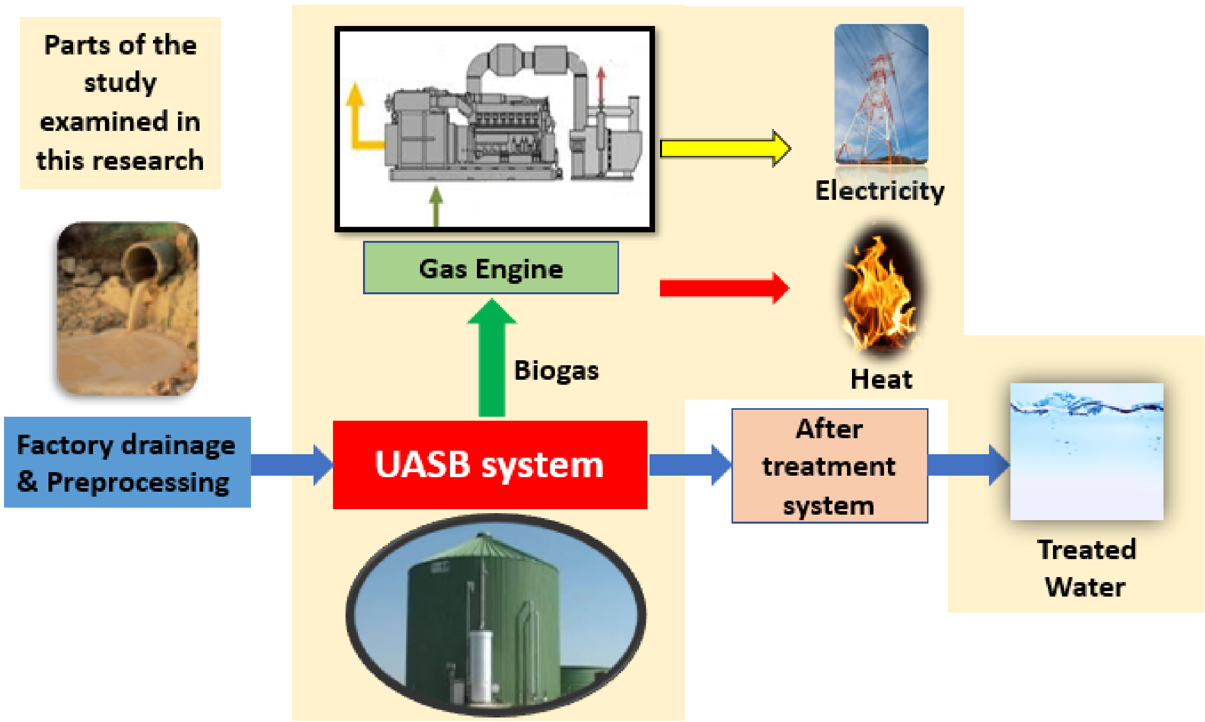


Fig. 9 Schematic of the proposed system in this research

This research aims to develop a simulation model to calculate how the detailed amount of organic pollutants removed from the sewage generated in the fish processing plant, by using the UASB system. Then, based on the removal rate, the amount of generated biogas from the system will be calculated. In the next step, the amount of heat and electricity which can be generated from the biogas will be estimated. Finally, an economic evaluation will be conducted based on the income generated by selling the electricity, heat, and treated water to determine whether the system is suitable for installation.

The following topics and contents are presented in each chapter.

- Chapter 1 describes the mechanism of UASB and the methanogens used.
- Chapter 2 describes the model which was developed in this study.

Section 2-1 describes the important terms in water treatment.

Section 2-2, the dynamics of biomass is explained. The Monod model is a kinetic equation that is determined by the concentration of the substrate required for the growth of bacteria.

Section 2-3, the Mass balance equation was presented, representing the wastewater treatment in terms of UASB height and time axis. It uses the kinetic equations for diffusion, flow velocity, and treatment.

Section 2-4, the UASB model is explained as a combination of the “Monod model” and the “Mass balance model”. This model is PDE.

Section 2-5 describes the determination of the coefficients necessary for the calculation of the UASB model.

Section 2-5.1, the diffusion coefficient is described. It is calculated mainly from the flow velocity and kinematic viscosity.

Section 2-5.2, the coefficients of the Monod equation are presented.

- Section 2-6, presented a model to calculate the production of methane gas.
- Chapter 3, the results of the model is discussed. This was done by using the calculation model in chapter 2 under the same conditions as other materials and confirming that the coefficients were included in the range and that the results were the same. In particular, it was necessary to consider the washout coefficient, which determines the amount of bacteria flowing out of the UASB.
- Chapter 4, a case study was conducted. An actual fish processing factory in Indonesia was used as a model for the calculations.

Section 4-1, based on the actual model, the removal rate of pollutants and the amount of methane gas generated were estimated using the UASB model equation. The electricity and heat generated by burning the methane gas in a gas engine were estimated. Then, the mass balance and energy balance were discussed.

Section 4-2 Conducted an economic evaluation with an eye to actual implementation. This was calculated using LCOE and NPV and IRR. Two scenarios, the Retrofit scenario and Grassroot scenario, were considered and evaluated, respectively.

Chapter 2

THE UASB MODEL DEVELOPMENT

2.1 Basic Terms:

・SRT: Sludge Retention Time[d]
The average number of days that suspended sludge remains in the treatment system [d].

$$SRT = \frac{Amount\ of\ activated\ sludge\ solids\ in\ the\ water\ treatment\ system: kg}{Amount\ of\ activated\ sludge\ solids\ discharged\ out\ of\ the\ system\ per\ day: kg/day} \tag{2.2}$$

・HRT: hydraulic retention time[h]
The average time that the inflow water remains in the treatment tank [h].

$$HRT = \frac{Volume\ of\ the\ processing\ unit: m^3}{Treatment\ volume: m^3/h} \tag{2.2}$$

・COD: Chemical Oxygen Demand [mg/L]:
It is primarily used to study the water quality of lakes and waters. The amount of oxygen required to participate in the study is converted from the amount of oxidation using potassium permanganate as an oxidizing agent.

・BOD: Biochemical oxygen demand [mg/L]:
It is mainly used to study water quality in rivers. It represents the amount of oxygen required for aerobic microorganisms to decompose organic substances in water.

・SS: Suspended solids [mg/L]:
Insoluble substances suspended in water, such as suspended solids and suspended solids, which pass through a 2 mm sieve and remain on a one μm filtration medium.

2.2 Monod Model

2.2.1. Biomass Kinetic

The kinetic process addresses how the microorganisms convert a substrate into biogas by using organic matter in wastewater as feed. The kinetic process can be divided into four stages, as shown in the following figure 10 [11].

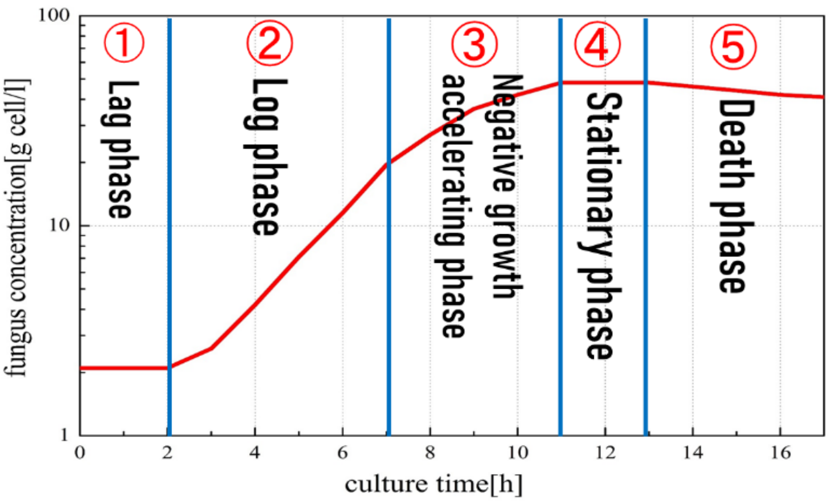


Fig. 10 Phase of biomass growth and death

According to the above figure 10, the main processes are as follows:

①Cell number does not increase, but cell size increases.

②The cells begin to increase and the number of cells doubles at regular intervals.

③Cell division begins to stop when nutrients are depleted, or products accumulate.

④When nutrients are depleted, cell division is wholly stopped, the growth rate is zero, and the number of living cells remains constant.

⑤As autolysis progresses, proliferation by cell division becomes impossible, and death occurs.

During the Log phase, when the nutrient substrate is abundant, the biomass proliferates. When the substrate is reduced and the proliferation stops, the biomass begins to die off and gradually decreases.

2.2.2 Monod Model

The Monod model was developed by Jacques Monod in 1942 and is the most frequently used kinetic model [13]. It is an equation of the same form as an enzymatic reaction, which in this study is expressed as a relationship between the specific growth rate of a bacterium and the concentration of a substrate and is incorporated into the kinetic model. The specific growth rate μ is the growth rate per unit cell volume. Among the various factors that affect the specific growth rate, the concentration of a particular component is often important. The main factor affecting the specific growth rate is the growth-limiting substrate, which is the most defective component in the medium necessary for cell metabolism, which regulates the entire biological reaction. In many cases, the specific growth rate is expressed as a function of this growth-limiting substrate's concentration by the following Monod equation.

$$\mu = \frac{\mu_{max} \cdot S}{K_s + S} \tag{2.3}$$

The Monod equation is an empirical equation where K_s [-]is the affinity constant and μ_{max} [1/d] is the maximum specific growth rate. S[mg/L] is substrate concentration. The Monod equation and the maximum specific growth rate and substrate affinity were calculated as shown in the following figure 11.

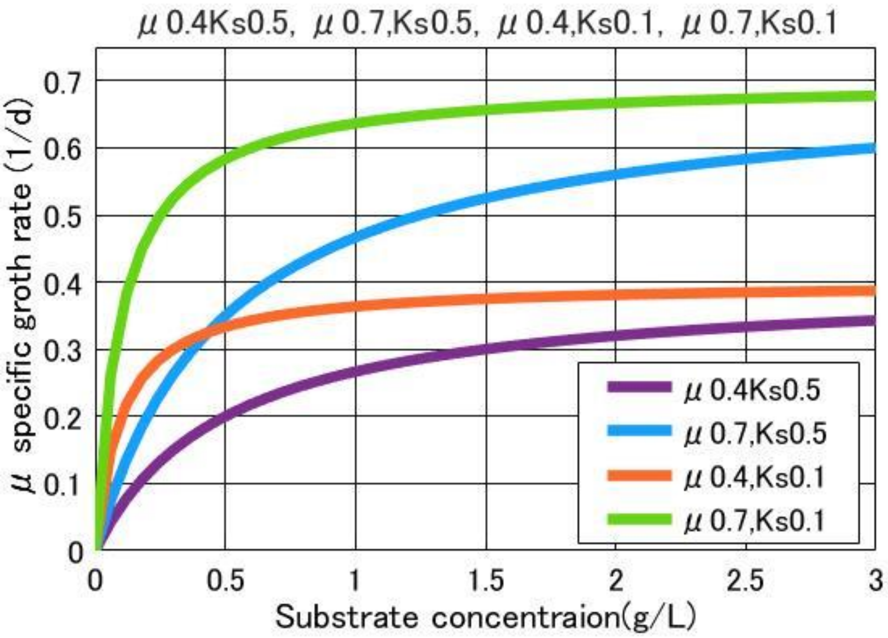


Fig. 11 Analysis of coefficients in the Monod formula

All the effects of factors other than the limiting substrate concentration on the specific growth rate can be reflected in the maximum specific growth rate value. In other words, the equilibrium value was determined by the value of the maximum specific growth rate.

As for substrate affinity, cells with a low affinity constant K_s proliferate faster when placed in a surrounding environment with a low growth-limiting substrate.

2.3 Mass Balance Model [13] [14]

The UASB model describes the mass balance of the substrate in the bulk fluid in the reactor, including advection and dispersion along the reactor. It also describes the mass transfer between the anaerobic sludge granules and the organic matter dissolved in the liquid. Furthermore, it discusses the relationship between mass transfer in the stagnant fluid around the anaerobic aggregates and the fluid velocity. Initially, it is assumed that the particles have the same size, but this is later mitigated in support of the particle size distribution.

Due to the complexity of microbial ecosystems, where several physical, chemical and biological processes take place simultaneously, some simplifications are needed to evaluate the system. Therefore, a series of assumptions were made in developing the mass balance model for a UASB reactor:

1. All processes inside the reactor are considered to depend only on the vertical axis (z), i.e., it is a one-dimensional model.
2. The reactor volume is not divided into the different zones, considering diffusion rates and changes in

concentration of the components, which varies along with the height of the reactor; e.g., dispersion and particle densities (Figure 6).
3. The model is transient, i.e., the concentration of organic matter varies with time and location in the reactor.
4. The system is isothermal, and the substrate consists basically of biodegradable soluble substances.
5. Only reactions inside the particle are taken into account. The possible reaction in the stagnant film is ignored.
6. Regarding the biomass present in the reactor, the granules are considered to be a porous biocatalyst with a spherical shape. In the development of the model, it is assumed that the granules are of equal size. Later, the model is improved to take into account the granules of different sizes. It is also assumed that the number of granules and their size is constant with time.

The mass balance in the differential elements of the reactor height was considered, as shown in Figure 6. The advection-dispersion equation was used to describe the processes in the reactor. The equation in the transient state is as follows.

The equation for substrate concentration is as follows;

$$\frac{\partial S}{\partial t} = D\frac{\partial^2 S}{\partial z^2} — v\frac{\partial S}{\partial z} — K * S \tag{2.4}$$

Where D [m^2/d]] is the dispersion coefficient of the substrate; S [kg/m^3] is the concentration of substrate in the bulk water; V [m/d]is the up-flow velocity; K [1/d] is a substrate reaction rate constant; z is the axial direction of the reactor, and t[day] is the time of observation.

The term on the left side is the accumulation of substrate at the differential elements in the bed, expressed in [kgm^3/d]. The first term on the right side takes into account the dispersion of the substrate in the bed, the second term corresponds to the transport of the substrate by advection (flow) and the last term is the reaction term and represents the amount of substrate consumed per unit of bed volume in a unit of time.

The expression for microorganism behavior is as follows;

$$\frac{\partial X}{\partial t} = D\frac{\partial^2 X}{\partial z^2} + K''.X \tag{2.5}$$

Where K'' [1/d] is a substrate reaction rate constant

As an initial condition, the substrate concentration S in the reactor at zero time is considered to be S_{in}, which can be a function of the height direction z. For t>0, a constant mass flux of substrate is assumed at the reactor inlet (z=0), i.e., substrate enters the reactor at z=0 by convection and diffusion. At the reactor exit, the substrate is assumed to leave the reactor only by convection. That is, the substrate concentration gradient is zero at z = L.

The initial conditions (I.C.) are as follows;
Substrate concentration:

$$t = 0, S(z,0) = S_{in} \tag{2.6}$$

Biomass concentration

$$t = 0, X(z,0) = X_{in} \tag{2.7}$$

The boundary conditions (B.C.) are as follows
B.C.1: Bottom side
Substrate concentration:

$$z = 0, v * S_{in} = v * S|_{z=0} — D * \frac{\partial S}{\partial z}|_{z=0} \tag{2.8}$$

Biomass concentration:

$$z = 0, — D * \frac{\partial X}{\partial z}|_{z=0} = 0 \tag{2.9}$$

B.C.2: Top side
Substrate concentration:

$$z = L, \frac{\partial S}{\partial z} = 0 \tag{2.10}$$

Biomass concentration:

$$z = L, \frac{\partial X}{\partial z} = 0 \tag{2.11}$$

The model describes the advection, dispersion and biological decomposition of organic matter, including mass transport at interfaces and diffusion within granules.

2.4 Model Combinations

The model incorporated the "mass balance model" described in sections 2.3 above into the constant reaction rate. This study was carried out by incorporating section 2.2.b “MONOD MODEL” into the reaction rate constant of the "mass balance model" shown in section 2.3 above. The reaction rate constant was formulated considering the damping constant (K_d), and the washout fraction (w).

Attenuation constants are those resulting from lack of substrate or nutrient availability or accumulation of toxic metabolites [15], predation (protozoa are predators of bacteria) [16] and dissolution [17], etc., over time, and are the result of the biomass generation. It represents the conditions that prevent proliferation [14].

The washout fraction represents the fact that biomass can start flowing at the start of operations before the biomass fungus forms granules or during fast flow conditions.

By incorporating these two conditions and the Monod model into equations (2.4) and (2.5) of the mass balance model, the equation for substrate concentration is as follows;

$$\frac{\partial S}{\partial t} = D\frac{\partial^2 S}{\partial z^2} — v\frac{\partial S}{\partial z} — \left(\frac{\boldsymbol{\mu_{max}}}{\boldsymbol{Y}}\frac{\boldsymbol{X}}{\boldsymbol{Ks+S}}\right)S \tag{2.12}$$

The equation for biomass concentration is as follows;

$$\frac{\partial X}{\partial t} = D\frac{\partial^2 X}{\partial z^2} + \left(\boldsymbol{\mu_{max}}\frac{\boldsymbol{S}}{\boldsymbol{Ks+S}} - \boldsymbol{K_d} - \boldsymbol{wv}\right)X \tag{2.13}$$

Where, Y [g VSS/g COD] is the Yield coefficient, K_d [1/$\boldsymbol{h}$] is Decoy constant. The initial and boundary conditions are the same as in equation (2.6) to (2.11).

Yield is the ratio of the amount of bacteria produced (g/l of dried bacteria) to the amount of consumption (g/l) of a certain medium component required to grow a microorganism in culture.

2.5 Determination of the parameters:

2.5.1 Calculation of Diffusion Coefficient (D):

Dispersion is mainly caused by gas bubbles rising through the reactor and granules in the up-flow. The degree of dispersion is expressed in terms of the dimensionless Peclet (Pe) number.

The following equation expresses the Peclet number;

$$Pe = \frac{vL}{D} \tag{2.14}$$

V [m/s] is the up-flow velocity of liquid; L [m] is the length of the reactor; and the D [m^2 /s] is the dispersion coefficient of the substrate.

The Reynolds number (Re) can also be used to study to the flow of substrate in the UASB reactor, as follows:

$$Re = \frac{ud\rho}{\mu} = \frac{ud}{\nu} \tag{2.15}$$

Where u, [m/h] is the relative velocity of the particle (here assumed as the liquid up-flow velocity); and d[m] is a particle diameter.

An approximation of the variance D for large Reynolds numbers is given by Davies (1972) as follows [13]:

$$D = 1.01\nu Re^{0.875} \tag{2.16}$$

According to reference [13], by applying this equation (2.16) to a UASB reactor, which is considered to be a circular tube, the relationship between Re and Pe can be extracted as shown in Figure 12.
In this estimation, a UASB reactor with a diameter of 2 m, a height of 10 m, and an up-flow velocity of 0.75-1.5 m/h was assumed for the Re values below 2300, indicating laminar flow, Pe values ranged from 11-13.

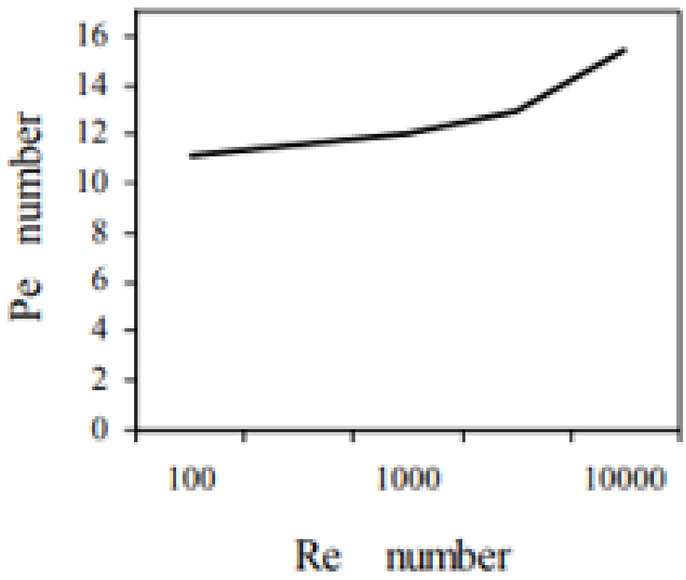


Fig. 12 The relationship between the Peclet number and the Reynolds number [13]

The kinematic viscosities required for the calculation of the Peclet number, Reynolds number and diffusion coefficient are reported in Table 6.

Table 6 Kinematic viscosity and density of water at different temperatures [18]

Temp. [°C]	Kin. Viscosity [mm²/s]	Density [g/cm³]	Temp. [°C]	Kin. Viscosity [mm²/s]	Density [g/cm³]
2	1.67	0.99	25	0.89	1.0
3	1.62	1	26	0.87	1.0
4	1.57	1	27	0.85	1.0
5	1.52	1	28	0.84	1.0
6	1.47	0.99	29	0.82	1.0
7	1.43	1.00	30	0.80	1.0
8	1.38	1.00	31	0.78	1.0
9	1.34	1.00	32	0.77	1.0
10	1.31	1.00	33	0.75	1.0
11	1.27	1.00	34	0.74	1.0
12	1.23	1.00	35	0.72	1.0
13	1.20	1.00	36	0.71	1.0
14	1.17	1.00	37	0.70	1.0
15	1.14	1.00	38	0.68	1.0
16	1.11	1.00	39	0.67	1.0
17	1.08	1.00	40	0.66	1.0
18	1.05	1.00	45	0.60	1.0
19	1.03	1.00	50	0.55	1.0
20	1.00	1.00	55	0.51	1.0
21	0.98	1.00	60	0.47	1.0
22	0.96	1.00	65	0.44	1.0
23	0.93	1.00	70	0.41	1.0
24	0.91	1.00			

Other methods of calculating the diffusion coefficient considered are shown below. With respect to the determination of the diffusion coefficient and the reaction rate term, this is the case where the diffusion resistance in the large flow station around the granule is negligible, only the mass resistance in the granule is important, and the mass transfer resistance in the stagnant liquid is dominant. The absence of external resistance means that the granule surface concentration is equal to the concentration of the gas in the bulk liquid. The assumption is that the substrate is transported by molecular diffusion within the biofilm and is degraded by the bacteria present in the granules.

The diffusion processes in the stagnant liquid film can be described by the Sherwood number (Sh), which represents the ratio of convective to diffusive mass transport:

$$Sh = \frac{k_m d}{D} \tag{2.17}$$

Where, *d* is a particle diameter[m] and km is the mass transfer coefficient in the liquid film, [m/s].

The Sherwood number may be expressed as a function of Reynolds number for the particle (Bird 2001):

$$Sh = 2 + 0.991\left(Re_p Sc\right)^{1/3} \tag{2.18}$$

Sc is the Schmidt number, which represents the physical properties of the liquid and is given by

$$Sc = \frac{\mu}{\rho D} = \frac{\upsilon}{D} \tag{2.19}$$

It is understood that k_m can be obtained by knowing the up-flow velocity, the diffusion coefficient and the diameter of the biomass from the values multiplied by the equation (2.19).
The amount of biogas emitted is estimated by calculating the Mass Balance formula using these calculated coefficients.

Peña [19] evaluated the overall hydrodynamic behavior of a full-scale UASB focusing on the macro-mixing processes of the reactor. Multiple linear correlations between Peclet number (Pe), up-flow velocity, V_{up} [m/h] and biogas production rate, Q_b [m^3/h] was found:

$$Pe = 10.3 - 8.4V_{up} - 0.3Q_b \tag{2.20}$$

Here, the anaerobic granules were assumed to be a spherical porous medium as shown in Figure 13, and the mass balance was calculated for the substrate in the granules.

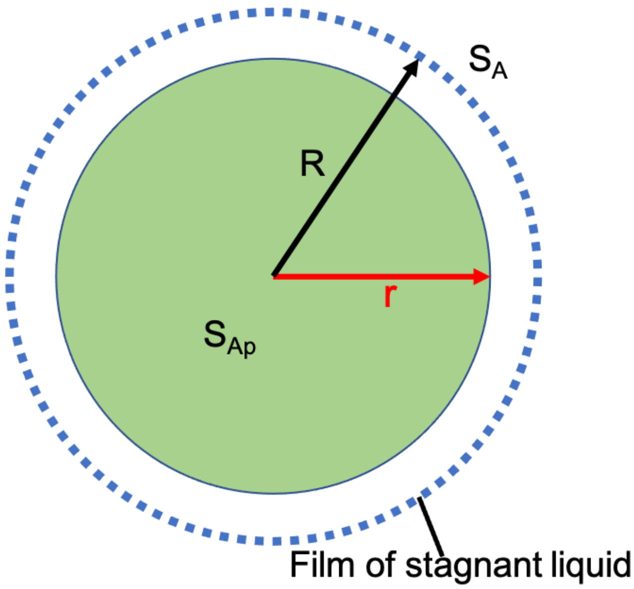


Fig. 13 Calculation of the internal concentration of spherical granules

The equation for the mass balance is as follows [13]:

$$\frac{1}{r^2}\frac{d}{dr}\left(r^2\frac{dS_{Ap}}{dr}\right)=\frac{k}{D}S_{Ap} \tag{2.21}$$

The boundary conditions are

$$r=R,\ D_A\frac{dS_{Ap}}{dr}=k_m(S_A-S_{Ap})\ \text{(Surface)} \tag{2.22}$$

$$r=0,\ S_{Ap}=finite\ \text{(Particule center)} \tag{2.23}$$

The following equation gives the analytical solution of the above ordinary differential equations:

$$\frac{S_{Ap}}{S_A}=\frac{R}{r}\frac{Rk_m sinh\left(\emptyset\frac{r}{R}\right)}{D\big(\emptyset cosh(\emptyset)-sinh(\emptyset)\big)+Rksinh(\emptyset)} \tag{2.24}$$

In this $\emptyset$,

$$\emptyset=\sqrt{\frac{\boldsymbol{k}}{\boldsymbol{D}}}\boldsymbol{R} \tag{2.25}$$

Based on Equation 2.24, the substrate concentration ratio inside the granule and at the film boundary was calculated and compared with the reference material. These values used for comparison are shown in Table 7 below.

Table 7 Value of parameters used to calculate the internal concentration

Parameter	value	Definition
V[L]	2.5	Reactor volume
S_0[mg/L]	3000	Initial substrate concentration
X_0[mg/L]	5	Initial biomass concentration
q[L/d]	3	up-flow rate
μ_{max}[1/d]	0.21	Maximum organism-specific growth rate
Y[-]	0.000780	yield
km [mg/L]	0.00012	half saturation coefficient

The calculation results and comparison materials are shown in Figure 14 below.

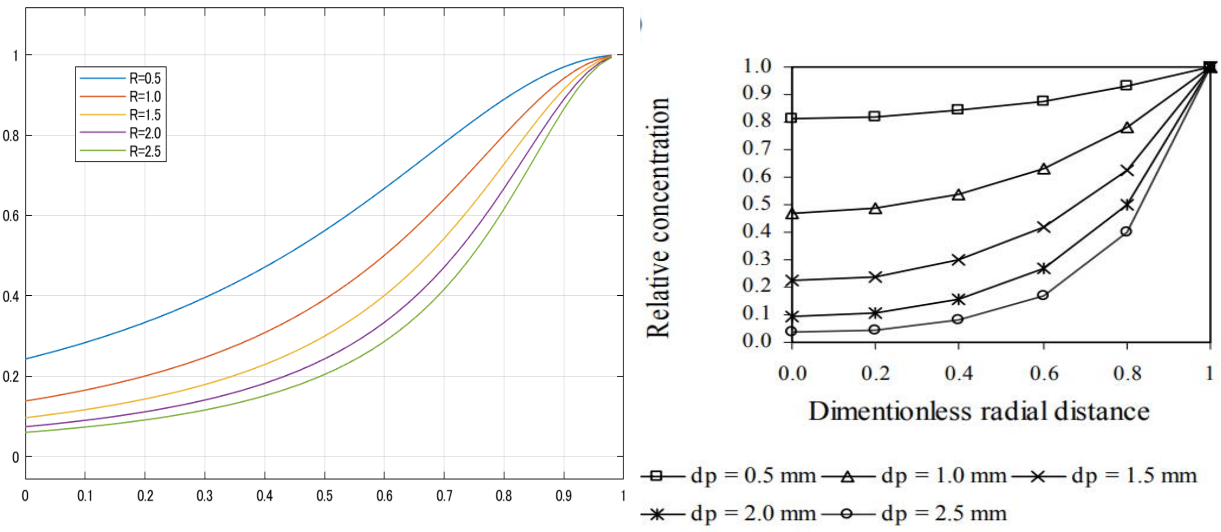


Fig. 14 Comparison of the concentration ratio between the boundary and the interior of the granule

The results showed that the relative concentration increases exponentially to reach 1 (the internal location to be calculated is the same as the film boundary). However, when the granule diameter was small, around 0.5 mm, the concentration of the interior was smaller than the value of the material. Calculations with larger diameters gave results comparable to the materials.

The size (diameter) of the granules is necessary for these calculations in order to determine the coefficients. The actual size of the granules is about 0.5-2.0 mm. However, it is necessary to make assumptions about the size growth in the simulation. Since the results vary greatly depending on the assumptions made when calculating the model, they were excluded.

2.5.2 Coefficients in the Monod Model:

The Monod formula is an empirical formula. Therefore, many of the coefficients are calculated from approximations based on data from experimental models. However, the values of the coefficients vary greatly depending on the conditions of the testing environment (temperature, pH, etc.). In this study, we focused on the temperature that is easy to adjust physically. Methanobacterium tkermomtotrophicum, which has an optimum temperature of 65 to 70°C, is the exception, and all the methanogens are mesothermic bacteria that have an optimum temperature of 30 to 45°C. Basically, the UASB is not recommended to use in low-temperature regions at high latitudes. On the other hand, UASB is not suitable for low-latitude tropical regions because the temperature is higher than the operating temperature.

Table 8 below shows the coefficients of the temperature-based Monod equation used in this study. [20]

Table 8 Bio-kinetic constants for UASB reactors treating municipal wastewater

Kinetic parameter	Temperature[℃]	
	32	15
Ks[mg/L]	601	729
k_d[1/d]	0.0033	0.0034
Y	0.422	0.185
μ_m[1/d]	0.16	0.043

The treatment conditions in this document are "Using an up-flow anaerobic sludge blanket (UASB) reactor; municipal wastewater was treated at temperatures of 6, 11, 15, 20, and 32 ◦C and water table retention times (HRT) ranging from 48 hours to 3 hours during approximately 860 days of operation.

2.6 Biogas calculation model:

One of the advantages of UASB is the generation of biogas, which can be utilized for surplus electricity generation. The main component of biogas is methane gas, which can be burned to generate electricity and heat. The generated electricity can be used to supplement the power needed for wastewater treatment. The surplus electricity can be sold to the network. The thermal energy can be used to preheat the inlet sewage water to the optimal temperature for treatment and other benefits concerning heat generation.

To estimate daily COD mass removed from the system, the following formula may be used [21]:

$$COD_{removed} = Q \times E_{COD} \quad (2.26)$$

Where, $COD_{removed}$[kg COD/d]: daily COD mass removed from the system; E_{COD}[%]: efficiency of COD removal

The following formula is used to estimate the daily COD mass used by the biomass:

$$COD_{sludge} = COD_{removed} \times Y_{COD} \quad (2.27)$$

Where, $CO_{SO_4converted}$[kg SO_4/d]: daily COD mass converted into biomass; Y_{COD} [kg COD_{sludge} /kg $COD_{removed}$]: sludge yield, as COD ;

The amount of sulfate load converted into sulfide is computed as follows:

$$CO_{SO_4converted} = Q \times C_{SO_4} \times E_{SO_4} \quad (2.28)$$

Where, $CO_{SO_4 converted}$ [kg SO_4/d]: load of SO_4 converted into sulfide; C_{SO_4} [kg SO_4 / m^3]:average influent SO_4 concentration; E_{SO_4} [%]: efficiency of sulfate reduction

And finally, the total amount of the daily COD mass used in sulfate reduction will be estimated by using the following equation:

$$COD_{CH_4} = COD_{removed} - COD_{sludge} - COD_{SO_4} \tag{2.29}$$

$$Q_{CH_4} = \frac{COD_{CH_4} \times R \times (273 \div T)}{P \times K_{COD} \times 1000} \tag{2.30}$$

Where, COD_{CH_4} [kg COD_{CH_4} /d]: daily COD mass converted into methane; Q_{CH_4} [m^3/d] theoretical volumetric production of methane; R [(0.08206 atm L /mol K] gas constant; T [°C]: operational temperature of the reactor; P [1atm]: atmospheric pressure; K_{COD} [0.064 kg COD_{CH_4}/mol]: COD of one mole of CH_4

The input data which are used in the above calculation are listed in the following table 9.

Table 9 Parameter of calculation methane gas

Parameter	Unit	Scenario Worst	Typical	Best	Reference
Contributing population (Pop)	inhab.	1,000–1,000,000			
Per-capita wastewater contribution (QPC)	m^3 $inhab^{-1}$ d^{-1}	0.12–0.22			von Sperling & Chernicharo (2005)
Per-capita COD contribution (QPC_{COD})	kg $inhab^{-1}$ d^{-1}	0.09–0.11			von Sperling & Chernicharo (2005)
Expected efficiency of COD removal (E_{COD})	%	60	65	70	von Sperling & Chernicharo (2005)
Sulfate concentration in the influent (C_{SO_4})	kg SO_4 m^{-3}	0.08	0.06	0.04	Singh & Viraraghavan (1998); Metcalf & Eddy (2003); Glória *et al.* (2008)
Efficiency of sulfate reduction (E_{SO_4})	%	80	75	70	Souza (2010)
Operational temperature of the reactor (T)	°C	20–30			von Sperling & Chernicharo (2005)
COD_{CH4} lost as waste gas (p_W)	%	7.5	5.0	2.5	Souza & Chernicharo (2011)
Other COD_{CH4} losses (e.g. biogas leaks) (p_O)	%	7.5	5.0	2.5	Souza & Chernicharo (2011)
Dissolved COD_{CH4} lost with the effluent (p_L)	kg m^{-3}	0.025	0.020	0.015	Souza & Chernicharo (2011)
Percentage of CH_4 in the biogas (C_{CH4})	%	70	75	80	von Sperling & Chernicharo (2005)

Chapter 3

MODEL APPLICATION AND VALIDATION

The detailed simulation model of the UASB reactor was performed, using MATLAB software. The substrate concentration and biomass were obtained in three dimensions on the height and time axes of the reactor.

A flowchart was created to summarize the calculation model created in Chapter 2. The calculation process begins with setting the specifications and conditions based on the actual size of the UASB. From those, Washout changes the value of the equilibrium state and the period of arrival. Then, the value of Washout has adjusted so that the value at equilibrium and the value of outflow COD and the diffusion coefficient D were calculated. The next step is to check whether the value of the diffusion coefficient D is within the range or not. If it is outside the range, the UASB settings will be re-checked. Then, the model determines the Monod coefficient based on temperature and other conditions. At that time, adjustments are made based on the removal rate, which is the Washout Fraction. Finally, the calculated value of the washout fraction is checked within the range and the calculation will be finalized.

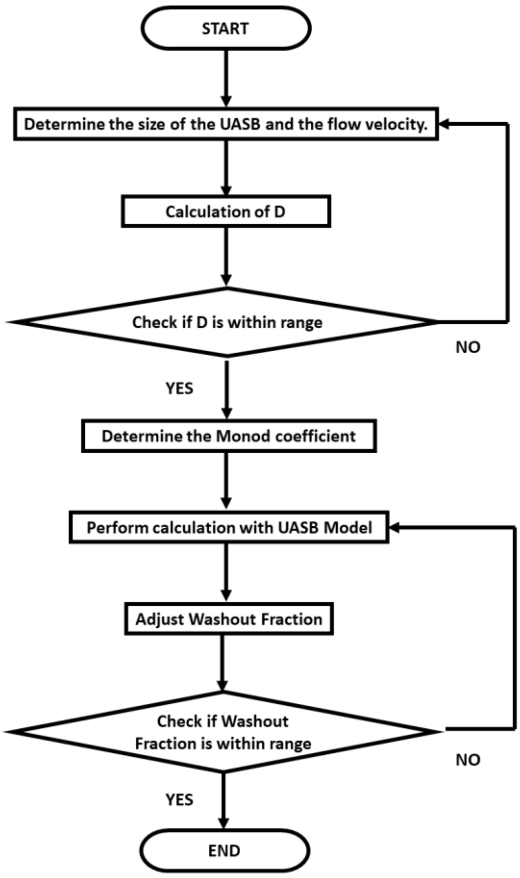


Fig. 15 Flowchart of the UASB calculation model

The specifications of a test pilot UASB reactor which was studied in this research is given in Table 10

Table 10 Specifications of the experimental UASB used in the model calculation

Parameter	Value
UASB reactor volume [L]	8
Height [m]	1.02
Inside diameter [m]	0.1
HRT [h]	10, 8, 6, 4
Temperature[℃]	32, 15

The Monod coefficients are collected from Tables 11 to 12 at two different temperatures of 32 and 15 degrees Celsius. The diffusion coefficient, Peclet number, and Reynolds number were calculated based on the given specifications of the reactor.

Table 11 kinetic parameters per HRT(32℃))

HRT [h]	Q [L/d]	V_{up} [m/d]	D $[m^2/d]$	Re	Pe	Inlet COD [mg/L]
10	19	2.44	0.21	3.68	11.9	320
8	24	3.06	0.26	4.60	12.2	268
6	32	4.07	0.33	6.14	12.7	278
4	48	6.11	0.47	9.12	13.3	218

Table 12 kinetic parameters per HRT(32℃))

HRT [h]	Q [L/d]	V_{up} [m/d]	D $[m^2/d]$	Re	Pe	Inlet COD [mg/L]
10	19	2.44	0.22	2.49	11.3	354
8	24	3.06	0.27	3.11	11.6	340
6	32	4.07	0.34	4.14	12.1	350
4	48	6.11	0.49	6.21	12.7	264

The influent flow rate (Q) and the rate of increased velocity were calculated for various values of HRT. The estimated values of the diffusion coefficient are in the standard range of $9.58.10^{-3}$ to 8.3.10-1 m^2/h [17]. As a range of diffusion coefficients, the values referred to are 9.58.10-3 to 8.3.10-1 m^2/h [17].

The estimated values of the Reynolds number (Re) was very small, probably due to the small size of the experimental selected reactor. The actual size of the UASB is much larger and will be considered in its calculation than the selected case in this study. The amount of COD is assumed to be the same as the amount of substrate concentration in the influent wastewater.

Based on the data given in Chapter 3-1, calculations were performed with HRT set at 4, 6, 8, and 10 hours. From this, the results near the bottom and the top of the UASB were extracted. The following Tables 13 to 14 show the results of the calculations. The simulation results for the concentration of the substrate and biomass in the bottom and top sides of the UASB reactor are shown in Figure 16 to 17, considering 100 days of the treatment operation.

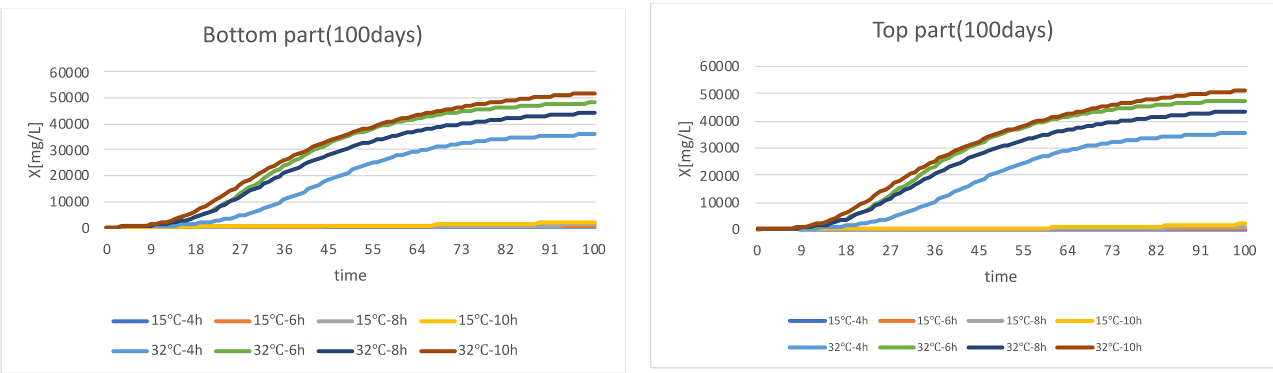


Fig. 16 Biomass concentration vs time (15 and 32 ℃)

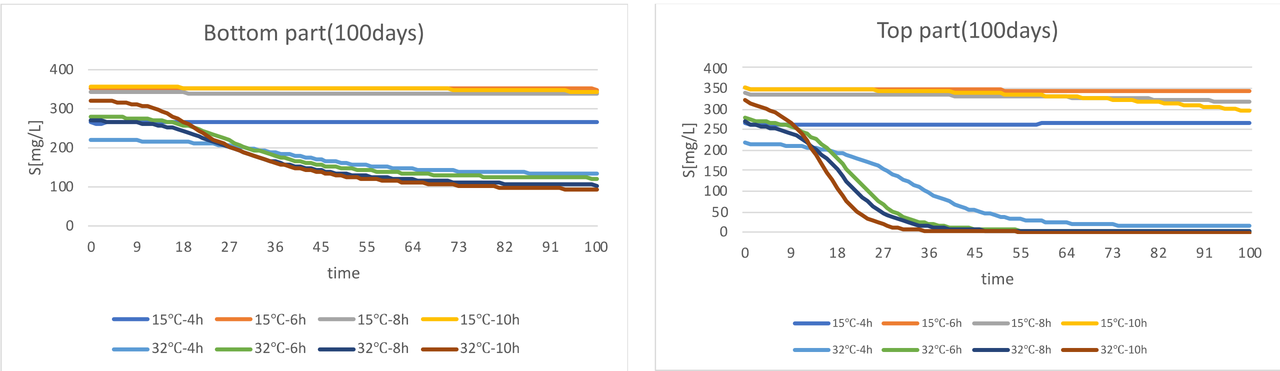


Fig. 17 Substrate concentration vs time (15 and 32 ℃)

Since the treatment process was not terminated at 15-degree process within 100 days did not produce results, so the simulation was performed with a period of 2000 days (Figure 18 to19). In the 15-degree process, the simulation with a period of 100 days did not produce results, so the simulation was performed with a period of 2000 days.

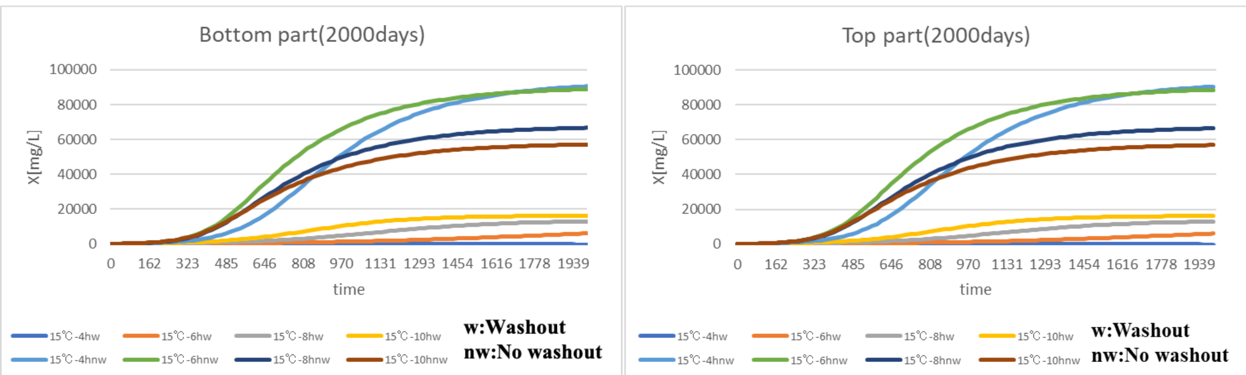


Fig. 18 Biomass concentration vs time (Comparison of washout Fraction,15℃)

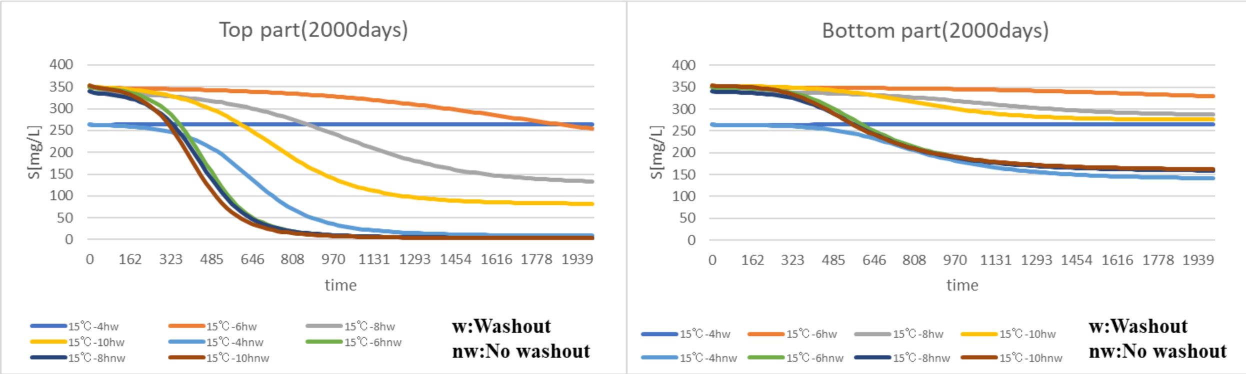


Fig. 19 Substrate concentration vs time (Comparison of washout Fraction,15℃)

Table 13 Substrate concentration in the treated water and adjusted washout values. Validation of the model results (32℃)

HRT [h]	Reference Eff-COD[mg/L] [20]	Result Eff-COD[mg/L]	Washout fraction
10	40	39.8	0.00125
8	48	46.2	0.00095
6	56	55.6	0.00088
4	62	60.9	0.00047

Table 14 Substrate concentration in the treated water and adjusted washout values. Validation of the model results (15℃) [20]

HRT [h]	Reference Eff-COD[mg/L] [16]	Result Eff-COD[mg/L]	Washout fraction
10	54	54.3	0.0002
8	68	67.4	0.000175
6	72	72.2	0.00014
4	78	85.0	0.00008

The treatment reaction at 32°C, which is closer to the suitable temperature of biomass, started earlier in any HRT than at 15°C. The results revealed that, the higher HRT, the more efficient processing of the substrate, and the higher the removal rate.

The top-side of the reactor has a lower substrate concentration than the bottom-side, and conversely, the biomass concentration is lower. Therefore, the bottom side of the reactor is more suitable for the growth of biomass.

The simulation results show that the system has a long start-up period but can be processed in a low-temperature environment and a very long-time treatment processing is possible.

Furthermore, Washout plays a key role in tuning the strat-up period of the process and should be adjusted carefully. There is a lack of information about the theoretical and empirical equations which express the relationship between the washout and HRT and temperature. However, few references have explained the possibility of the washout values in the range of 0.001-0.0001 orders, as shown in the model results.

Chapter 4

TECHNO-ECONOMIC ANALYSIS

The model was applied to a commercialized UASB reactor to conduct the Techno-Economic analysis, using real data for the water quality from the actual fish processing factory in Indonesia. The amount of methane gas generated was estimated using the methane gas calculations presented in Chapter 3, and the power generation and calorific value were calculated using a gas engine. Based on these calculations, the energy balance and mass balance were calculated, and economic evaluation was conducted. The cost-benefit analysis of the proposed system was evaluated over the medium and long term periods.

4.1 Technical evaluation:

The main technical specification of the case study reactor is given in Table 15.

Table 15 Parameters of UASB and Calculation Conditions for Wastewater Treatment

Parameter	Value
HRT [h]	8 [22]
Volume (column) [L]	1148 (1022) [22]
Height [m]	4 [22]
Internal diameter [m]	0.56 [22]
Temperature [℃]	32
Conditions for drainage and coefficients	
Influent COD [mg/L]	2900 [6]
D: Dispersion coefficient[m/d]	3.935
Ks: the affinity constant	601
Y: Yield [g VSS/g COD]	0.422
$\boldsymbol{\mu_{max}}$: the maximum specific growth rate [1/d]	0.16
Kd: Decoy constant	0.0033
w: Washout fraction	0.0082105

The temperature was set to be 32 degrees Celsius. Indonesia has a tropical climate with high temperatures throughout the year, and the temperature is around 32 degrees Celsius during the daytime, so this temperature was used for the calculations. In areas where the temperature drops depending on the season or latitude, heating may be necessary to increase the efficiency of the UASB. In this respect, Indonesia has advantages in terms of UASB operation.

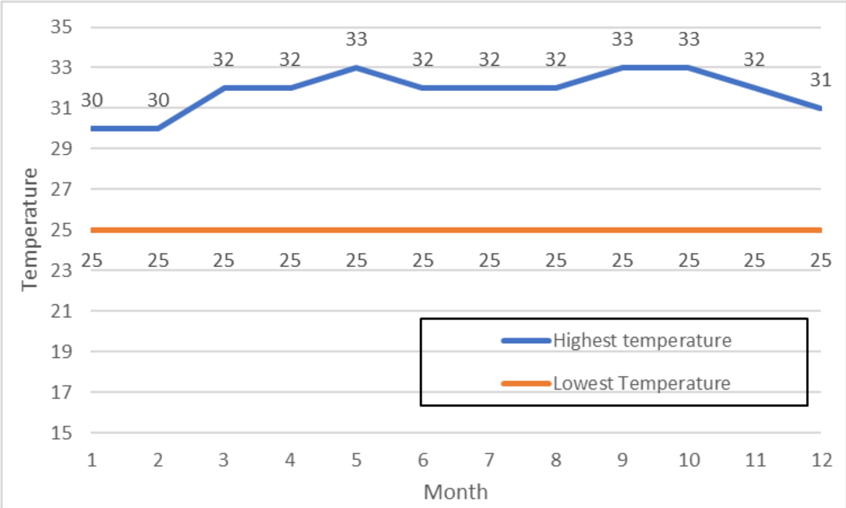


Fig. 20 Average temperature in Jakarta, Indonesia

The calculation results are shown in Figure 21 below.

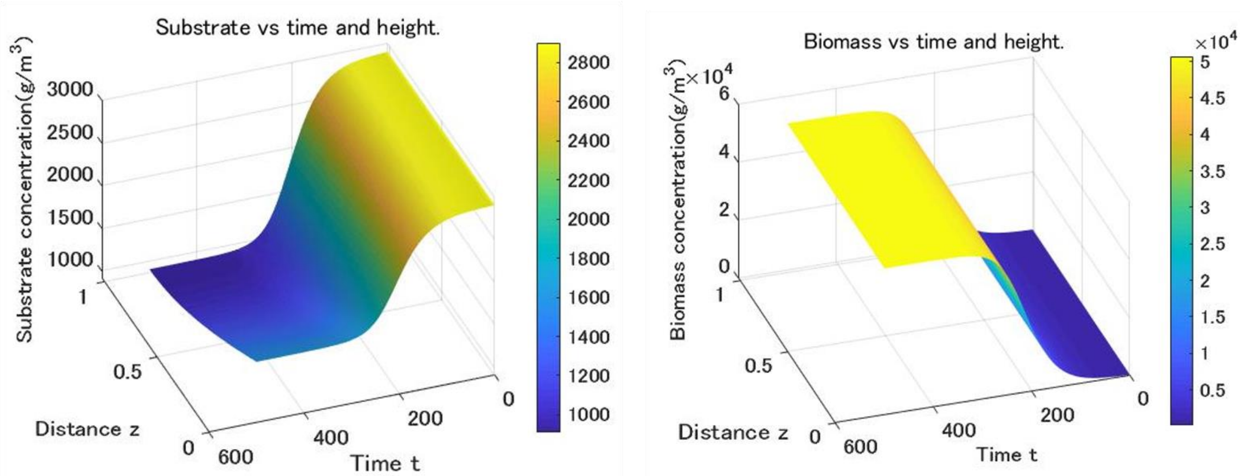
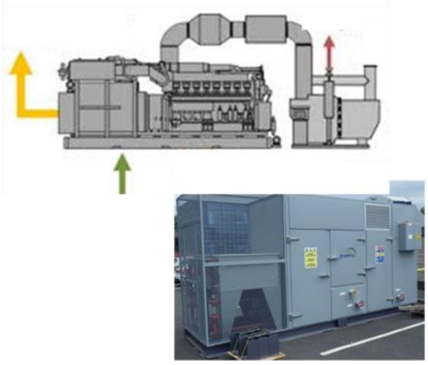


Fig. 21 Calculation results of substrate concentration and biomass concentration

It took about 300 days to reach the steady-state operation. The substrate concentration in the effluent is about 928 [mg/L], and the removal rate is 68%; the removal rate of UASB is estimated to be around 60 % to 80 %, [23] which is consistent with the reference data that it takes about 100 to 300 days to reach steady-state operation.

Based on the results of this calculation, the amount of biogas generated was calculated. During the steady-state operation (after about 300 days), it was estimated that 0.434m^3 of methane gas would be calculated when 1m^3 of wastewater was treated.

Methane gas has a GWP (Global Warming Potential) of 28 (carbon dioxide is 1), and its emission has a huge impact as a greenhouse gas. It can be utilized to generate electricity more efficiently than other fuels. For the purpose of power generation, It was assumed that the generated biogas could be burned in a gas engine or a gas turbine directly, which is shown in Figure 22.



Specifications	
Power generation output	150[kW]
Heat suply	637[MJ/ h]
Gas consumption	72[Nm^3/ h]
Power generation efficiency	38.1[%]

Gas Engine (Ohara tekkousyo) .

Fig. 22 Gas-powered generators and their specifications [24]

The main focus is given to electricity generation. This is because electricity can be used in fish processing plants or sold to the grid. Besides, the heat generated could be recovered to raise the inlet wastewater temperature in the UASB for more efficient treatment process.

Figure 23 shows the mass and energy balance, based on the model's results. [25]

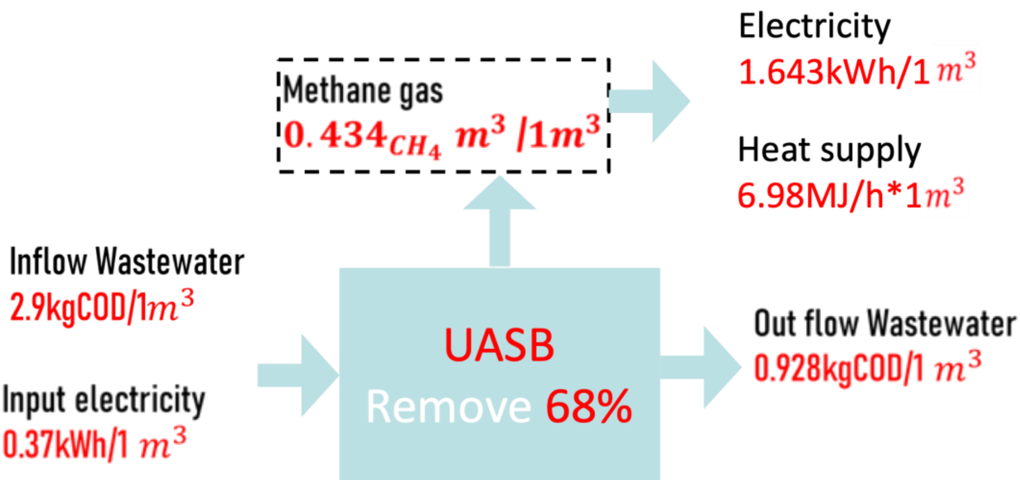


Fig. 23 Mass balance and energy balance

Although the removal rate is high, the treated water that flows out has still very high COD. Secondary treatment is necessary to achieve the discharge standard. As for the energy balance, the electricity generated by power generation is larger than the electricity required for treatment, which is a great advantage. The amount of heat that can be recovered is also large and can be utilized.

4.2 Economic evaluation:

LCOE stands for Levelized Cost Of Electricity, which is the sum of the costs required for power generation, such as construction, operation and maintenance, fuel costs, profit margins, and is calculated based on the expected power generation during the operation period.

$$LCOE = \frac{Capital\ cost + Operation\ and\ maintenance\ cost + Fuel\ cost + Social\ cost[\$]}{Electricity\ generated[kWh]} \quad (4.1)$$

NPV stands for Net Present Value, which indicates how much profit can be obtained from an investment. if NPV = 0, there is no profit from investing in the project, and if NPV is greater than 0, it is advantageous, and the greater the value, the better.

$$NPV = \sum_{t=0}^{T} \frac{C_t}{(1+r)^t} \quad (4.2)$$

IRR stands for Internal Rate of Return, and it indicates the discount rate at which the NPV of the cash flow for the investment period is zero.

$$0 = NPV = \sum_{t=0}^{T} \frac{C_t}{(1+IRR)^t} \quad (4.3)$$

4.2.1. Scenario analysis:

Two scenarios of retrofit and grassroot systems were considered for the economic evaluation of the proposed system. For both scenarios, the plant is also expected to treat 100 m3 of wastewater per day. Figure 24 demonstrates the application of the proposed scenarios in this study.

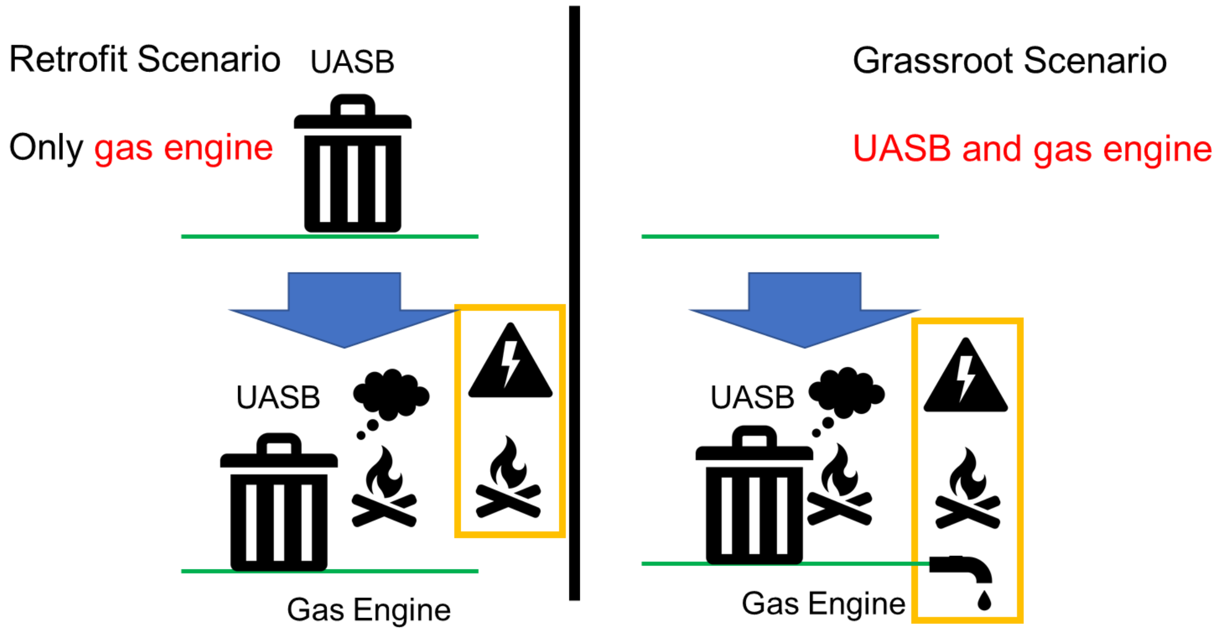


Fig. 24 Two scenarios of economic evaluation

It is also assumed that the operating period is 20 years, and the annual rate of return in Indonesia is 5.1%. [26]. Table 16 shows the prices of electricity, natural gas, reclaimed water, and drinking water.

Table 16 Sales price of each energy and resource in Indonesia

	Unit	Value
Electricity	$/kWh	0.072 [27]
Natural Gas	$/mmBTU	6.000 [28]
Recycled water	$\$/m^3$	0.596 [29]
Clean water	$\$/m^3$	0.895 [29]

4.2.1. Retrofit scenario:

A new biogas generator is installed in the existing UASB and post-treatment facility. The impact of the energy recovery system can be evaluated, by considering the cost of power generation based on the Levelized Cost Of Electricity (LCOE) and calculating the energy creation capacity of UASB. In the Retrofit scenario, the gas engine's cost is given as the initial and maintenance cost. In addition, the company will earn income from electricity and heat sales. For electricity sales, it is assumed that electricity is used at the fish processing plant, and the achieved income equals the reduction of the electricity usage fee. As for heat sales, the amount of heat was converted to be equal to natural gas consumption, and the value based on the price was used as the income.

Table 17 shows the cost of the main components and benefits from heat and electricity in the retrofit scenario.

Table 17 Expenditure (initial, operation, and maintenance cost) and income from resources in the retrofit scenarios

Expenses	Unit	Value
Gas engine initial cost	[$]	10000 [30]
Gas engine Operation and Maintenance cost	[$/year]	1200 [30]
Income		
Electricity (During steady-state operation)	[$/year]	4289
Electricity (1^{st} year)	[$/year]	246
Heat (During steady-state operation)	[$/year]	1449
Heat (1^{st} year)	[$/year]	83

The estimated value of LCOE in this scenario is 1.13[$/kWh]. In the following Figure 25, the LCOE of renewable energy for each region is shown for reference. The reason for this is that the size of the generator is determined by the amount of wastewater to be treated by the UASB, and in this scenario, there was no suitable size, and a larger generator type was considered. Another reason is that the biogas from the UASB is a by-product and not the primary source of power generation.

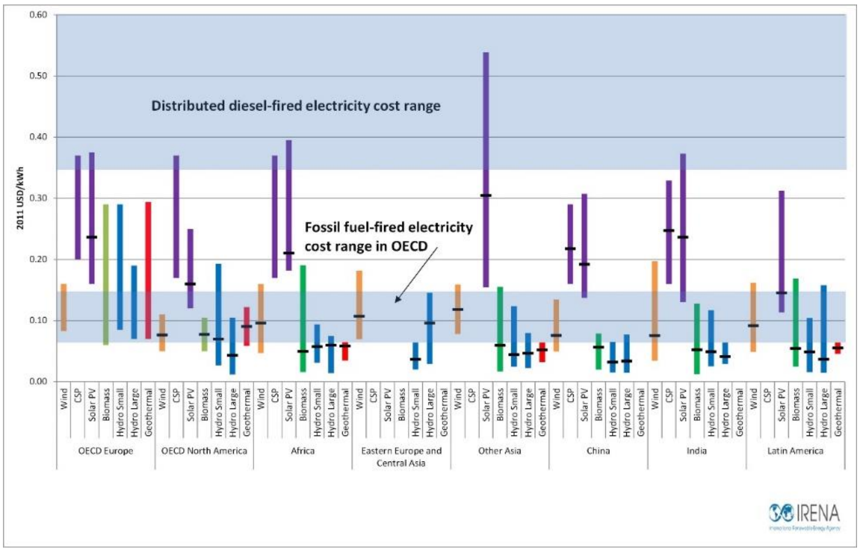
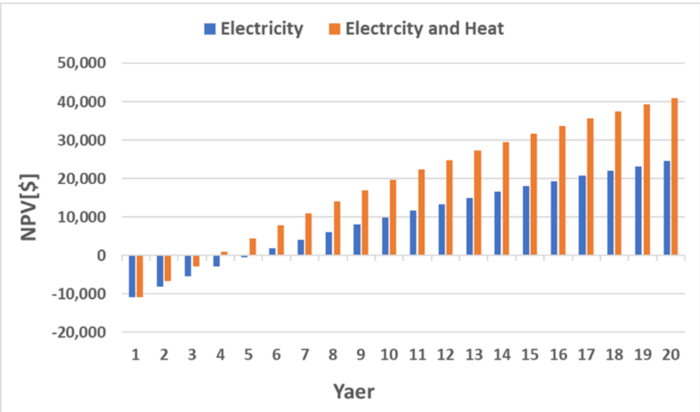


Fig. 25 LCOE for renewable energy in each region [31]

The results of NPV and IRR are shown in the following Figure 26. Although the LCOE was high, the cost balance for the UASB equipment group showed a large profit, and the NPV perspective also showed a large gain. The results show that the capital can be recovered in 4 years when both electricity and heat sales are taken into account.



	NPV[$]	IRR[%]
Gas engine(Electricity)	24645	22.9
Gas engine(Electricity + Heat)	40931	32.1

Fig. 26 NPV evolution of Retrofit Scenario over 20 years

Grassroot scenario: A new water treatment facility and a biogas generator are installed at the same time. In addition to the cost of the energy recovery system, the total cost of the entire water treatment takes into account in the calculation process.

The Grassroot scenario includes the initial and maintenance costs of the UASB, secondary treatment, and the cost of the gas engine. In addition, the treated water is assumed to be utilized as reclaimed water or drinking water for income. Water treatment by UASB is specialized to treat highly concentrated sewage, but it is not possible to remove it completely. Therefore, secondary treatment and other methods are required to bring the concentration up to the discharge standard. In this scenario, it is assumed that CEPC (Chemical-Enhanced Primary Clarification) is used for pretreatment, and UF (Ultrafiltration) and

RO (Reverse Osmosis) are used for secondary treatment. These treatments will remove toxic substances to the extent that drinking the treated water will not cause health problems. The following Table 18 shows the removal rates of major substances for each treatment.

Table 18 Removal rate of toxic substances for each water treatment system

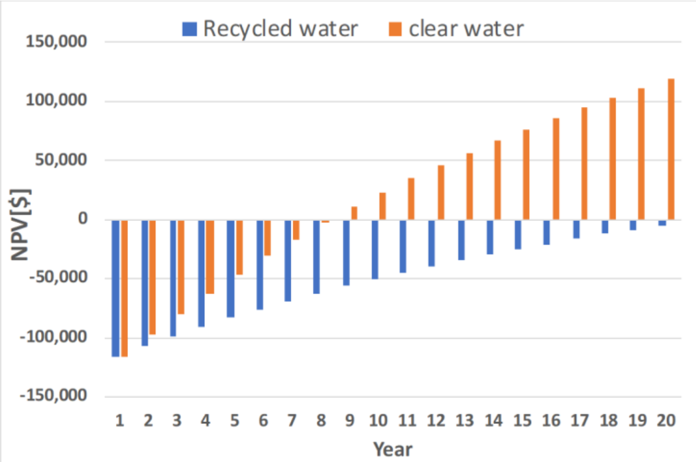
Component	CEPC [32]	UASB [33]	UF [34]	RO [34]
BOD	54	68	77	89
COD	58	68	75	91
TSS	86	0	96	100
SS	88	0	96	100
E.coli	91.3	92.1	100	100
Campylobacter (bacteria)	88.9	93.7	100	100
Salmonella spp. (bacteria)	88.9	90.0	100	100
Adenoviruses (virus)	99.7	80.0	100	100
Noroviruses (virus)	99.7	36.9	100	100
Rotavirus (virus)	99.7	0.0	100	100
Cryptosporidium	27.6	49.9	100	100
Giardia spp.	76.0	49.9	100	100

Table 19 shows the cost of the main components and benefits from heat and electricity in the grassroot scenario.

Table 19 Expenditure (initial, operation, and maintenance cost) and income from resources in the retrofit scenarios

Expenses	Unit	Value
Gas engine initial cost	[$]	10000 [30]
UASB initial cost	[$]	89063 [35]
Gas engine Operation and Maintenance cost	[$/year]	1200 [30]
UASB Operation and Maintenance cost	[$/year]	16606 [35]
Income		
Electricity (During steady-state operation)	[$/year]	4289
Electricity (1st year)	[$/year]	246
Recycled water (During steady-state operation)	[$/year]	21769
Recycled water (1st year)	[$/year]	0
Clean water (During steady-state operation)	[$/year]	32690
Clean water (1st year)	[$/year]	0
Heat (During steady-state operation)	[$/year]	1449
Heat (1st year)	[$/year]	83

The results of NPV and IRR are shown in Figure 27 below. The difference between reclaimed water and drinking water was significant. When the water is treated up to the secondary treatment, the treated water is at a level where it can be drunk without causing health problems. If the water is marketed as recycled water, the NPV over 20 years is negative, and the economic benefit is small. However, it is a system that can be considered when complying with government effluent standards. It will be of great benefit the treated water is sold as drinking water. The capital can be recouped in 9 years and can generate a large profit. If the water is sold as recycled water, the NPV can be made positive by lowering the water quality and lowering the price of treatment.



	NPV[$]	IRR[%]
UASB(Recycled water)+Gas	-5057	4.6
UASB(clear water)+Gas	119094	14.5

Fig. 27 NPV evolution of Grassroot Scenario over 20 years

Chapter 5

CONCLUSION

In this study, a simulation model of the UASB was developed and validated, and calculations were performed assuming actual water treatment conditions in Indonesia. Then, the Techno-economic analysis was conducted based on the results.

The UASB calculation model was introduced as a combination of the Monod model and the Mass Balance model. The diffusion coefficients were calculated based on the kinematic viscosity of water and confirmed using the relationship between the Peclet number and Reynolds number. The washout fraction was adjusted and was found to be similar to the substrate concentration after steady-state treatment of the material, confirming the validity of the model.

Using the UASB calculation model, a case study was conducted on the assumption that a real UASB would be constructed, referring to the data of factory effluent in Indonesia. About 300 days were required for the UASB treatment model to reach steady-state treatment, and the treatment rate was 68%. According to the results, about $0.434m^3$ of methane gas is generated from $1m^3$ of water treated. It was assumed that this gas would be used as energy through power generation and heat recovery by a gas engine. In particular, the amount of generated electricity, $1.27kWh/1m^3_{wastewater}$, indicating that there are significant advantages in energy utilization for this system.

Two scenarios were considered in this study. The scenario of adding a gas engine to the existing UASB (energy utilization considerations) resulted in significant revenue because of the large amount of electricity generated and the low price of the gas engine. The income from power generation and heat recovery resulted in a positive NPV (return on capital) in four years. In the grassroot scenario, in which a new UASB and gas engine are installed (UASB is operated for water treatment), it was assumed that most of the highly concentrated wastewater would be treated by the UASB and then by the secondary treatment UF and RO methods to a level that is safe to drink. In addition to the electricity and heat, the treated water can be sold as reclaimed water or tap water. In the case of selling the treated water as reclaimed water, the NPV could not be recovered in 20 years due to the disproportionate cost of secondary treatment, etc. However, when the water is sold as tap water, it can be recovered in 9 years, resulting in considerable revenue.

Therefore, the quality of the treated water can be determined based on the demand requirements in the region. By considering the quality and cost of secondary treatment, economic efficiency can be guaranteed.

The results show that the introduction of water treatment by UASB can bring significant benefits in terms of both the environment and economy to Indonesia’s fish industry. In the future, the incorporation of recycling systems and control systems in water treatment will enable more efficient and faster treatment.

REFERENCES

[1] A. l. o. o. p. A. A. Sherbinin, "A global indicator of wastewater treatment to inform the Sustainable Development Goals (SDGs)," 2015.

[2] 独立行政法人　国際協力機構, "汚水処理の途上国における開発課題," 2019.

[3] United Nations, "Sustainable　Development Goals," [Online]. Available: https://www.un.org/sustainabledevelopment/water-and-sanitation/.

[4] I. Ibrahim, "Indonesia country update status," The ministry of environment and forestry, republic of Indonesia.

[5] Nihon Suido Consultants Co., Ltd, Co-benefits Project On Wastewater treatment For Fish Processing Industry, 2019.

[6] NovaTec Consultants Inc. , "Wastewater Characterization of Fish Processing Plant Effluents.," 1994.

[7] 環境省, "インドネシア工場排水　水質基準値," [Online]. Available: https://www.env.go.jp/air/tech/ine/asia/indonesia/files/law/files/I14_table2016.pdf.

[8] 環境省, "環境技術実証事業　広報資料　有機性排水処理技術分野," 2015.

[9] 田村　博, "でん粉工場における排水処理技術," 06 03 2010. [Online]. Available: https://www.alic.go.jp/starch/japan/report/200910-01.html.

[10] 片岡直明, "嫌気性生物処理技術の特徴と発展の流れ," エバラ時報, 2010.

[11] 日本エネルギー学会, バイオマスハンドブック, オーム社, 2009.

[12] 国立環境研究所, "環境儀　No.35 環境負荷を低減する産業・生活排水の処理システム～低濃度有機性排水処理の「省」「創」エネ化～," 2010.

[13] L. Korsak, Anaerobic treatment of wastewater in a UASB reactor, Stockholm, Sweden : Department of chemical enginiering and technology , 2008.

[14] R. R. Gómez, Upflow anaerobic sludge blanket reactor: modelling, School of chemical science and engineering Department of chemical engineering and technology Royal institute of technology, 2011.

[15] K. M., "Kinetics of Subsequent Phases of the Anaerobic Processes. In," 2003.

[16] B. G, "Wastewater Microbiology (Wiley Series in Ecological and Applied," 2005.

[17] F. V. L. P. Kalyuzhnyi S., "Dispersed Plug Flow Model for Upflow Anaerobic Sludge Bed Reactors with Focus on Granular Sludge Dynamics.," 2006.

[18] Anton Paar, "Viscosity of Water," [Online]. Available: https://wiki.anton-paar.com/en/water/.

[19] M. D. a. G. P. Peña, "Dispersion and treatment performance analysis of an UASB reactor under different hydraulic loading rates.," 2006.

[20] Kripa Shankar Singh, T.Viraraghavan, "Effect of temperature on bio-kinetic coefficients in UASB treatment of municipal wastewater," 2001.

[21] C. A. L. C. a. C. L. S. L. C. S. Lobato, Estimates of methane loss and energy recovery potential in anaerobic reactors treating domestic wastewater, Water Science & Technology, 2012.

[22] 高. 関由里絵, "UASB リアクター内の嫌気性原生動物の補食特性".

[23] 田中康男、北山和茂、福永栄、羽賀清典, "UASBリアクターと散水ろ床を組み合わせた処理システムの豚舎汚水処理性能," 日本水処理生物学会誌, 1999.

[24] 株式会社大原鉄工所, "大型バイオガス発電機," [Online]. Available: https://www.oharacorp.co.jp/products/biogas/.

[25] "Life cycle assessment comparison of industrial effluent management strategies," [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0959652614005435?via%3Dihub.

[26] 株式会社国際協力銀行, インドネシアの投資環境2019, 2019.

[27] 一般財団法人日本エネルギー経済研究所, "平成２９年度国際エネルギー情勢調査（諸外国のエネルギー政策動向及び国際エネルギー統計等調査事業）諸外国のエネルギー政策動向に関する調査報告書平成２９年度国際エネルギー情勢調査（諸外国のエネルギー政策動向及び国際エネルギー統計等調査事業）諸外国のエネルギー政策動向に関する調査報告書," 2018.

[28] 独立行政法人国際協力機構　産業開発部, "インドネシア共和国 クリーンコールテクノロジー（ＣＣＴ） 導入促進プロジェクト 詳細計画策定調査報告書," 2011.

[29] 独立行政法人　国際協力機構(JICA), "インドネシア国南バリ再生水利用事業準備調査 （PPP インフラ事業）," 2012.

[32] S. Oakley, "Preliminary treatment and primary sedimentation," 2018.

[33] M. v. S. M. V. Stewart Oakley, "Anaerobic sludge blanket reactor," 2018.

[35] A. l. o. o. panelMatthewO'ConnorGilGarnierWarrenBatchelor, "Life cycle assessment comparison of industrial effluent management strategies," 2014.

[36] R. W. S. a. E. Bird, "Transport phenomena.," 2001.