Thai Environmental Engineering Journal Vol. 36 No. 3 (2022) : 1-9
www.eeat.or.th

Climate Friendly Technology for Domestic Wastewater; Comparative Study of Activated Sludge Process and Facultative Pond

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Abstract

This study compared greenhouse gas (GHG) emissions from activated sludge process (AS) and facultative pond (FP). The GHG emissions were estimated from 4 centralized wastewater treatment plants in urban areas of Thailand. The study was conducted by collecting data for 3 years to estimate GHG emissions by the IPCC method. The results show that AS had low methane (CH_4) emissions. GHG emissions from electricity consumption were the major source of GHG emissions accounting for 46 - 79% of total GHG emissions at the study sites. Total GHG emissions of AS and FP were 0.13 - 0.32 and 0.17 - 0.30 $kgCO_2eq/m^3$, respectively. The AS had lower direct GHG emissions than the FP, although there were indirect GHG emissions from electricity consumption.

Keywords : Domestic Wastewater; Facultative Pond; Greenhouse Gas Emissions; Greenhouse Gas Emissions from Wastewater Treatment Plants

Introduction

According to Intergovernmental Panel on Climate Change (IPCC) reports, GHG emission from the waste sector corresponds to approximately 3% of the anthropogenic emissions on a global scale, and wastewater treatment constitutes approximately 20% of the waste sector [1]. The source of GHG emission from wastewater treatment plants (WWTP) can be classified into two types: (1) Direct GHG emission such as carbon dioxide (CO_2), Methane (CH_4) and Nitrous oxide (N_2O), produced from the biological wastewater treatment process. CH_4 from wastewater was found to contribute 5% of the global CH_4 emissions [2]. The Major source of CH_4 generation is anaerobic process. However, CH_4 emissions in partial aerobic process can occur, they are not zero and substantial for some plants receiving sewage from expansive sewer networks [3]. N_2O is produced by the Nitrification and Denitrification processes. N_2O emission occurs mainly in the activated sludge units (90%) while the remaining 10% come from the grit and sludge storage tanks [4]. The IPCC report states that CO_2 emissions from wastewater are not considered because these are of biogenic origin that turned back it to the atmosphere [5]. The other source of GHG emission is (2) Indirect GHG emission from energy consumption and added chemical processes [6]. The GHG emissions of AS system from the previous studies were 0.71 - 3.3 $kgCO_2eq/m^3$ [1, 2, 7, 8]. The factors that affect GHG emission such as temperature affect to the rate of digestion and CH_4 production. An increase of population affected the consumption of protein and the concentration of nitrogen entering to WWTP increased accordingly.

In Conference of the Parties 26 (COP26) in 2021, Thailand announces the Net-zero policy. As a result, the measurements for which the Thai government is taking action in the wastewater sector are the collection of untreated sewage into the treatment system and increasing the number of domestic WWTP. The study and data collection of Thailand's GHG emissions in 2016, showed that the wastewater treatment and discharge system is one source of GHG emissions in the waste sector, accounting for approximately 49.55% of GHG emissions from the waste sector [9]. The GHG emissions estimated by the average wastewater quality of the country such as wastewater and Biochemical Oxygen Demand (BOD) generation rate for calculating CH_4 emission and protein consumption for calculating N_2O emission. However, the estimation of GHG emissions from each WWTP has not been sufficiently studied in Thailand because the calculation excludes GHG emissions from electricity consumption at WWTP.

There are 117 centralized WWTPs in Thailand but only 98 sites are still in operation. Facultative Pond (FP) and Activated Sludge (AS) are 43.6 and 32.5% of total WWTP, respectively [10]. The urban area of Thailand uses the AS system for domestic wastewater treatment because it produces better quality of effluent and lower requirement of land than other systems. On the other hand, the rural area uses the FP because of low operating costs and low electricity consumption. The aim of this study is to determine the climate friendly technology by comparison of GHG emissions from AS and FP. The direct and indirect GHG emission from WWTP in urban areas were estimated. The results indicated the amount of GHG in WWTP and confirmed the measures taken by Thailand's Pollution Control Department for using aerobic wastewater treatment technology to reduce GHG generation. Moreover, the estimation GHG emission from each WWTP can be used as a guideline for GHG emission reduction in wastewater sector of Thailand in the future.

Materials and Methods

1. Study site

The study sites are Din Daeng and Rattanakosin, Nonthaburi WWTP and Pattaya WWTP. There is a selection of WWTP in urban areas with different wastewater treatment processes under the AS system (i.e., biological AS with nutrients removal, two-stage AS, extended aeration with oxidation ditch and conventional AS) and a variety of wastewater data shown in Table 1. The 4 WWTP type of this study are accounting for 55.3% of AS systems and 17.9% of total WWTP in Thailand. In this study, wastewater characteristics and specific data that were used for the calculations such as electricity consumption, flow rate, population, BOD and total Nitrogen (TN) were collected from each WWTP. The average data are presented in Table 1.

2. Methodology

Methodology for calculating GHG Emissions is according to IPCC 2019 [3]. The researchers adjusted the calculation formula according to be Thailand's WWTP information. The GHG Emission in this study was classified into two type such as Direct GHG emission and Indirect GHG, as follows:

2.1 Direct GHG emission

CH_4 emission is originated from biological process in WWTP, even in the AS tank that aeration is available all the time. The volume of CH_4 from WWTP may be small, which can be caused by other processes that are not the aeration process such as primary treatment or sewer network [3]. The CH_4 emission is figured out by multiplying activity data and Emission Factor (EF).

The step of CH_4 emission estimation starts with calculation activity data as Equation 1 which was modified from IPCC 2019. The different WWTP processes result in methane emissions. CH_4 emission should be reflected in the calculation of total organics in wastewater (TOW) [3].

$$TOW = P \times BOD \times I \times 0.001 \times 365 \quad (1)$$

Where: TOW is the total organics in wastewater (kg BOD/year) which is a function of human population and BOD generation per person. P is amount of population in the service area (persons). BOD is BOD_5 removed in wastewater treatment processes (g/person/day). I is correction Factor for additional industrial BOD discharged (Thailand has collected wastewater into centralized WWTP, for which the default value from the IPCC is 1.25) and 0.001 is conversion from grams of BOD to kg of BOD. The emission factor (EF; kg CH_4/kg BOD) for CH_4 emission is a function of the

Table 1 The design criteria data and characteristics of wastewater of study sites (collected data from January 2018 to December 2020)

Details	Study sites			
	Din Daeng	**Rattanakosin**	**Nonthaburi**	**Pattaya city**
Type of WWTP	*Biological AS with Nutrients Removal*	*Two-Stage AS*	*Extended Aeration with Oxidation Ditch*	*Conventional AS*
Capacity of wastewater (m^3/day)	*350,000*	*40,000*	*38,500*	*65,000*
HRT (hr)	*24*	*24*	*10*	*24*
Electricity consumption (kWh/day)	35,040	9,300	2,958	28,404
Flow rate (m^3/day)	194,062 - 266,989	15,173 - 32,101	11,436 - 22,238	49,265 - 80,103
Population (person)	419,899 - 452,469	33,194 - 37,459	252,491 - 257,132	47,753 - 49,202
BOD_{inf} (mg/L)	34.65 - 70.56	48.60 - 78.70	32.65 - 54.80	21.73 - 90.90
BOD_{eff} (mg/L)	3.26 - 5.14	6.23 - 10.59	5.40 - 15.20	4.84 - 15.90
TN_{inf} (mg/L)	12.69 - 18.36	3.11 - 9.09	2.35 - 13.42	11.27 - 27.45
TN_{eff} (mg/L)	7.96 - 8.63	1.51 -7.32	5.14 - 11.90	4.90 - 10.00
BOD removal efficiency (%)	89.6	85.9	80.8	81.0
TN removal efficiency (%)	43.6	52.7	13.1	58.0

Note: The italic letter is the design criteria data and the normal letter is the collection data for WWTP.

maximum CH_4 producing capacity (B_o) and the methane correction Factor (MCF), as shown in Equation 2. The B_o can be produced from a given quantity of organics as expressed in BOD (the default value from the IPCC = 0.6 $kgCH_4/kgBOD$). The MCF indicates the extent to which the CH_4 producing capacity (B_o) is realized in each pathway or system (The default value for a centralized and aerobic treatment plant = 0.03). However, the default data such as I, B_0, MCF and EF are the average data from literature review in other studies by IPCC [3]. The IPCC reviewed and accepted data from measurement of CH_4 emissions from full-scale domestic WWTP and defined them as averages for each type of WWTP.

$$EF = B_o \times MCF \quad (2)$$

$$CH_4 \text{ emission} = TOW \times EF \quad (3)$$

N_2O emissions are a by-product of the biological total Nitrogen removal by Nitrification and Denitrification process in the AS tank [6]. N_2O is generated from 2 sources; N_2O from domestic WWTP ($N_2O\ Plants_{DOM}$) and N_2O from domestic wastewater effluent ($N_2O_{\ EFFLUENT,\ DOM}$) (Figure 1). Firstly, the activity data from total nitrogen in domestic wastewater (TN_{DOM}) for $N_2O\ Plants_{DOM}$ and $N_{EFFLUENT,\ DOM}$ for $N_2O_{\ EFFLUENT,DOM}$ could be calculate according to the Equation 4.

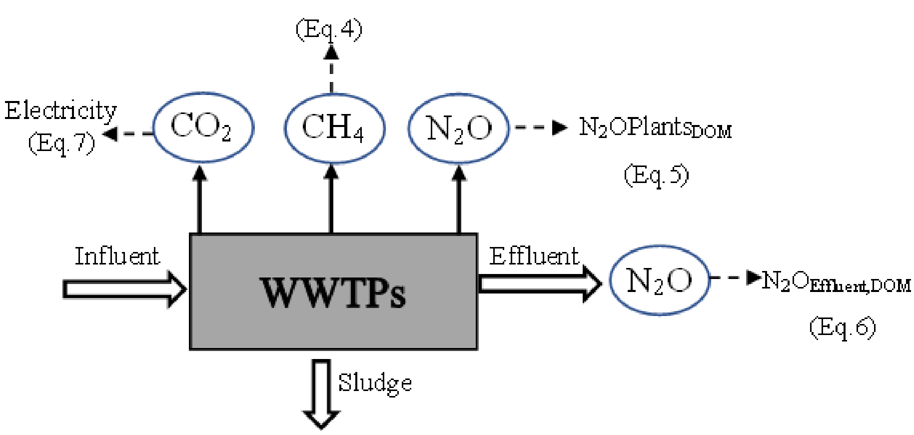

Figure 1 Schematic diagram of Greenhouse Gas emissions from wastewater treatment systems

$$TN_{DOM} \text{ or } N_{EFFLUENT,DOM} = Q \times TN \times 0.001 \times 365 \quad (4)$$

Where: Q is Flow rate of each WWTP (m^3/day). TN is concentration of Nitrogen removal in process (for TN_{DOM}) or concentration of Nitrogen in effluent (for $N_{EFFLUENT,DOM}$) (mg/L).

The N_2O emission from WWTP (N_2O $Plants_{DOM}$) and N_2O from wastewater effluent (N_2O $_{EFFLUENT,DOM}$) could be figured out by multiplying activity data as TN_{DOM} or $N_{EFFLUENT,DOM}$ (kg N/year) and Emission Factor (EF) as Equation 5 and 6, respectively.

$$N_2O\ Plants_{DOM} = TN_{DOM} \times EF_{plants} \times (44/28) \quad (5)$$

$$N_2O_{EFFLUENT,DOM} = N_{EFFLUENT,DOM} \times EF_{EFFLUENT} \times (44/28) \quad (6)$$

Where: The Factor 44/28 is the conversion of kg N_2O-N into kg N_2O. The EF of N_2O emission is default value from IPCC 2019 [3] and is classified by type of treatment system and discharge pathway. EF_{plants} from centralized and aerobic treatment plant is 0.016 kgN_2O-N/kgN. $EF_{EFFLUENT}$ use for discharge to freshwater, estuarine, and marine discharge is 0.005 kgN_2O-N/kgN.

2.2 Indirect GHG Emission

Indirect GHG Emission is calculated from amount Emission Factor (kgCO_2/kWh) and electricity consumption (kWh/day) from pumping station, aeration process and return sludge, see Equation 7. The Emission Factor uses default data for the grid changed to energy that imported to supply to WWTP, recommended by Thailand Greenhouse Gas Management Organization (TGO) at 0.477 kgCO_2/kwh.

$$\text{GHG Emission} = \text{Electricity Consumption} \times EF \quad (7)$$

Results and Discussion

1. Direct GHG emission

For this study, GHG emissions are estimated in the unit of kgCO_2eq/m^3 of wastewater (3 years average). Direct GHG emission of WWTP such as CH_4 and N_2O are caused by biological wastewater treatment processes. The results of the estimation of direct GHG emissions are shown in Figure 2. The highest direct GHG emissions from Pattaya is 0.12 kgCO_2eq/m^3, due to increased BOD values in some months that results in a high amount of BOD and TN per capita as well. Followed by Din Daeng, Rattanakosin and Nonthaburi are 0.08, 0.06 and 0.05 kgCO_2eq/m^3, respectively. In 2020, TN influent from Nonthaburi WWTP was less than TN effluent. These results may be due to unknown errors. Therefore, the result of N_2O emission only show N_2O from domestic wastewater effluent. The N_2O is the major direct GHG emission from Din Daeng, Nonthaburi and Pattaya WWTP. The Rattanakosin WWTP has lower N_2O emission than CH_4 emission due to the data collection in 2019 and 2020, found that TN is less due to the lower population of the area (35,356 and 33,194 PE, respectively from 37,454 PE in 2018).

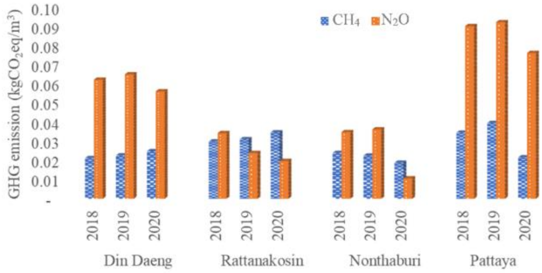

Figure 2 Direct GHG emission of each WWTP

In addition, the responsibility area of Rattanakosin is also a tourist attraction but with the epidemic situation of COVID-19, the tourists numbers decreased. There are also resulting in lower protein consumption. Therefore, the N_2O emission is decreased accordingly. The degree of TN removal showed a good correlation with direct N_2O emission [6]. N_2O is generated as a by-product of Nitrification or an intermediate product of Denitrification. There are many factors affecting N_2O emission such as temperature and dissolve oxygen (DO) concentration of wastewater [3]. In addition, the increase of population in the WWTP services area has resulted in an increase in protein-containing diets, which cause higher nitrogen concentrations in wastewater and may also lead to higher N_2O emissions from WWTPs [11]. However, N_2O emission occurs in small quantities but have a high Global Warming

Potential (GWP), which are the main GHG emissions in WWTP. N_2O emission in this study ranged from 0.3 - 0.9 $kgCO_2eq/m^3$. These results are in the same range as N_2O emissions from WWTP in India (0.2 - 0.4 $kgCO_2eq/m^3$) [12]. In addition, the large uncertainty range for N_2O emission is 0.05 - 25% of TN load [13]. In addition, BOD removal efficiency is related to GHG emissions. Table 1 in the Materials and Methods topic, shows that BOD removal efficiency was 89.6, 85.9, 80.8 and 81.0% for Din Daeng, Rattanakosin, Nonthaburi and Pattaya, respectively. WWTPs with higher BOD removal efficiency have lower CH_4 emissions.

The variation in CH_4 emissions is related to the BOD_5 removal process, if there have a good efficiency from the plant, that will be more gas emissions [2]. The different AS type has similar BOD removal efficiency. Some of the AS system in Thailand is designed to have a nutrient removal system such as Rattanakosin where have 2 aerobic tanks for removing BOD and another tank for removing nutrients such as Nitrogen and Phosphorus. The advantage of AS systems is good quality effluent and low land requirement that compared to other system. The disadvantage is high electricity consumption, sludge disposal is required on large scale and must have experienced person to control the system [14]. Table 2 show the comparison strengths and weaknesses of each AS type.

2. Indirect GHG emission

Indirect GHG emission depend on the proportion between the flow rate of influent wastewater and electricity consumption control, which must be maintained to be consistent. For example, Din Daeng is the largest sites. However, there is an energy efficient design for return sludge that uses gravity flow principles to reduce energy consumption. The average of electricity consumption in each WWTP and value of indirect GHG emission are shown in Table 3. The highest electricity consumption also has the highest indirect GHG emissions which are Rattanakosin, Pattaya, Nonthaburi and Din Daeng, respectively. Excluding the Nonthaburi WWTP, it operates only 10 hours per day. It is possible to explain more GHG emission from electricity consumption at small scale WWTP than at large scale WWTP. These results are according to the previous studies, which found that the energy consumption was 0.43 and 0.33 kWh/m^3 from medium and large-sized WWTP, respectively [15]. The average electricity consumption of conventional AS in different countries was 0.2 - 1.9 kWh/m^3 [16]. All of the previous studies results can be concluded that the smaller WWTP tend to have higher specific electricity consumption per inlet wastewater, resulting in higher GHG emissions than larger WWTP [15-17]. The details of WWTP in the literature review are shown in Table 2.

Table 2 The strengths and weaknesses of each AS type

information	Site study			
	Din Daeng	Rattanakosin	Nonthaburi	Pattaya city
Type of AS	Biological AS with Nutrients Removal	Two-Stage AS	Extended Aeration with OD	CAS
specific nutrient removal process	yes	yes	no	no
BOD removal Efficiency (%)	89.6	85.9	80.8	81.0
TN removal Efficiency (%)	43.6	52.7	13.1	58.0
Electricity consumption (kWh/day)	35,040	9,300	2,958	28,404

Note: OD is Oxidation Ditch, CAS is Conventional Activated Sludge

Table 3 The details of study sites and the comparison with WWTP in the literature review

sites	Population (person)	Type of system	Energy consumption (kWh/m^3)	indirect GHG emission ($kgCO_2eq/m^3$)
Din Daeng (HRT=24hr)	419,899 - 452,469	AS-N	0.150	0.072
Rattanakosin (HRT=24hr)	33,194 - 37,459	Two-Stage AS	0.457	0.218
Nonthaburi (HRT=10hr)	252,491 - 257,132	EA with OD	0.176	0.084
Pattaya (HRT=24hr)	47,753 - 49,202	Conventional AS	0.421	0.201
Greek (Medium) [15]	10,000 - 100,000	EA, whereas few had CAS&ASD	0.43	-
Greek (Large) [15]	> 100,000	CAS&ASD	0.33	-
Australia [16]	-	CAS	0.46	-
China [16]	-	CAS	0.269	-
USA [16]	-	CAS	0.33 - 0.60	-
Japan [16]	-	CAS	0.30 - 1.89	-

Note: AS-N is Biological AS Process with Nutrients Removal, CAS is the conventional activated sludge, EA is Extended Aeration, OD is Oxidation Ditch and ASD is anaerobic sludge digestion

3. Total GHG emissions of each WWTP

The figure 3 shows the percentage of total GHG emission from each WWTP. The major source of GHG emission in WWTP is electricity consumption with 46, 79, 63 and 63% of total GHG emission in Din Daeng, Rattanakosin, Nonthaburi and Pattaya, respectively. The largest electricity consumption was from the secondary treatment or aeration tanks that were caused by continuous aeration [16, 18]. The aeration process requires an air blower or aerator for additional air to help aerobic bacteria to biodegrade the organic substances, which means a lot of electricity consumption [11]. Also, 60% of GHG emission in the extended aeration AS is electricity consumption for the blower and air pump [1].

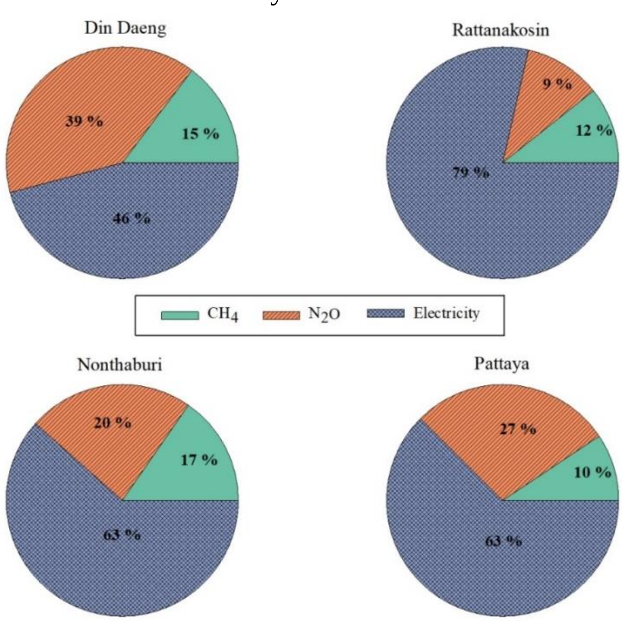

Figure 3 Total GHG emission of each WWTP

4. Alternatives for climate friendly systems

In developing countries, facultative pond treatment technology (FP) is very popular for domestic wastewater treatment. However, anaerobic ponds and FP are the major sources of direct GHG emission with 66% and 33% of the total contribution, respectively [2]. In the case that the countries are planning to build WWTP. They should consider using climate friendly technology. This study also compared GHG emissions from the AS and FP systems. The characteristics of wastewater from each WWTP (Din Daeng, Rattanakosin, Nonthaburi and Pattaya) have been assessed for GHG emission using FP treatment technology (not AS). The estimation method and Emission Factor for GHG emissions were applied from default data of IPCC. The GHG emission from FP is only direct GHG emission (CH_4 and N_2O) because electricity is not consumed. The results of the comparison GHG emission are shown in Figure 4. The GHG emissions from AS were 0.16, 0.20, 0.13 and 0.32 $kgCO_2eq/m^3$ and GHG emission from FP were 0.21, 0.24, 0.17 and 0.30 $kgCO_2eq/m^3$ for Din Daeng, Rattanakosin, Nonthaburi and Pattaya, respectively. The FP system mostly expresses higher GHG emission than the AS system. The major GHG emissions is CH_4, which is higher than those in the AS system. It can be concluded that the AS system has fewer GHG emissions than other wastewater treatment systems. Due to the available aeration process, the amount of GHG generated will be reduced. However, the increased electricity consumption for wastewater treatment must affect to the price of electricity. According to the previous research, they studied GHG emission from FP. When the FP system is upgraded to Sequencing Batch Reactor (SBR), the SBR is a type of AS system. The results show that the GHG emission from FP is double the GHG emission of SBR [7]. Therefore, for an aerobic process, indirect GHG emission from electricity consumption is higher than for FP.

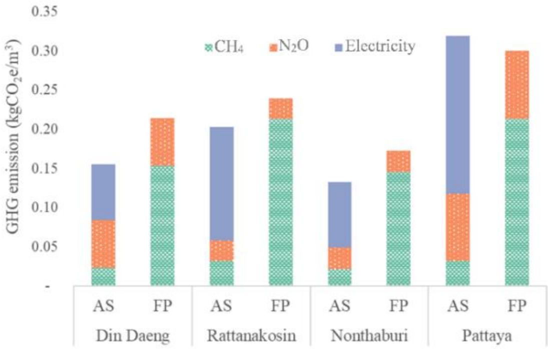

Figure 4 Comparison of GHG emission from the AS and FP by characteristics of wastewater data from each WWTP (the average data in 2018 - 2020)

However, the AS system still has a lower total GHG emission because of the absence of CH_4 emissions. On the other hand, the Pattaya WWTP shows that wastewater treated by AS has higher GHG emissions than wastewater treated by FP because there are already a lot of direct GHG emissions. When direct GHG emission is combined with indirect GHG emission, the total GHG emissions are higher than treatment by FP.

Conclusions

The GHG estimation by the IPCC method is based on the wastewater quality data of each WWTP, such as the biological wastewater treatment process (shown in BOD and TN values), population in the area of responsibility, flow rate of wastewater entering the system and the electricity consumption in the system which if there is good wastewater management will reduce gas emissions. The major source of GHG emission from the AS system is electricity consumption. The direct emission as N_2O emission was higher than CH_4 emission due to the AS system's continuous aeration process. The comparison of AS and FP revealed that AS system have lower total GHG emission than FP system. Although the AS system is considered a source of GHG emission from electricity consumption.

The uncertainty of the estimation is due to the fact that this research was only used to estimate GHG emissions using the IPCC method and we conducted it during the COVID-19 situation, so there was no field visit to collect data and wastewater samples. The limitation of electricity consumption data is that there are no monthly data collections or other treatment sub-unit information. There should be more data collection for a thorough study of GHG emissions from electricity consumption. The suggestion from the study is to analyze the wastewater samples to compare with the assessment according to the IPCC Methods.

Consequently, the selection of wastewater treatment systems that encourage the reduction of GHG emissions must consider the suitability of the area and the amount of wastewater that the system can support in each area. In addition, there is necessary to consider the cost of electricity consumption. However, the main purpose of WWTP is to treat wastewater in accordance with legal standards. The operation of the WWTP, which has the main goal of reducing GHG emissions may be difficult and have a high cost.

Acknowledgements

This research was inspired by the study on “Good Practices and Technologies for Climate friendly Municipal Solid Waste and Domestic Waste Water” conducted by Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) and the Pollution Control Department (PCD) under the Thai German Climate Programme (TGCP).

The authors sincerely acknowledge the related persons of each WWTP for their support and the data they provided for this study.

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