EnvironmentAsia
The international journal by the Thai Society of Higher Education Institutes on Environment

EnvironmentAsia 18 (Special Issue) (2025) 1-8
DOI 10.14456/ea.2025.16
ISSN 1906-1714; ONLINE ISSN: 2586-8861

Potential Carbon Dioxide and Methane Gas Fluxes from Municipal Sedimentation Pond Sludge in Tropical Zone

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Abstract

Rapid urbanization, particularly in tropical cities, has intensified challenges in waste and wastewater management, contributing to greenhouse gas emissions. This study evaluates carbon dioxide and methane emissions from sludge in the sedimentation pond of the Phetchaburi Municipal wastewater treatment system. Sludge samples were analyzed over 30 days under aerobic and anaerobic conditions. Carbon dioxide emissions peaked early due to aerobic microbial digestion, while methane production peaked between days 6 and 15 during anaerobic degradation. Methane emissions declined thereafter due to carbon depletion and an unfavorable C:N ratio of 6.18:1, inhibiting further methanogenesis. Temperature fluctuations influenced gas production, with higher emissions observed during initial digestion stages. Estimated total emissions from the collection pond were approximately 102,317.23 mg/day of methane and 31,840.67 mg/day of carbon dioxide. While the results can be extrapolated into the potential source of greenhouse gas emission into the atmosphere, the study also suggested that with the potential further studies on the vertical profile of these gases emission through the water column would be needed as the chemical interaction would affect to overall concentration at the surface. Thus, these findings underscore the need for improved sludge management strategies to mitigate the climate impact of municipal wastewater treatment in tropical regions.

Keywords: Municipal Wastewater; Sludge gas emission; GHG emission

1. Introduction

Urbanization in tropical cities has increased environmental challenges, particularly in waste and pollutant management. The widespread use of combined sewer systems supports domestic wastewater treatment, however, greenhouse gas (GHG) emissions from wastewater processes remain a significant concern. Human-induced GHG emissions, primarily from fossil fuel combustion, have raised atmospheric carbon dioxide levels by nearly 50% since pre-industrial times (Hughes *et al.,* 2021; Hughes *et al.,* 2021). According to the United Nations Framework Convention on Climate Change, major GHGs include carbon dioxide, methane, and nitrous oxide.

Globally, wastewater treatment contributes approximately 2% of total anthropogenic GHG emissions, with non-CO_2 emissions projected to range from 0.56 to 0.71 Gt CO_2-eq per year between 2005 and 2030 (Tong *et al.,* 2024). Understanding these emissions is especially crucial for tropical cities. In Phetchaburi Municipality, domestic wastewater is collected via a combined sewer system and held for 24 hours in the Klong Yang collection pond before treatment

(Chunkao *et al.,* 2014; Jinjaruk *et al.,* 2018). This retention alters wastewater's physical, chemical, and biological properties, allowing for solid-liquid separation, with sludge accumulating at the bottom (Khan *et al.,* 2024).

In suggesting that, the byproduct of wastewater treatment wastewater being the sludge contains high levels of organic matter, including carbohydrates, proteins, fats, and synthetic detergents (Michalska *et al.,* 2022). In Phetchaburi Province, Biological Oxygen Demand concentrations in municipal wastewater reach approximately 907 mg/L (Jinjaruk *et al.,* 2019). While sludge can be a valuable resource for soil carbon stabilization and organic fertilizer, improper management can pose environmental and health risks (Seleiman *et al.,* 2020). With growing concerns over sludge disposal, sustainable recycling strategies are necessary. Wastewater treatment also generates GHGs, particularly carbon dioxide during aerobic treatment and methane from sludge due to microbial activity (Nguyen *et al.,* 2019).

This study assesses the potential carbon dioxide and methane emissions from sludge in the sedimentation pond of the Phetchaburi Municipal wastewater treatment system. It examines GHG emissions over one month (30 days) quantifying and qualifying its potential emission as the results can be applied as a base for studies and research in their emission in tropical municipal wastewater treatment ponds.

2. Methodology

2.1 Site of Collection

The sample collection site was located in Phetchaburi municipality, where the city sewer system collected majority of the domestic wastewater in which the sewage pipelines are connected to the collection which is located within the city. (Maskulrath *et al.,* 2021). Where it was seen that within the collection pond, the general scheme is made out of the 2 big ponds with the total volume of 7,200 m^3 while to ranges in the wastewater transferring into the system ranges from 4500 to 6500 m^3 (seasonal differences) Making the retention time within the collection pond from 25 - 30 hours before pumping into The King's Royally Initiated Laem Phak Bia Environmental Research and Development Project (LERD) project.

2.2 Samples Collection

Having define that the hydrologic retention time of approximately 30 hours, sludge sediments accumulate and settle in the sedimentation pond (Abderrazak *et al.,* 2016; O'Melia, 1998). This study collected samples from the sedimentation pond at Klong Yang station, part of the Phetchaburi Municipal wastewater treatment system. The pond is divided into two sections, with wastewater inflow alternating daily between the two sides.

The samples were collected at six points three on each side of the pond (Figure 1). At each sampling point, sludge was collected within a 5.0 m diameter and a depth of 0 – 30 cm. A total of 10 kg of sludge was obtained per point, with 1500 grams used for greenhouse gas emission analysis and 2000 grams for initial soil/sludge quality assessment.

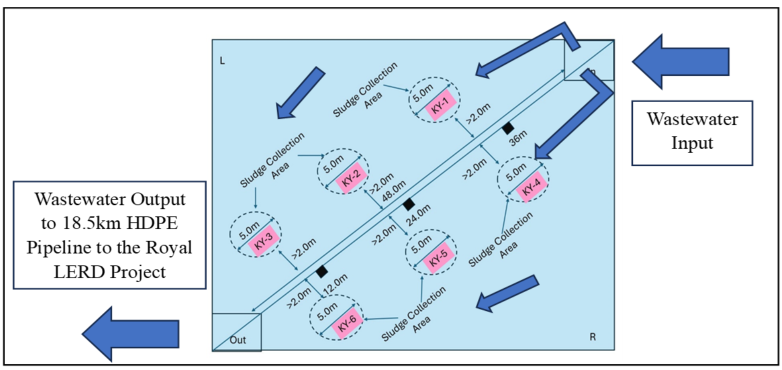

Figure 1. Sample points for data collection from sedimentation pond of Phetchaburi Municipality

2.3 Greenhouse Gas Collection

In this study, amber glass growler jars for the closed chamber method were used to collect carbon dioxide and methane by adding 1.5 kg of sludge to each glass jar with 3 replications from each sample point. The mouth of the jug is closed with a stopper which has two small holes. One hole is inserted with the thermometer, and another is inserted with glass tube that are sealed with silicon by using glue gun. The silicon tube from glass jar is connected to the gas air sampling bag. The emitted gas of gas from the glass jar is collected every day at the same time for 30 days from April 30, 2024, to May 29, 2024. The room temperature, the temperature in the glass jars and volume of the gas emissions will be recorded.

2.4 Measurement of Gas Concentrations

The samples to be tested were taken from the gas sampling bag which has 0.5 Liters in volume by using thin wall hypodermic needle (0.60 x 25 mm) until all the gas gone out for each day. The collected gas volume was recorded and added 20 mL of gas sample to vial which has 20 ml in volume. The vials were stored in the refrigerator before being sent to the analysis station.

The model of gas chromatography (GC) used Hewlett Packard hp 6890 series GC system and the column for GC machine is high resolution gas chromatography column named Agilent J&W GC columns for GC capillary columns for optimum performance (Kachenchart, 2023).

In analyzing the amount of gas by ppm (parts per million) by gas chromatography and then calculate the concentration of the gas by the following equation (1).

$$E\text{gas} = \text{p}\frac{V}{A}\frac{dCgas}{dt}\ \frac{273}{273+T} \qquad (1)$$

Where, Egas was concentration of gas production, Ƿ was the density of the gas under standard conditions; V was collection volume of gas enclosed, A was surface area of the device, dCgas/dt (Difference in gas concentration and time) was the amount of gas change in a certain time, T was the average temperature in Celsius.

2.5 Soil/Sludge Quality Analysis

The soil test was performed two times; with the first sample being the representing the initial sludge quality while the second analysis was made using the remaining sludge samples after 30 days. The soil sludge samples parameters are quantified as follows; Texture, Soil Organic Matter (OM), Organic Carbon (OC), Total nitrogen (TN), Total Phosphorus (TP) and pH, respectively.

2.6 Statistical analysis

Having the collection being in 3 replication the analysis of variance at performed, with collected data were analyzed for significant differences thus the Data are reported as average ± standard deviation. P value > 0.05

3. Result and Discussion

3.1 Concentration of Greenhouse Gas Production

From the collection and the analysis of the wastewater sludge gas samples, the result showed that the average concentration of carbon dioxide is measured from day 1 to day 30 (Figure 2). With the concentration of carbon dioxide at day 1 is 1109.91 ± 0.05 mg/kg and from day 1 to day 2 the concentration is high to 1289.53 ± 0.06 mg/kg. From Day 2 to 5, the concentration of carbon dioxide dropped to 685.81 ± 0.04 mg/kg. The concentration of is stabilized from Day 6 to 9 and rise again in Day 10 at 752.69 ± 0.12 mg/kg. The concentration rises to day 11, which is 786.58 ± 0.11 mg/kg and drops down at day 12 which is 545.8785 ± 0.09 mg/kg and rises again from Day 13 to 14 at 841.71 ± 0.05 mg/kg. From Day 14 to 18, the concentration significantly drops down, thus from Day 18 has the lowest concentration of carbon dioxide recorded at 379.82 ± 0.13 mg/kg. Starting from day 19 to 22, the concentration is slowly high from 430.67 ± 0.07 to 669.09 ± 0.13 mg/kg and then the concentration falls from Day 23 and 24 which is from 548.98 ± 0.1 to 472.80 ± 0.05 mg/kg. And the concentration rises again from Day 25 which is 614.0946 ± 0.07 mg/kg and stabilizes until the end of the research period (Day 30) which is

624.52 ± 0.16 mg/kg. In explaining for the volume and concentration carbon dioxide production it was seen that there was a greater volume and higher concentration during Days 1 to 6 as this was the result of the digestion process by bacteria (Pan *et al.,* 2025). In supporting the roles of the digestion process, it was also seen with the sludge samples that before the incubated in the lab, it was that the soil pH levels are ranged from 6.0 - 6.5 (slightly acidic), while the organic carbon, nitrogen and phosphorous are sufficient with the average concentration being that 8.10 ± 0.51, 6.97 ± 1.12 and 0.41 ± 0.09, respectively.

Describing that the initial increase in the CO_2 concentration as based suggested to be promoted by the acidogenesis process being promoted in using the carbon compounds with the sludge. Together, this was supported in the present of oxygen within the sludge samples by which the microorganisms used this oxygen to break down under the aerobic digestion and carbon dioxide is produced as an exchange gas after process (Wut *et al.,* 2024). After that, in the seal closed condition, the oxygen availability is limited as thus in the sludge and the bacterial digestion system is changed to the anaerobic digestion promoting the methanogenesis condition after day 6. (González *et al.,* 2018)

3.2 Concentration of Methane production

The average concentration of methane gas production is low compared to carbon dioxide production especially in day 1 to day 5. With the concentration of methane gas at day 1, 2 and 3 being at 15.22 ± 0.01mg/kg, 23.76 ± 0.03 mg/kg and 22.51 ± 0.08 mg/kg. From Day 4 to 5, the rate of concentration increases slightly from 33.03 ± 0.02mg/kg to 34.14 ± 0.04 mg/kg. On Day 6, the concentration decreases and is quite similar to the concentration of Day 3, which is 21.64 ± 0.01 mg/kg. From day 6 to 10, the rate of concentration increases rapidly to 75.39 ± 0.01 mg/kg which is the highest concentration of methane gas.

From days 11 to 13 the concentration significantly drops down from 69.97 ± 0.08 mg/kg to 20.42 ± 0.06 mg/kg., the concentration is slightly rising from 34.8193 ± 0.001 mg/kg to 43.7378 ± 0.001 mg/kg from day 14 to 15. On day 16, the concentration drops down and the rate is quite similar to that of day 3 and 6 which is 22.40 ± 0.09 mg/kg, while from day 17 to 19, the concentration further decreases from 42.74 ± 0.05 mg/kg to 28.95 ± 0.07 mg/kg and continues decreasing to Day 27 which has the lowest concentration of methane gas, 5.15 ± 0.01 mg/kg. On Day 28, the concentration increases slightly compared to day 27 which

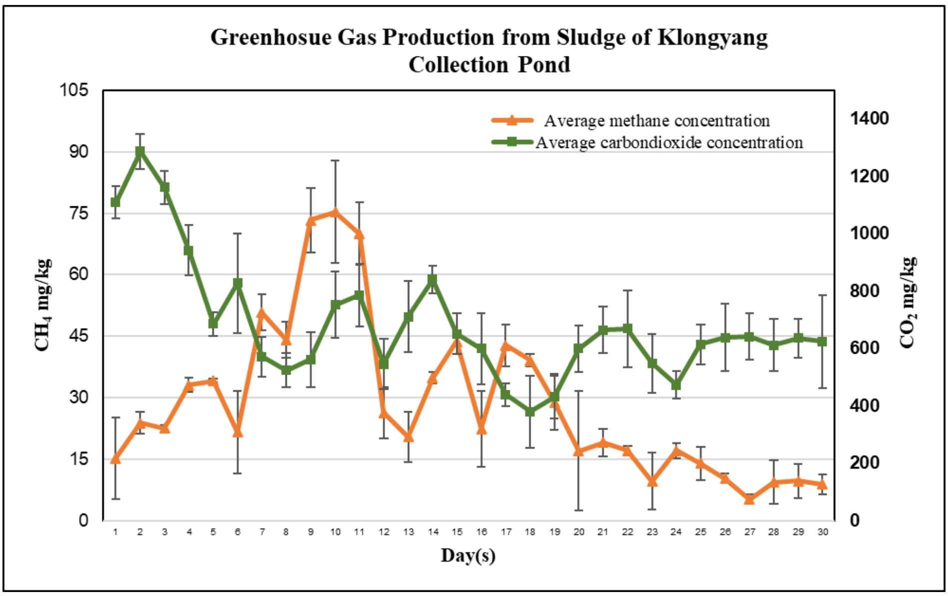

Figure 2. Concentration of carbon dioxide and methane gas production

is 9.36 ± 0.05 mg/kg. From Day 28 to 30, the rate of gas production remained unchanged and 9.36 ± 0.05, 9.62 ± 0.04, 8.80 ± 0.02 mg/kg respectively.

Having the sludge mainly contains three things: protein, carbohydrate and lipid (Supaporn, *et al.,* 2019). These materials are broken down by microorganisms by anaerobic digestion at hydrolysis stage. Hydrolysis is the first stage of anaerobic digestion and carbon dioxide is produced as an output gas and protein, carbon and lipid are break down into amino acid, glucose and fatty acid respectively (Christy *et al.,* 2014) .The next step is acidogenesis and in this stage the acidogenic bacteria change the remaining compound and methane gas emission has occurred (Ekwenna *et al.,* 2023). Finally, volatile fatty acid and alcohol gas such as acetate, hydrogen and carbon dioxide. There at this stage the methanogenesis process is seen at the 6th to the 15th day. Being the 12th day methane production at this stage is peak supported to the C:N ratio at the start being 100:88 suggesting for a sufficient amount of carbon and nitrogen sources.

However, passing the 12th day, it was seen that the methane gas concentration decrease as the production trend drops until reaching a constant until day 30. Where these trends are in parallel with the study of (Choudhury *et al.,* 2023) which the application of aquaculture sludge are used to determined their potential their greenhouse gas potential, where the methane production occurred on the 7th day and peaked at the 11th day before declining. This can be explained by the process of methane production (methanogenesis), where substrates such as acetate, CO_2, and hydrogen gas are utilized, while having tested for the ratio of carbon and nitrogen after the 30 days process it was seen that the C:N ratio was now 6.18:1 which is not suitable to continue anaerobic digestion process. it is too low, meaning there is excessive nitrogen relative to carbon (Geng *et al.,* 2023). This can lead to ammonia accumulation, which inhibits methanogenesis and disrupts the anaerobic digestion process, explain that there is excessive nitrogen relative to carbon. This can lead to ammonia accumulation, which inhibits methanogenesis and disrupts the anaerobic digestion process. While also changing the sludge condition going into a base (pH = 7.6) (Yang *et al.,* 2024; Finn *et al.,* 2023).

In this research, the temperature (Figure 3) of the sludge samples is measured and recorded with the incubation room being kept with the collection average temperature that would be in replication with the actual pond temperature at 30 °C (Tudsanaton *et al.,* 2024). The range of average temperature is between 32 ± 0.52 °C and 36 ± 0.55 °C during 30 days of experiment as show in Figure 4. Day 2 has the highest temperature which is 36 ± 0.55 °C and day 25 has the lowest temperature which is 31.7 ± 0. 8 °C. The temperature is highest range during the first week of research and fall at day 9 from 35.2 ± 0.4 °C to 33.8 ± 0.76 °C. From day 9 to day 22, the temperature ranged between 33 °C and 34 °C. From day 26 to day 27, the temperature is slightly increasing from 31.8 ± 0.89 to 32.9 ± 0.2 °C. And then, the temperature remains mostly constant to the end of the experiment. According to the results, the temperature is high during the first week of the experiment because digestion of sludge by aerobic method can generate heat which results in the sludge samples resulting in rising high temperatures as this is the result of hydrolysis (Pembroke & Ryan, 2019). Explaining that after hydrolysis, volatile fatty acids (VFAs) are formed, leading to methane generation. The methane production reaches its peak, followed by a decline (Al-Sulaimi *et al.,* 2022). During the preparation phase, methane accumulation begins, and after 16 days, the available carbon is largely depleted (Strazzera *et al.,* 2018; Vázquez-Fernández *et al.,* 2022).

In the calculation of the production of methane gas to the Klong Yang Collection it was seen that with the dimension of the pond and the average sludge depth, the 0.53 ± 0.12 meters it was that the estimated total methane and carbon Dioxide emission (considering the ambient gas condition that was taken from day 0) from the collection pond would be ranging from 26.24 ± 1.92 mg/kg for methane 84.32 ± 20.69 mg/kg for carbon dioxide while for the estimated total emission from the collection was around and 102,317.23 mg/day for methane and 31,840.67 mg/day.

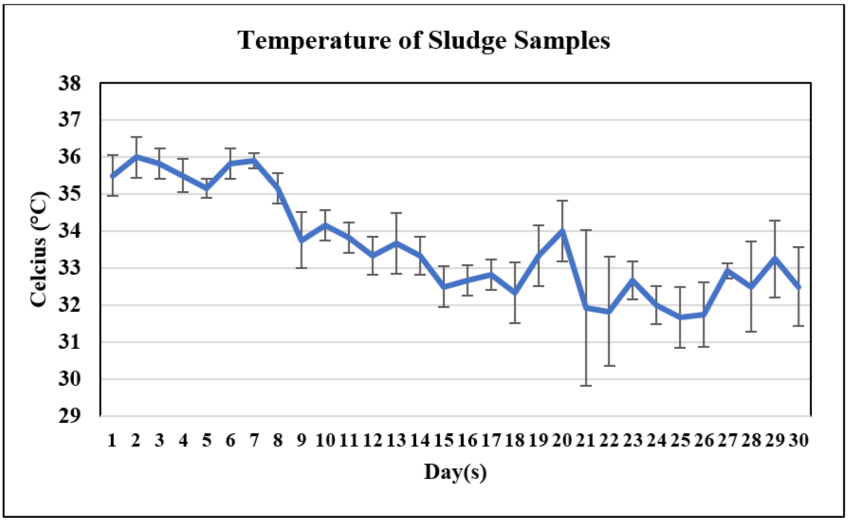

Figure 2. Concentration of carbon dioxide and methane gas production

Taken into account that this was the daily emission daily where the wastewater input daily from the municipality. In is also important that this estimation of the protentional greenhouse gas emission would be the recalculated from the collection pond, in which the estimate amount of greenhouse gas are then shown to have their direct emission, however, as this is taken directly from the collection pond, these sludges are found at the bottom of the pond in which there are cover with the wastewater in which the emission of the gas would be effected by the gas concentration and composition, thus that for further analysis, the accumulation of the greenhouse gases at different levels of the water column. While the application can also be associate with their uses for biogas (Jameel *et al.,* 2024).

4. Conclusion

This study assessed the greenhouse gas emission potential from wastewater sludge in the sedimentation pond of the Phetchaburi Municipal wastewater treatment system. The results indicated that carbon dioxide emissions peaked during the early days due to aerobic microbial digestion, followed by a transition to anaerobic conditions, which led to methane production through methanogenesis. Peak methane concentrations occurred between days 6 and 15, aligning with the methanogenesis phase, but declined afterward due to carbon depletion and a reduced C:N ratio of 6.18:1, which inhibited further anaerobic digestion. The findings of this study can be further explored by examining the vertical emission of these gases through the water column. Overall, this research provides valuable insights into wastewater sludge emissions in tropical municipal systems and supports efforts toward sustainable waste management and climate impact mitigation.

Acknowledgement

This work was funded and supported by the Graduate School, Kasetsart University, The King's Royally Initiated Laem Phak Bia Research and Development Project for financial requirements and the Department of Environmental Science, Faculty of Environment, Kasetsart University, Bangkok. The author also would like to acknowledge Faculty of Environment, Mahidol University, Nakhon Pathum for assistance with laboratory analysis.

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