Estimation of greenhouse gases from sewage from on-site sewage management system

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Abstract. Reducing greenhouse gases (GHGs) emissions plays an important role in preventing global warming and climate change. It is generally known that domestic wastewater management activities are significant contributors to the emissions due to its biological process that produces methane, nitrous oxide, and carbon dioxide. Various studies related to GHGs emissions from this sector have been conducted. However, only limited studies focused on the on-site sewage treatment. Since 72% of total existing wastewater treatment facilities in Indonesia are on-site systems, this study attempted to estimate GHGs emissions from each component in the system using the IPCC method. Depok City was chosen as the study case and the estimation was limited to on-site treatment tank, wastewater collection tank, and fecal sludge treatment system. Our study estimated that the total annual emissions from the on-site sewage system in Depok City were 232.45 Gg CO₂eq, consisted of 232.39 Gg CO₂eq of on-site emissions and 0.0662 Gg CO₂eq of off-site emissions. Among the system component, direct emissions from the on-site treatment such as septic tanks is the highest contributor to the total emission (70% followed by direct emission from fecal sludge treatment plant (19%). Through scenario evaluations, this study suggests that converting private septic tanks into the communal type is the most effective strategy in reducing total GHGs emissions from on-site wastewater treatment systems.

1. Introduction
Wastewater management sector plays an important role in preserving the water quality by removing pollutants and pathogens from wastewater [1]. However, sector is -classified as one of the significant sources of GHGs emissions which are the main factor causing global warming and climate change [2]. In Canada, the waste sector accounted for approximately 3.5% of total emissions (720, 000 Gg CO2eq), whereas in the USA, the use of energy in the water sector contributes to 5% of total energy consumption[2,3]. Consequently, increases in waste treatment capacity or treatment loadings can contribute to large amounts of GHG emissions released into the atmosphere [4]. In addition, among GHG emission sources, the wastewater management sector ranks fourth after the sector of land-use change, forest and peat fires, the energy sector, and the agricultural sector with an emission contribution of 6.7% [5]. During the operation and process, this sector emits various types of GHGs, including CO₂ from electrical consumption, CH₄ from sludge landfilling, and activities of microorganisms in anaerobic biological treatment units N₂O emissions from the nitrification and denitrification process of wastewater [6].

Indonesia's wastewater management system is generally an on-site system, where people mostly use septic tanks equipped with an infiltration area to treat blackwater from households locally. A Septic tank is a tank with a water-tight wall which functions to separate solids from the wastewater and degrade...
organic contaminant through anaerobic bacteria activity [7]. In several years (1-2 years), the accumulated fecal sludge at the bottom of the tank is sucked and transported to the fecal sludge treatment plant (FSTP). Based on oxygen availability during the process, treatment units in an FSTP could be divided into aerobic and anaerobic. Fecal sludge treatment under anaerobic conditions will produce CH4 whereas aerobic systems usually produce little to negligible CH4 whereas aerobic treatment usually emits CO2 and N2O due to the aerobic degradation of organic matter [5].

Various study in estimating GHGs from wastewater management sector has been reported. In various countries, it was estimated that the total emissions of GHG per m3 of treated wastewater were in the range of 0.9-2.4 Kg CO2eq/m3 [1][8][9][10][11]. Sludge treatment, biogas emission, and net power consumption in the wastewater management sector were the highest contributor to the total GHGs emission [10]. Unfortunately, studies on GHGs emissions from the wastewater management sector are still focused on a centralized wastewater management system whereas studies on GHG emissions from on-site systems are still extremely limited. Focus on the on-site system is also critical as this system dominates wastewater management in developing countries including Indonesia. Also, as Sustainable Development Goals (SDGs) programs target 100% proper sanitation by 2030, massive wastewater management infrastructures plan and development will be expected. Hence, it is necessary to estimate and project GHG emissions from each component of on-site wastewater management so that the components that cause the greatest emissions could be identified and technical recommendations to reduce GHG emissions and mitigate global warming climate change could be suggested.

2. Materials and methods

2.1. Study area
Depok City, West Java Province, was chosen as the study area in this study. The wastewater management sector could be divided into three components: 1) On-site treatment, 2) Collection system, and 3) Fecal sludge treatment.

2.1.1. On-site treatment. Based on Depok City Housing and Settlement Service data in 2018, the number of households owning septic tanks was 458,099 out of 545,066 households, or the equivalent of 84.04% [12].

2.1.2. Collection system. The collection system transport fecal sludge from on-site treatment to the fecal sludge treatment plant. In 2019, the number of trucks operating in FTSP Kalimulya is 12 with 11 large (6 tires) and 1 small truck (4 tires). The trucks collect the fecal sludge from factories, hospitals, hotels, restaurants, and residential areas.

2.1.3. Fecal sludge treatment. FSTP Kalimulya serves as the fecal sludge treatment facility in Depok City since 2015. It was designed to treat 280 m3/day of fecal sludge. The plant used anaerobic digester technology to decompose organic contaminants, belt press to reduce the water content in sludge, anaerobic-aerobic biofilter to process the resulting supernatant of belt press unit (Figure 1).

2.2. The System boundary
The calculation boundary of GHGs emissions is presented in Figure 2. In the on-site treatment component, the emissions are on-site (CH4 and N2O) and originating from the septic tank's biological process. In the collection system, the emissions are also on-site (CO2) due to the collecting trucks' fuel consumption. In the fecal sludge treatment, on-site emissions (CH4 and N2O) were originating from the biological process whereas off-site emissions (CO2) were due to electrical consumptions.
2.3. Calculation methods

In this study, the calculation of emissions used the method suggested by IPCC 2006 Guidelines for National Greenhouse Gas Inventories: Chapter 6 Wastewater Treatment and Discharge [5]. The more detailed calculation steps and equations are provided in the guidelines.

2.3.1. CH₄ Emissions. CH₄ emissions were calculated as described in Equation 1.

\[ CH_4 = (T.EF)(TOW - S) - R \]  

(1)

Where TOW is the total organics in wastewater in inventory year, kg BOD/year, S is the organic component removed as sludge in inventory year, kg BOD/year, EF is the emission factor of CH₄, kg CH₄/kg BOD, and R is the amount of CH₄ recovered in inventory year, kg CH₄/year.

2.3.2. N₂O Emissions. N₂O emissions were calculated as described in Equation 2.

\[ N_2O = N_{\text{effluent}} \times EF \times 44/28 \]  

(2)

Where \( N_{\text{effluent}} \) is the nitrogen loading in the effluent discharged to aquatic environments, kg N/year, EF is the emission factor for N₂O emissions from discharged to wastewater, kg N₂O-N/kg N, and the factor 44/28 is the conversion of kg N₂O-N into kg N₂O.
2.3.3. CO₂ Emissions. CO₂ emissions originating from electricity consumption were described in Equation 3.

\[ CO₂_{EL} = P \cdot EF_{EL} \] (3)

Where \( P \) is the electricity usage (Kwh) and \( EF_{EL} \) is the emission factor for electricity consumption (Kg CO₂/kwh). CO₂ emissions originating from fuel consumption of collecting trucks were described in Equation 4.

\[ CO₂_{FL} = V \cdot \rho \cdot NCV \cdot EF_{FL} \] (4)

Where \( V \) is the usage of fuel (liter), \( \rho \) is the specific weight of the fuel (g/l), \( NCV \) is the calorific value of the fuel (TJ/Gg of fuel), and \( EF_{EL} \) is the emission factor for the fuel consumption (Kg CO₂/TJ).

2.4. Input data

The wastewater sector's operational and process data was based on the records provided by the operator of FSTP, interviews, and the Depok Statistical Agency. The calculations were carried out on a monthly basis. Emission factors for Equation 1-2 were provided by IPCC guidelines whereas the emission factors for Equation 3-4 were provided from The Guidelines of GHG Emissions Inventory for Energy Sector published by The Ministry of Energy and Mineral Resource, Indonesia\cite{5}\cite{13}.

| No | Emission Factor Type | Value |
|----|----------------------|-------|
| 1  | CH₄ from Septic Tank (kg CH₄/kg BOD) | 0.3\cite{5} |
| 2  | CH₄ from Anaerobic Digester (kg CH₄/kg BOD) | 4.8\cite{5} |
| 3  | CH₄ from Aerobic-Anaerobic Biofilter (kg CH₄/kg BOD) | 0.06\cite{5} |
| 4  | N₂O from on-site treatment (kg N₂O/kg BOD) | 0.005\cite{5} |
| 5  | N₂O from fecal sludge treatment (kg N₂O/kg BOD) | 3.2\cite{5} |
| 6  | CO₂ from electricity consumption (kg CO₂/kwh) | 0.725\cite{13} |
| 7  | CO₂ from fuel consumption (kg CO₂/TJ) | 2.2\cite{13} |

2.5. Projection of GHGs emissions

In addition to GHGs emissions of the existing condition, the future emissions projection was also carried out. In this projection, we assumed that the emissions have a linear relationship with the population of Depok City without considering other factors such as economic growth, spatial planning of the city. The population growth of Depok City was assumed to be linear as described in Equation 5.

\[ P(t) = 78,451t - 155,981,356 \] (5)

Where \( P(t) \) is the population of Depok in year \( t \). The projection of GHGs emissions was carried out during 2017-2040.

3. Results and discussion

3.1. GHGs emissions

The calculation of GHG emissions from wastewater management in this study is divided into CH₄ emissions from on-site treatment and fecal sludge treatment, N₂O emissions, as well as CO₂ emissions as indirect emissions from the use of electricity and fuel consumption for fecal sludge collection. GHG emissions calculated include CH₄, N₂O and CO₂ converted to carbon dioxide equivalent (CO₂eq) by global warming potential (GWP) with values of 1 for CO₂, 25 for CH₄, and 298 for N₂O.
Figure 3 shows that the most dominant GHG emissions are CH$_4$ emissions, both from the on-site treatment (69%) and the fecal sludge treatment (24%). The total CH$_4$ emission in 2017 was 10.22 Gg CH$_4$ or 4.53 kg CH$_4$/ capita. Compared to DKI Jakarta in 2014 and Bandung City in 2016, which was 2.73 kg CH$_4$/capita and 4.41 kg CH$_4$/capita, respectively, the emission per capita in Depok was relatively large. This finding may be related to aerobic centralized wastewater treatment systems in DKI Jakarta and Bandung City which emit less GHGs. N$_2$O emissions resulting from the wastewater management sector were relatively small (1%, respectively). This is supported by studies that carried out direct measurements and found that the N$_2$O emissions resulting from wastewater treatment were insignificant.

### 3.2. Projection of GHGs emissions

The projection of GHGs emissions during 2017-2040 was based on three scenarios. The first scenario is business as usual which the only variable that changed is the population of Depok City. Since the dominant emissions were originating from CH$_4$, two intervention strategies were developed for both scenarios 2 and 3. In scenario 2, the largest CH$_4$ emitter is on-site wastewater treatment as suggested in the previous section. Thus, in this scenario, communal wastewater treatment facilities were built to replace the on-site treatment. In scenario 3, the emissions of CH$_4$ from fecal sludge treatment were found to be large. Hence, the methane recovery unit was installed to FSTP Kalimulya to reduce the emissions (Table 2).

The results from Scenario 1 estimated that the total GHG emissions increased from 232 Gg CO$_2$eq/year in 2017 to 788 Gg CO$_2$eq/year in 2040. The direct emissions of CH$_4$ dominated the total GHG emissions by, on average, 98.62%, then followed by N$_2$O emissions by 0.91%. The proportion of direct emissions resulting from data processing is similar to studies in Greece, Canada, and Malaysia which suggested that direct emissions of CH$_4$ are larger than indirect emissions [2][10][14]. It has to be noted, however, the three studies calculate indirect emissions only from electricity consumption for operations. Shahabadi [1], reported that about 62% of total emissions are indirect emissions. This is because the calculation of indirect emissions in the study included emissions from electricity consumption and also emissions from technology for the manufacture. Also, a study in China estimated that 71% of total emissions are indirect emissions, where emissions from sludge processing alone are 45% of indirect emissions [9].

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**Figure 3.** Contribution of each wastewater management component to the total GHGs emissions

**Table 2.** The setting of scenarios for projection of GHGs emissions

| Scenario 1 | Scenario 2 | Scenario 3 |
|------------|------------|------------|
| 2017: Ownership of septic tank | 2017: Communal WWTP | 2017: FSTP anaerobic digester only |
| 82.75% | 0.17% | 2019-2040: FSTP anaerobic digester+ methane recovery |
| 2040: Ownership of septic tank | 2040: Communal WWTP | |
| 100 % | 45.91% | |
Results of the projection for scenario 2 showed that GHG emissions increased rapidly until 2030. The emission was 231.63 Gg CO\textsubscript{2}eq in 2017 to 434.86 Gg CO\textsubscript{2}eq in 2030, or by 46.73%. However, from 2030 to 2040, the projected emissions increase at a slower rate, with an average rate of 3.13%, until it reached 448.90 Gg CO\textsubscript{2}eq in 2040. In general, the emissions resulting from scenario 2 increased by 48.4% during the 2017-2040 period. The lower rate of increase from 2030 to 2040 is due to a decrease in methane emissions based on the increased use of communal IPALs with methane recovery facilities.

Results of the projection for scenario 3 showed that GHG emissions were 232.45 Gg CO\textsubscript{2}eq in 2017, increased to 603.57 Gg CO\textsubscript{2}eq in 2040 (61.49%). A slight decrease was observed during 2018-2019 from 249.99 Gg CO\textsubscript{2}eq in 2018 to 247.82 Gg CO\textsubscript{2}eq in 2019 (0.87%). The total emission in the final year is 603.57 Gg CO\textsubscript{2}eq. In this scenario, methane recovery is carried out only in the anaerobic digester unit. However, in general, emissions from this second scenario have increased both in direct and indirect emissions. This is due to an increase in population and the use of septic tanks.

In general, scenario 1 in 2040 results in a total emission of 788.20 Gg CO\textsubscript{2}eq. Compared to this value, the intervention strategy in scenarios 2 and 3 has cut 43.05% and 23.42% of the total emission in scenario 1, respectively. This result indicated converting private septic tanks into the communal type is the most effective strategy in reducing total GHGs emissions from on-site wastewater treatment systems.

4. Conclusion
The study had performed estimation and projection of GHG emissions from on-site wastewater management system in Depok City. The results found that emissions of CH\textsubscript{4} due to biological processes in on-site treatment such as septic tanks or latrine were the highest among other components. The study also found that the emission per capita in Depok is larger than the cities that have a centralized wastewater management system. In addition, the orientation of wastewater treatment system capacity expansion is suggested to be the communal system as it significantly reduces the total projected GHG emissions.

Acknowledgments
This work was funded through the Grant PITTA B (contract number: NKB0755/UN2.R3.1/HKP. 05.00/2019) from the Directorate of Research and Community Service University of Indonesia.
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