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Development of Integrated Assessment Tool for Wastewater Treatment Plant Considering Classification by Carbon Origin

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To estimate greenhouse (GHG) gas emissions from wastewater treatment plants (WWTP), there is a need to model and evaluate the entire WWTP. Accordingly, a benchmarking tool that combines Activated Sludge Model (ASM), which describes biological treatment in a bioreactor, and Anaerobic Digestion Model (ADM), which describes anaerobic digestion in a digester, has been used. However, an elemental balance is required for consideration including sludge incineration and since carbon dioxide composed of biogenic carbon does not contribute to global warming, it is necessary to consider only fossil-derived carbon for a more reliable Life Cycle CO_2 ($LCCO_2$) assessment. Accordingly, firstly, an integrated assessment tool combining elemental balance including carbon, ASM, and ADM was developed. This makes it possible to carry out $LCCO_2$ assessments of GHG emissions from entire WWTPs. Second, the carbon origins of the entire WWTP were classified. Using previous studies, it is established a percentage of fossil-derived carbon per parametric component, which were defined and classified in ASM and ADM model and applied to the entire WWTP. The $LCCO_2$ assessment, which takes into account the origin of the carbon, shows that WWTP emits 8.71 % more GHGs compared to the result without considering the origin of the carbon. Through the integrated assessment tool presented in this study, a quantitative evaluation of GHG emissions from WWTPs can be expected and it is possible to get a closer look at the CO_2 emissions that contribute to global warming.

1. Introduction

Global warming due to the emission of greenhouse gas (GHG) has become an international problem. Japan also aims to build a decarbonized society with virtually zero carbon dioxide emissions by 2050, under its "Virtuous Circle of Environment and Economy". The wastewater treatment plant (WWTP) has not only direct GHG emissions but also indirect emissions due to energy consumption.

To estimate GHG emissions from WWTP, there is a need to model for the entire WWTP. Accordingly, a benchmarking tool that combines Activated Sludge Model (ASM) (Gujer et al., 1999), which describes biological treatment in a bioreactor, and Anaerobic Digestion Model (ADM) (Batstone et al., 2002), which describes anaerobic digestion in a digester, has been used and an elemental balance is required for consideration including sludge incineration.

Carbon entering the WWTP has traditionally been regarded as fully biogenic carbon, and CO_2 from this carbon has not been counted as GHG, but newer and revised guidelines from the Intergovernmental Panel on Climate Change (IPCC) recommend a more significant assessment of fossil carbon in WWTPs (IPCC, 2019).

According to Law et al. (2013), fossil carbon is introduced from the influent and is present throughout the WWTP. Some is emitted in the form of carbon dioxide from bioreactors, and according to Liu et al. (2021), some are also contained in digestion gas emitted by anaerobic digestion in digesters, and fossil carbon contained in dewatering sludge is incinerated in incinerators and directly emitted as incineration gas. However, these are experimental analyses of fossil carbon and do not examine the proportion of fossil carbon in each component of the treated water, such as dissolved organic matter and bacteria. And different literature analyzes total carbon (TC), total organic carbon (TOC), dissolved organic carbon (DOC), and particulate organic carbon (POC),

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making direct comparisons impossible. In order to more accurately measure GHG generation data, it is necessary to present the percentage of fossil carbon fuel for each component in the treated water and to understand the behavior of the component in each facility in the WWTP, such as anaerobic digestion in digesters and aerobic degradation in bioreactors.

In this study, an integrated assessment tool for WWTP was developed that integrates ASM, ADM, and elemental balance. It also calculated the origin of carbon in WWTP based on existing studies, with the origin set by element. The reliability of the integrated assessment tool was evaluated by comparing the calculated result with actual data. Finally, the $LCCO_2$ assessment using the developed tool was used to quantitatively compare the difference in GHG emissions with and without fossil fuel-derived carbon components.

2. Materials and methods

To identify and calculate GHGs generated by WWTPs, it is necessary to calculate not only the physical removal process of pollutants inside the WWTP but also the biological removal process by bacteria. To calculate the incineration gas generated in the sludge incinerator, it is necessary to calculate the heat balance and material balance to calculate the combustion process in the sludge incinerator.

2.1 Development of WWTP Integrated Assessment Tool (WIAT)

For bioreactors, the EAWAG Bio P model for phosphorus removal was adopted based on the ASM3 model proposed by IWA (Rieger et al., 2001). In the digester, the ADM1 model was adopted. Each model was calculated using the ode15s function in MATLAB™. For the sludge incinerator, elemental and heat balances were calculated in MS-Excel™.

Although the three models representing the bioreactor, digester, and incinerator are different in the parameters they handle, a method for combining them is needed to model the entire WWTP. Two methods are proposed for combining them (Takács and Vanrolleghem, 2006). The first is to create a supermodel that includes all the parameters from the submodels. The supermodel requires that all parameters be accounted for in the submodel and has the disadvantage of increasing the complexity of the model by adding parameters that are only used on one side, such as denitrifying bacteria. The second way is to create "model interfaces," which are ways of thinking about the connections between each model. A model interface sits between two different models and does not require changes to be made to each model. The continuity-Based Interface Model (CBIM) is a method of looking at parameters on an element-by-element basis, maintaining the connectivity of elements, charges, and CODs altogether (Volcke et al., 2006).

In this study, it is necessary to consider CO_2 emitted directly from the sludge incinerator, so multiple model interfaces must be considered. In addition, the elemental balance must be considered for the calculation of the carbon balance of the incinerator, but the calculation of the elemental balance is complicated in the supermodel. Thus, we decided to consider a combination method that describes all parameters in a sub-model like a supermodel but maintains elemental connectivity by identifying the elemental composition of each parameter like CBIM. As a result, the elemental composition of all models in the WWTP and parameters used in the solid-liquid separation process can be identified, and the elemental flow of the entire WWTP can be understood. To combine the EAWAG Bio P model with ADM1, the following four conditions were taken into account.

- Parameters handled by EAWAG Bio P and ADM1 will be used as they are, but convert the units to before and after the digester as needed.
- Parameters handled by EAWAG Bio P or ADM1 will be continued to use them in treated models, but ignore their biological behavior in untreated models. In this case, it is assumed that they do not participate in biological reactions and do not reproduce and self-destruction. However, calculations assuming a continuous reactor were performed.
- Similar components were integrated or separated before and after the digester.
- ADM1 calculates ionic equilibrium to calculate the inhibition of biological reactions and deals with parameters representing ionic components; however, their concentrations are too small to be handled by other models and are strongly affected by the solid-liquid separation process. In this study, the ionic component is only considered by ADM1 and not handled by other models.

2.2 Classification of Carbon by Origin

Biomass-derived carbon (BC) does not contribute to the greenhouse effect because its origin is atmospheric CO_2 produced by plants and absorbed by photosynthesis. Accordingly, to assess only fossil fuel-derived carbon (FC) emissions, it is necessary to track and categorize the origin of carbon.

First, we selected the parameters covered by WIAT that contain carbon and categorized them into soluble inorganic carbon, biodegradable soluble organic carbon, inert soluble organic carbon, degradable solid organic carbon, inert solid organic carbon, and bacteria. We also set the percentage of FC in each category. The classification and set values of each parameter are presented in Table 1. These ratios were based on several literature sources. First, because bacteria preferentially degrade BC over FC (Liu et al., 2021), we set the FC percentage of inert soluble organic carbon to be higher than the FC percentage of biodegradable soluble organic carbon. Additionally, Griffith's research showed that dissolved organic carbon has a higher FC ratio than solid organic carbon. (Griffith et al., 2009) Finally, the settings were fine-tuned to ensure that the calculated values were within the measured range based on the measurements taken in previous studies. The referenced measurements are presented in Table 2 below.

Table 1: Set the value of the FC ratio for each parameter

Parameter	Model Behavior	Classification	Set Value [%]
Dissolved methane	ADM1	Soluble inorganic carbon	0.4
Dissolved inorganic carbon	ADM1	Soluble inorganic carbon	0.4
Alkalinity	EAWAG Bio P	Soluble inorganic carbon	0.4
Dissolved active organic matter	Both	Biodegradable soluble organic carbon	0.05
Dissolved inert organic matter	Both	Inert soluble organic carbon	0.15
Solid organic matter	Both	Degradable solid organic carbon	0.1
Carbohydrate	ADM1	Degradable solid organic carbon	0.1
Protein	ADM1	Degradable solid organic carbon	0.1
Lipids	ADM1	Degradable solid organic carbon	0.1
Solid inert organic matter	Both	Inert solid organic carbon	0.07
Bacteria	Both	Bacteria	0.05

Table 2: Referenced measurement value of FC ratio (Sa: Primary Sedimentation, Sb: Final Sedimentation)

Reference	Unit	WWTP influent	Sa effluent	Sa sludge	Sb effluent
Griffith, 2009	DOC [%]			18.4	
	POC [%]			9.3	
Nara, 2010	DOC [%]	21.1			20
		13.9			
		7.9			
Law, 2013	TOC [%]	10.2	9.4	6	9.6
		14.3	13.2	1.8	17
		8.6			18.8
		4.2			8.8
		7			11.4
Tseng, 2016	TC [%]	2.1	5.4	0.5	21
		9	4	0.9	48.5
		7.6	15.6	5.2	20.7
		27.9			
		19.2			

3. Results and discussions

3.1 WIAT development results

The WIAT was developed by combining the EAWAG Bio P model of the bioreactor, the ADM1 model of the digester, and the elemental and heat balance model of the sludge incinerator. Using the WIAT, calculations were performed based on the 2019 average influent data of a specific WWTP (hereinafter referred to as WWTP A) located in Osaka, Japan. The calculations provided a mass flow of carbon, nitrogen, phosphorus, sulfur, and inorganic materials within the WWTP. The measurement data of influent and effluent was provided by WWTP A. As an example, a Sankey diagram of the carbon flow in WWTP A is shown in Figure 1.

WWTP A has an inflow of 28.3 t/d of carbon, expressed as 100 %C, and the effluent contains 19.7 %C carbon. The bioreactor off-gas contains 23.9 %C, the digestion gas contains 26.0 %C, and the incineration gas contains 32.9 %C.

The carbon flow chart shows two important points. The first is that we can see the elemental balance of the entire WWTP. The inputs to WWTP A are influent and auxiliary fuels, with an annual inflow of 29.5 t of carbon. The outputs are bioreactor off-gas, digestion gas, incineration gas, and effluent, with an annual outflow of 29.3 t of carbon. The error ratio of 0.800 % in the elemental balance can be evaluated as reasonable. The second is that it facilitates the classification of carbon by origin, which will be discussed later.

Also, to assess how valid the WIAT is in practice, we decided to evaluate its validity in the form of an error ratio compared to the calculated value using the average of the measured data of WWTP A in 2019. Total solids, fixed total solids, volatile total solids, dissolved solids, and suspended solids in the WWTP effluent, as well as ash from the sludge incinerator, moisture content of the sludge from the primary and final Sedimentation, and organic content of the sludge from the gravity thickening and centrifugal thickening, were considered. The error ratio is expressed in Eq(1) (A: Actual data, B: Calculation results).

$$\text{Error ratio (\%)} = \frac{|A-B|}{A} \times 100 \qquad (1)$$

The results of the feasibility evaluation are shown in Table 3. The validation showed that all error ratios were less than 10 %, with an average error ratio of 5.01 % for effluent. This suggests that the modeling is valid. Since the calculation assumes that incineration ash consists of minerals and phosphorus, the error ratio of 0.44 % for incineration ash indicates that the modeling of the solid-liquid separation process, which affects the removal of minerals, and the bioreactor, which is responsible for the removal of phosphorus, is highly reliable. The error ratio for the solid-liquid separation process also averaged 2.49 %. Consequently, WIAT is considered dependable.

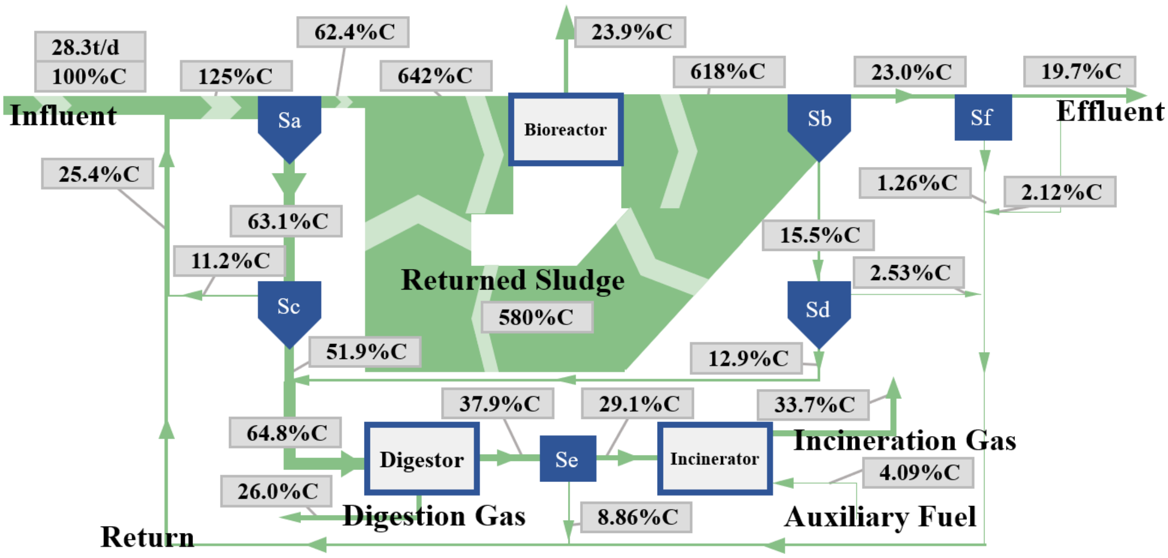

Figure 1: Sankey diagram of the carbon flow in WWTP A (Sa: Primary Sedimentation, Sb: Final Sedimentation, Sc: Gravity Thickening, Sd: Centrifugal Thickening, Se: Dewatering (Belt Press), Sf: Rapid Filtration)

Table 3: Result of feasibility evaluation

Effluent	Actual data [mg/L]	Calculation results [mg/L]	Error ratio [%]
Total Solids	285	271	4.64
Fixed Total Solids	225	208	7.44
Volatile Total Solids	59.2	62.8	6.06
Dissolved Solids	282	269	4.68
Suspended Solids	2.74	2.80	2.21
Incinerator	Actual data [t/d]	Calculation results [t/d]	Error ratio [%]
Ash discharge	4.46	4.44	0.443
Sludge moisture content	Actual data [wt%]	Calculation results [wt%]	Error ratio [%]
Primary sedimentation	99.4	98.8	0.609
Final sedimentation	99.7	99.5	0.209
Sludge organic content	Actual data [wt%]	Calculation results [wt%]	Error ratio [%]
Gravity thickening	88.0	84.4	4.14
Centrifugal thickening	87.6	83.2	5.02

3.2 Result of classification of carbon by origin

Since it is possible to calculate the parameters containing carbon flowing in the WWTP, it is possible to understand the flow of carbon in the WWTP as shown in Figure 1. After applying the FC ratio of carbon contained in each parameter as shown in Table 1, the FC ratio in the WWTP can be identified as shown in Table 4. It is observed that the FC ratio of the effluent is higher than that of the sludge in the solid-liquid separation process. This is because the FC ratio of dissolved organic carbon is higher than the FC ratio of solid organic carbon. Overall, the settings were consistent with Table 2, but the error rate of comparing the calculated values with the literature was calculated as high as 32.7 %. This is considered to be the result of differences in the influent water quality of the treatment plants targeted by each reference.

Table 4: Result of the value of FC ratio (Sa: Primary Sedimentation, Sb: Final Sedimentation)

Unit	WWTP influent	Sa effluent	Sa sludge	Sb effluent	Sb sludge
TC [%]	12.5	15.1	9.93	15.3	8.34
TOC [%]	9.98	11.2	9.35	14.6	8.27
DOC [%]	12.6	13.3	13.2	15.0	15.0
POC [%]	9.23	9.10	9.10	7.74	7.74
Unit	Returned Sludge	Bioreactor effluent	Digester influent	Digester effluent	Incinerator influent
TC [%]	8.34	8.59	9.27	8.99	7.62
TOC [%]	8.27	8.50	8.99	8.45	7.44
DOC [%]	15.0	15.0	13.5	14.8	14.8
POC [%]	7.74	7.74	8.82	6.89	6.89

3.3 $LCCO_2$ assessment

The $LCCO_2$ assessment was conducted by WIAT. In addition to direct emissions, indirect GHG emissions from the generation of electricity consumed, production of additives, and transportation were also considered. Figure 2 below shows the results of the $LCCO_2$ assessment.

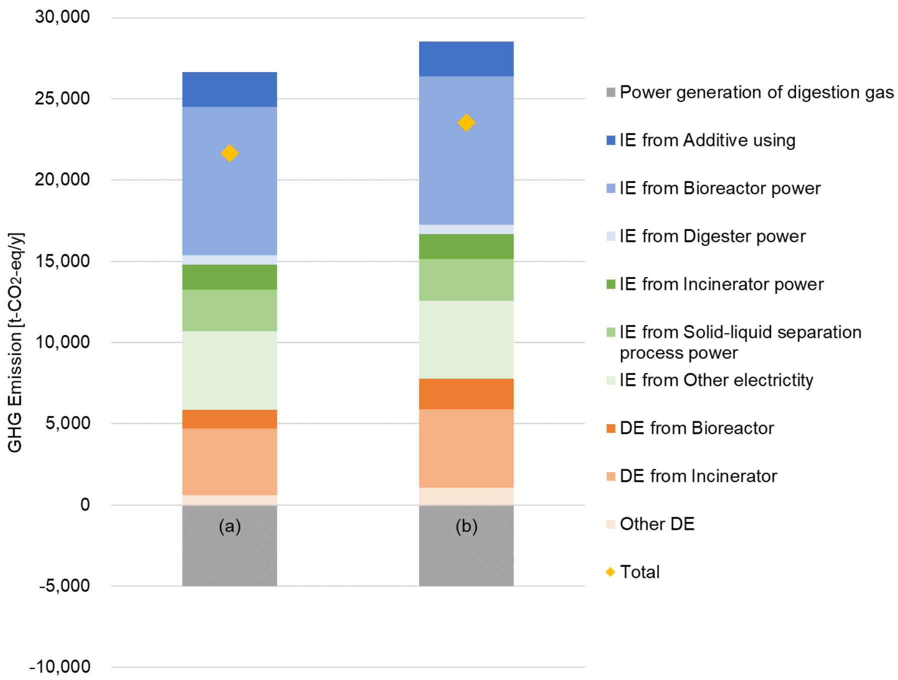

Figure 2: Result of $LCCO_2$ assessment of (a) without and (b) with the classification of carbon by origin. (IE: Indirect emissions, DE: Direct emissions)

(a) is the result of assuming that all the carbon in the WWTP influent is BC, and (b) is the result of applying the FC ratio and considering only FC in the directly emitted carbon. When the origin of the carbon is taken into account, it is calculated that 8.71 % more GHGs are emitted than otherwise. This is approximately 2,000 tCO_2-eq/y, which is equivalent to indirect emissions from using additives. If the origin of the carbon is not taken into account, about 700 tCO_2-eq/y in terms of incineration gas is excluded from the calculation. As shown in Figure 1, this is the result of not accounting for FC, which is 29.1 % of the carbon in the dewatered sludge compared to the influent. In terms of bioreactor off-gases, approximately 700 tCO_2-eq/y are also excluded from the calculation. This is the result of not accounting for the FC in the bioreactor off-gas, which is 23.9 % of the carbon in the influent.When calculating the GHGs indirectly emitted from the generation of electricity for consumption in this study, it is assumed that 0.496 kg-CO_2 of GHGs are emitted per kWh (Japan MoE, 2019). This figure is expected to decrease as renewable energy becomes more widespread. This means that all of the indirect emissions from electricity in Figure 2 will be reduced and shows that there is an underestimating if the carbon is not classified by origin.

4. Conclusions

By combining the EAWAG Bio P model of the bioreactors, the ADM1 model of the digesters, and the elemental balance and heat balance models of the incinerator, the WIAT was able to capture the overall flow of several elements, including carbon, in the WWTP. This allows them to identify the elemental balance, classify the carbon by origin for each element, and understand how the behavior of the carbon moves through the facility inside the WWTP. This allows us to present comparable simulation results for different carbons, including TC. The results of the WIAT calculations were compared to the actual measurements and found to be reliable, with all error ratios below 10 %.

The LCCO_2 assessment showed that 8.71 % more GHGs were emitted when the carbon source classification was taken into account than without. If the indirect emissions of GHGs from electricity production are reduced through the promotion of renewable energy, a larger error ratio will be expected.

This study only considered WWTPs equipped with digesters and incinerators, and in order for the tool to be more general, it should consider a wider range of facilities inside WWTPs. If future studies take these into account and WIAT is generalized, it will be possible to identify GHG emissions on a global scale.

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