Research on model-based calculation of greenhouse gas emissions from domestic wastewater treatment systems in Vietnam

Nghiên cứu tính toán phát thải khí nhà kính từ hệ thống xử lý nước thái sinh hoạt dựa trên mô hình tại Việt Nam

Research article

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There are three important greenhouse gases: carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O), which are generated from the domestic wastewater treatment systems, including on-site and off-site sources. On-site emission of greenhouse gases occurs during process of wastewater treatment, while the off-site emission of greenhouse gases occurs during energy using and other supporting activities of the treatment system. The research established model to calculate greenhouse gas emissions from the domestic wastewater treatment systems, was named No.0 MTH model. The No.0 MTH model was based on balance equations of substrate and biomass, biochemical reactions and Monod kinetics equations for biological treatment reactors and written by programing Scalable language. Model was calibrated and applied on the Yen So wastewater treatment plant, Ha Noi and the results were obtained at 22°C as follows: off-site GHG emission is 29,560 kgCO₂-eq/day; on-site GHG emission is 13,534 kgCO₂-eq/day, and the rate of on-site emission is 2.506 kgCO₂-eq/ kg BOD. Maybe using the No.0 MTH model to calculate greenhouse gas emissions from the domestic wastewater treatment systems with similar biological methods.

Có 3 khí nhà kính quan trọng là khí Cacbonic (CO₂), khí Méta (CH₄), và khí Dinito monoxit (N₂O) được phát sinh từ hệ thống xử lý nước thái sinh hoạt gồm cả nguồn trực tiếp và gián tiếp. Phát thải trực tiếp khí nhà kính (KHK) xảy ra trong suốt quá trình xử lý còn phát thải gián tiếp khí nhà kính xảy ra trong quá trình sử dụng năng lượng và các hoạt động phụ trợ bên ngoài hệ thống xử lý. Nghiên cứu đã thiết lập mô hình tính toán phát thải khí nhà kính từ hệ thống xử lý nước thái sinh hoạt, được đặt tên là mô hình MTH số 0. Mô hình MTH số 0 đã được trên các phương trình Cần bàng khí lượng cơ chất và sinh khối, các phân ứng hóa sinh và phản ứng Monod đối với các thiết bị xử lý sinh học và được viết trên ngôn ngữ lập trình scala. Mô hình đã được hiệu chỉnh và được áp dụng tính toán tại nhà máy xử lý nước thai sinh hoạt Yên Sở, thành phố Hà Nội và kết quả thu được tại 22°C như sau: phát thải KHK gián tiếp là 29,560 kgCO₂-eq/ngày và phát thải KHK trực tiếp là 13,534 kgCO₂-eq/ngày với tỷ lệ phát thải khí nhà kính trực tiếp là 2,506 kgCO₂-eq/kgBOD. Có thể sử dụng mô hình MTH số 0 để tính toán phát thải khí nhà kính từ hệ thống xử lý nước thái sinh hoạt bằng phương pháp sinh học tương tự.

Keywords: greenhouse gas, on-site and off-site emissions, domestic wastewater treatment plant

1. Introduction

Climate change has been more and more complicated and serious, so the decrease in greenhouse gases (GHGs) emission plays an important role. The emission of GHGs from wastewater treatment systems is the problem of interest and can be measured and assessed to determine the sustainability of treatment systems. There are three main GHGs: carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O), which are generated from the domestic wastewater treatment systems, including on-site and off-site sources.
The off-site GHGs emission includes electricity production; production and transportation of fuel and materials; landfill treatment of the generated solid waste sludge from the on-site processes. The major on-site sources of GHGs generation are aerobic and anaerobic bioreactors, anaerobic digester, biogas leakage, chemical coagulation/flocculation process, and biogas combustion in recovery boilers. The aim of research was to establish the No.0 MTH model to estimate the GHGs emission from wastewater treatment systems. The model was based on balance equations of substrate, biomass, biochemical reactions and Monod kinetics equations for biological treatment reactors; the hypothesis was that during wastewater treatment process, \( \text{C}_{10}\text{H}_{19}\text{NO}_3 \) and \( \text{C}_3\text{H}_7\text{NO}_2 \) were used to represent the substrate and the biomass, respectively. The model was solved by numerical method and then was coded. It was obvious that the model could be significantly useful for assessment of domestic wastewater treatment systems in Vietnam, in order to increase the efficiency of wastewater treatment systems for sustainable development and deal with climate change.

2. Materials and methods

2.1. Research objective

The Yen So domestic wastewater treatment plant, Ha Noi was used to calculate the greenhouse gases (GHGs) emission.

2.2. Theoretical basis for the development of No. 0 MTH model

2.2.1. Estimation of the off-site greenhouse gas emissions

The main off-site sources of greenhouse gas emission include electricity production for on-site use, production and transportation of fuel and materials. The overall off-site emission of greenhouse gases is obtained by addition of the produced gases by each source.

\[
P_{\text{CO}_2, \text{off-site}} = P_{\text{CO}_2, \text{electricity}} + P_{\text{CO}_2, \text{natural gas}} + P_{\text{CO}_2, \text{material}}
\]

(2-1)

\[
P_{\text{CO}_2, \text{electricity}} = \text{QE} \times \sum (PF_i \times EF_i)
\]

(2-2)

where:

\( P_{\text{CO}_2, \text{electricity}} \): The GHG production due to electricity demands of the plant (kgCO\(_2\)/day)

\( \text{QE} \): The quantity of electricity used for the operation of the entire plant (kwh/day)

\( PF_i \): Percentage contribution of fuel i to satisfy electricity generation needs of the wastewater treatment systems (%)

\( EF_i \): GHGs emission factor of fuel i in producing GHGs (kgCO\(_2\)/kwh) (Table 2)

\[
P_{\text{CO}_2, \text{natural gas}} = [Q_{\text{natural gas}} \times EF_{\text{natural gas,CO}_2/10^3}] + 25\times [Q_{\text{natural gas}} \times EF_{\text{natural gas,CH}_4/10^3}] + 296\times [Q_{\text{natural gas}} \times EF_{\text{natural gas,N}_2O/10^3}]
\]

(2-3)

where:

\( P_{\text{CO}_2, \text{natural gas}} \): The off-site GHGs production because of natural gas consumption for space heating in the plant (kgCO\(_2\)/day)

\( Q_{\text{natural gas}} \): The quantity of natural gas used for space heating in the plant (m\(^3\)/day)

\( EF_{\text{natural gas,CO}_2} \), \( EF_{\text{natural gas,CH}_4} \), \( EF_{\text{natural gas,N}_2O} \): the overall natural gas \( \text{CO}_2\), \( \text{CH}_4\), and \( \text{N}_2O \) emissions factors (g/m\(^3\)) (Table 2)

\[
P_{\text{CO}_2, \text{material}} = \sum Q_{\text{material}} \times EF_{\text{material}}
\]

(2-4)

where:

\( P_{\text{CO}_2, \text{material}} \): The off-site GHGs production because of material consumption in the plant (kgCO\(_2\)/day)

\( Q_{\text{material}} \): The quantity of material used in the plant (kg/day)

\( EF_{\text{material}} \): The emission factor of material i in the plant (kgCO\(_2\)/kg material) (Table 3)

+ The off-site greenhouse gas emissions factors are in the below tables:

Table 1. Emission factors for different methods of electricity production [1,2,4]

| Fuel types | Hydro | Nuclear | Coal | Other fuel | Bio-energy, wind, tidal |
|------------|-------|---------|------|------------|------------------------|
| EF\(_i\) (gCO\(_2\)-eq/kwh) | 10 | 9 | 877 | 604 | 11 |
| PF\(_i\) (%) | 48.78 | - | 23.07 | 27.72 | 0.43 |

Table 2. Emission factors from production and transportation of fuel (g/m\(^3\)) [3]

| EF\(_{\text{natural gas,CO}_2}\) | EF\(_{\text{natural gas,CH}_4}\) | EF\(_{\text{natural gas,N}_2O}\) |
|-----------------|-----------------|-----------------|
| 431.9 | 2.1 | 0.0000022 |

Table 3. Emission factors of materials (kgCO\(_2\)-eq/kg material) [2]

| Material types | Methanol | Alkalinity | FeCl\(_3\),6H\(_2\)O |
|----------------|----------|------------|---------------------|
| EF\(_{\text{material}}\) | 1.54 | 1.74 | 2.71 |

2.2.2. Estimation of the on-site greenhouse gases emissions

2.1. Calculation in the first boundary

The removal of BOD, suspended solid (SS) in the primary clarifier:

\[
\text{BOD}_{\text{removal,clarifier}} = \text{Pr clarifier, BOD} \times Q_{o,v} \times S_{o,v}
\]

(2-5)

\[
\text{SS}_{\text{removal,clarifier}} = \text{Pr clarifier, SS} \times Q_{o,v} \times S_{o,v}
\]

(2-6)

where:

\( \text{BOD}_{\text{removal,clarifier}} \); \( \text{SS}_{\text{removal,clarifier}} \): the amount of BOD and SS removal in the primary sedimentation tank, respectively (g/day)

\( \text{Pr clarifier, BOD} \); \( \text{Pr clarifier, SS} \): the percentage of BOD\(_s\) and SS removal in the primary sedimentation tank, respectively (%)

\( Q_{o,v} \): influent wastewater flow rate (m\(^3\)/day)
The total suspended solid (SS) in the system could be obtained as:

$X_{\text{SS}} = f_d k_d X_{\text{SS}} + \frac{X_{\text{SS}_{\text{in}}}}{\text{HRT}}$ (2-14)

$b. Calculation in the second boundary$

The balance equations for substrate and biomass concentrations in the aerobic bioreactor as follows:

$V \frac{dS}{dt} = Q_s S_r -(Q_s S_r + Q_s S_s) + r_s V$ (2-7)

$V \frac{dx}{dt} = Q_s X_r -(Q_s X_r + Q_s X_s) + r_x V$ (2-8)

$r_s = \frac{k_s X}{K_s + S}$ (2-9)

$r_x = -Y r_s - k_d X$ (2-10)

Where:

$V$: The volume of the aerobic bioreactor (m$^3$)

$\frac{dx}{dt}$, $\frac{dS}{dt}$: the change rate of biomass and substrate concentration with respect to time, respectively (g/m$^3$.day)

$X, S$: Substrate and biomass concentrations inside the aerobic bioreactor, respectively (mg/l)

$Q_s$ : Inflow wastewater rate, outflow wastewater rate and discharge of sludge flow in the aeration tank, respectively (m$^3$/day)

$X_{\text{SS}}$: The concentration of effluent biomass and substrate, respectively (mg/l)

$r_s$: Net rate of biomass production in the aeration tank (g/m$^3$.day)

$r_x$: Substrate utilization rate in the aeration tank (g/m$^3$.day)

In the steady-state condition, $\frac{dS}{dt} = 0$ and $\frac{dx}{dt} = 0$ and using

$\frac{1}{\text{SRT}} = \frac{y k_s}{K_s + S} - k_d$ and $\text{HTR} = \frac{V}{Q_s}$

The substrate and biomass concentrations inside the aerobic bioreactor are obtained as:

$S = \frac{K_s [1 + k_d \text{SRT}]}{\text{SRT} (y k - k_d) - 1}$ (2-11)

$X = \left( \frac{\text{SRT}}{\text{HTR}} \right) \left( \frac{y (S_r - S)}{1 + k_d \text{SRT}} \right)$ (2-12)

The total suspended solid (SS) in the system could be obtained as:

$X_{\text{Total,SS}} = X + X_{\text{SS}} + X_{\text{nit}}$ (2-13)

$c. Calculation in the third boundary$

The total amount of CO$_2$ and CH$_4$ production in the anaerobic digester could be calculated as follows:

$\text{CO}_2_{\text{digester}} = Y_{\text{CO}_2 \text{decay}} \cdot \text{VSS}_{\text{decay}}$ (2-28)

$\text{CH}_4_{\text{digester}} = Y_{\text{CH}_4 \text{decay}} \cdot \text{VSS}_{\text{decay}}$ (2-28)

$d. Establishing of emission factors of greenhouse gases in wastewater treatment system$

In domestic wastewater, $C_{10}$H$_{17}$NO$_3$ and C$_2$H$_4$NO$_2$ were used to represent the substrate and the biomass, respectively. The chemical reactions in aerobic bioreactor: reactions of biomass decay, nitrification and denitrification as well as the anaerobic decays are as follows:

$0.02C_{10}H_{17}NO_3 + 0.01NH_4^+ + 0.01HCO_3^- + 0.1O_2$ → $0.03C_2H_4NO_2 + 0.11H_2O + 0.06CO_2$

$0.05C_2H_4O_2N + 0.25O_2$ → $0.2CO_2 + 0.05NH_3^+$ + $0.05HCO_3^- + 0.05H_2O$

$0.02C_2H_4O_2 + 0.1H_2O$ → $0.118CH_4 + 0.052CO_2$

$0.0025C_2H_4O_2N + 0.01175NH_3^+ + 0.0175HCO_3^-$

$0.1275NH_3^+ + 0.24O_2 + 0.01CO_2 + 0.0025HCO_3^-$ → $0.0025C_2H_4O_2N + 0.125NO_3^- + 0.25H^+ + 0.1225H_2O$
From the result of reactions, the coefficients of GHG emission are established as follows:

**Table 4: The coefficients of GHG emissions**

| Parameter | Unit | Value |
|-----------|------|-------|
| \( Y^{\text{CO2}} \) | gCO2/gBOD | 0.33 |
| \( Y^{\text{VSS}} \) | gVSS/gBOD | 0.422 |
| \( r^{\text{O2}} \) | gO2/gBOD | 0.4 |

Endogenous decay in aerobic process

| Parameter | Unit | Value |
|-----------|------|-------|
| \( Y^{\text{CO2,decay}} \) | gCO2/gVSS | 1.56 |
| \( r^{\text{O2,decay}} \) | gO2/gVSS | 1.42 |

Anaerobic process

| Parameter | Unit | Value |
|-----------|------|-------|
| \( Y^{\text{CO2,an}} \) | gCO2/gBOD | 0.28 |
| \( Y^{\text{CH4,an}} \) | gCH4/gBOD | 0.235 |
| \( Y^{\text{VSS,an}} \) | gVSS/gBOD | 0.035 |

Endogenous decay in aerobic process

| Parameter | Unit | Value |
|-----------|------|-------|
| \( Y^{\text{CO2,decay,an}} \) | gCO2/gVSS | 0.58 |
| \( Y^{\text{CH4,decay,an}} \) | gCH4/gVSS | 0.35 |

Nitrification process

| Parameter | Unit | Value |
|-----------|------|-------|
| \( Y^{\text{VSS,init}} \) | gVSS/gN | 0.55 |
| \( Y^{\text{NO3,init}} \) | gN-NO3/gN | 0.98 |
| \( r^{\text{O2,init}} \) | gO2/gN | 4.32 |
| \( r^{\text{CO2,init}} \) | gCO2/gN | 0.247 |

Denitrification process

| Parameter | Unit | Value |
|-----------|------|-------|
| \( Y^{\text{VSS,dnt}} \) | gVSS/gN-NO3 | 0.175 |
| \( Y^{\text{CO2,dnt}} \) | gCO2/gN-NO3 | 2.767 |
| \( r^{\text{BOD,dnt}} \) | gBOD/gN-NO3 | 2.059 |
| \( r^{\text{methanol,dnt}} \) | gCH3OH/gN-NO3 | 1.9 |

Anaerobic decay

| Parameter | Unit | Value |
|-----------|------|-------|
| \( Y^{\text{CO2,dr}} \) | gCO2/gBOD | 0.28 |
| \( Y^{\text{CH4,dr}} \) | gCH4/gBOD | 0.23 |
| \( Y^{\text{VSS,dr}} \) | gVSS/gBOD | 0.042 |

Biomass decay

| Parameter | Unit | Value |
|-----------|------|-------|
| \( Y^{\text{CO2,decay}} \) | gCO2/gVSS | 0.58 |
| \( Y^{\text{CH4,decay}} \) | gCH4/gVSS | 0.35 |

3. Results and discussions

3.1. Operational process of No. 0 MTH model

The No.0 MTH model was written by programing Scalsable language. Input parameters of the model are: the quantity of electricity used, the quantity of material used, the quantity of material used and treatment capacity, BOD, TSS, TN, temperature of tanks, hydraulic retention time (HRT), sludge retention time (SRT), etc. Through the processes of calculating in the model will be obtained output results, which are off-site and on-site greenhouse gas emissions from the domestic wastewater treatment system. The model operating procedures are described in Table 5 and Figure 2 below:

**Table 5. Operational process of No. 0 MTH model**

| Description | Operational process of No. 0 MTH Model |
|-------------|--------------------------------------|
| Inputs      | - The off-site greenhouse gases emissions: +The quantity of electricity used +The quantity of natural gas used +The quantity of material used - The on-site greenhouse gases emissions: +Treatment capacity; BOD, TSS, TN +Temperature of tanks +Hydraulic retention time (HRT) +Sludge retention time (SRT) +Underflow rate |
| Calculation process | Equations for calculation of the off-site greenhouse gases emissions Equations for calculation of the on-site greenhouse gases emissions |
| Outputs | Emission results of the off-site greenhouse gases Emission results of the on-site greenhouse gases Total emission results of the greenhouse gases |

![Figure 2. Flowchart of calculating greenhouse gas emissions from domestic wastewater treatment systems by No.0 MTH model](image-url)
treatment in HaNoi, with a treatment capacity of 120,000 m$^3$/day. Input parameters of the Yen So Plant and the results of calculation of greenhouse gas emissions indirectly were shown in table 6 and table 7. Through the No.0 MTH model simulated off-site greenhouse gas emissions from Yen So domestic wastewater treatment plants in Hanoi was 29,560.70 kgCO$_2$-eq / day.

Table 6. Inputs of the Yen So domestic wastewater treatment plant, Ha Noi

| Parameter                          | Unit  | Value         |
|------------------------------------|-------|---------------|
| Treatment capacity of plant        | m$^3$/day | 120,000      |
| The quantity of electricity used   | Kwh/day | 26,400        |
| The quantity of natural gas used   | m$^3$/day | -            |
| The quantity of material used      |       | -            |
| + Alkalinity                       | Kg/day | 1,800         |
| + PAC                              | Kg/day | 6,000         |
| + Polimer                          | Kg/day | 180          |

Table 7. Outputs of the off-site greenhouse gases emission of the Yen So wastewater treatment plant, Ha Noi

| Result                              | Unit       | Estimation value |
|-------------------------------------|------------|-----------------|
| $P_{CO_2, \text{electricity}}$     | kgCO$_2$-eq /day | 9,891.50       |
| $P_{CO_2, \text{natural gas}}$     | kgCO$_2$-eq /day | -              |
| $P_{CO_2, \text{material}}$        | kgCO$_2$-eq /day | 19,669.20      |
| $P_{CO_2, \text{off-site}}$        | kgCO$_2$-eq /day | 29,560.70      |
| $P_{CO_2, \text{off-site}}$        | ton CO$_2$-eq /year | 10,789.60      |

3.2.2. Estimation of the on-site greenhouse gases emission

The Yen So, Ha Noi Plant treated domestic wastewater treatment by aerobic biological methods, combined with nitrogen removal and decomposition of biological sludge using anaerobic methods. Table 8 showed the kinetic parameters in during aerobic treatment, Nitrification and denitrification processes and anaerobic sludge. Table 9 showed the input parameters of the plant. Using No.0 MTH model calculated on-site greenhouse gas emissions from the factory Yen, Hanoi was 13,534.32 kgCO$_2$-eq / day and Emission factor was 2.506 kgCO$_2$-eq/kg BOD and shown in Table 10.

Table 8. Kinetic parameters of the domestic wastewater treatment processes

a. Aerobic process

| Parameter | Unit      | Value at 20°C ($K_b$) | Value at 22°C $K_T$ (*) |
|-----------|-----------|-----------------------|-------------------------|
| $\mu_m$   | 1/day     | 4                     | 4.58                    |
| $Y$       | mg/mg     | 0.50                  | 0.60                    |
| $k = \mu_m/Y$ | 8          | 8                     | 7.63                    |

b. Nitrification and denitrification processes

| Parameter | Unit      | Value at 20°C | Value at 22°C $K_T$ (*) |
|-----------|-----------|---------------|-------------------------|
| $\mu_{m,nit}$ | 1/day | 0.7 |
| $Y_{nit}$ | mg/mg | 0.12 | 0.16 |
| $k = \mu_{m,nit}/Y_{nit}$ | 7.50 | 5.58 |
| $K_N$ | mg/l | 0.5 | 0.87 |
| $k_{d,nit}$ | 1/day | 0.08 | 0.04 |
| $K_{DO}$ | 1.3 | 1.3 |

Table 9. Input parameters of the Yen So wastewater treatment plant, Ha Noi

| Parameter       | Unit      | Value            |
|-----------------|-----------|-----------------|
| $Q_{in}$        | m$^3$/day | 120,000         |
| $S_{in}$        | mg/l      | 45              |
| $TKN_{in}$      | mg/l      | 34              |
| $TSS$           | mg/l      | 51              |
| $P_{NH_3}$      | %         | 30              |
| $P_{NO_2}$      | %         | 40              |
| $Q_{in}$        | m$^3$/day | -               |
| Temperature     | °C        | 22              |
| Aerobic reactor | SRT       | 5               |
| HRT             | hour      | 5               |
| $Q_{w}/Q_{in}$  | 0.2       |                 |
| Anaerobic       | Temperature | °C | 30 |
| digester        | SRT       | day             |

Table 10. Output parameters of the on-site greenhouse gases emission of the Yen So wastewater treatment plant, Ha Noi

| Result             | Unit      | Estimation value |
|--------------------|-----------|-----------------|
| Aerobic reactor    | kg/day    | 8,539.09        |
| CO$_2$ for aerobic reactor | kg/day | 4,830.72        |
| Anaerobic digester | kg/day    |                 |
| Parameter                              | Unit          | Value       |
|---------------------------------------|---------------|-------------|
| CO$_2$ anaerobic digester             | kg/ day       | 17.29       |
| CO$_2$ equivalent                     | kg/day        | 147.22      |
| Total on-site GHGs emission           | kg/day        | 13,534.32   |
| Total on-site GHGs emission           | tons/day      | 4,490.03    |
| Emission factor                       | kgCO$_2$-eq/kgBOD | 2.506      |

4. Conclusions

In this research, the No.0 MTH model was applied for estimating the greenhouse gas emission from domestic wastewater treatment systems. The model was written by programing Scalable language and model formulations were based on equations of substrate and biomass, biochemical reactions and Monod kinetics equations for biological treatment reactors.

The No.0 MTH model was applied in calculating the greenhouse gas emissions of Yen So domestic wastewater treatment plant in HaNoi. Calculation results showed that amount of off-site greenhouse gas emissions 2 times higher than the amount of on-site greenhouse gas emissions and on-site greenhouse gas emission factor as 2.506 kgCO$_2$-eq / kgBOD.

The No.0 MTH model can be applied to calculate the greenhouse gas emissions from domestic wastewater treatment systems with similar treatment method.

With variation of input parameters in the model, through the processes of calculating the model, will simulate the results of greenhouse gas emissions from domestic wastewater treatment systems. From these results, the operational and technological parameters could be chosen to reduce the greenhouse gas emission from these domestic wastewater treatment systems.

5. References

[1] Annual report of EVN, 2012 – 2013
[2] Bani Shahabadi M., Yerushalmi L., Haghighat F. (2009) Impact of process design on greenhouse gas (GHG) generation by wastewater treatment plants. Water Research 43:2679-2687
[3] Rashad S.M., Hammad F.H. (2000) Nuclear power and the environment: Comparative assessment of environmental and health impacts of electricity-generating systems, The 7th International Energy Conference (ENERGEX ’98), November 19, 1998 - November 21, 1998, Elsevier Ltd, Isa Town, Bahrain. pp. 211-229.
[4] The 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC,2006).
[5] The report reviews the management of urban wastewater in Vietnam, World Bank, 2013.
[6] Urban sewage treatment, Tran Duc Ha, 2006