Greenhouse gas emission reduction and carbon credit revenue in a waste leachate treatment plant

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Abstract. As the largest emitter, China faces great challenges of controlling greenhouse gas (GHG) emissions, including those from wastewater treatment plant. In recent years, however, emission trading is becoming an attractive approach to help the plant owners implement cleaner treatment technologies to reduce their GHG emissions. Among these, the advanced anaerobic process such as up-flow anaerobic sludge semi-fixed filter (UASSF) is competent in high strength wastewater treatment, and renders much more carbon credits than other conventional anaerobic systems. This paper presents a study on emission reduction based on the UASSF system in a waste leachate treatment plant (WLTP). The calculation results show that the total GHG emission reductions can achieve 16217.9 metric tons of carbon dioxide equivalents (tCO2e) per year. Owing to the emission trading and energy recovery, the running cost of the project is reduced from 4.12 to 1.69 € per ton leachate. Also, the good social and ecological benefits can be achieved due to the significant reductions of anthropogenic emission.

1. Introduction

Human activities produce greenhouse gases (GHGs), affecting the atmosphere composition and increasing the global average temperature [1]. Carbon dioxide (CO2) in GHG accounts for the largest proportion, methane (CH4) is less than CO2 but more than N2O. GHG emissions from wastewater, which is regarded as a kind of anthropogenic sources of GHG [2,3], are equal to about 0.18% of total emissions from the globe [4]. In Israel, for instance, emissions from wastewater treatment could make up 1% of the State overall GHG emissions [5]. CH4 is a main GHG from wastewater treatment and mostly produced by methanogens in anaerobic conditions [6], while N2O is an intermediate product between nitrification and denitrification and generated through the advanced wastewater treatment process [7,8]. The lifespan of CH4 in the atmosphere is only 9-15 years, which is shorter than that of CO2 (50-200 years), so the reductions in CH4 emissions could slow short-term climate change. What’s more, CH4 has a 23-fold global warming potential (GWP) compared to CO2; when combusted (for heat or electricity generation), each molecule of CH4 is converted to one molecule of CO2, reducing the global warming effect by 96%. Therefore, the capture of CH4 contributes to GHG emission reductions and energy recovery, which can be accomplished by using advanced anaerobic technology during wastewater treatment [9-13].

Anaerobic technology has been employed in wastewater treatment for scores of years, and the CH4
produced from anaerobic treatment is playing a more and more important role in the energy market [14]. In terms of sustainability, cost-effectiveness and energy production, anaerobic technology is much better than many other treatment methods. Anaerobic granular-sludge systems, which are designed to maximize biomass retention and CH$_4$ yield, seem to be the most promising, especially for high strength wastewater treatment, such as waste leachate. In a clean development mechanism (CDM) program of wastewater treatment, CH$_4$ can be effectively reduced and translated into carbon credits by using this advanced anaerobic technology. To improve treatment efficiency and claim carbon credits, conventional aerobic and low-rate anaerobic system can be updated to anaerobic granular-sludge ones. An example analysis based on project activity of an anaerobic granular-sludge system for waste leachate treatment is introduced in the paper. The GHG emission reduction and carbon credit are calculated according to the guidelines proposed by the Intergovernmental Panel on Climate Change (IPCC).

2. **Project activity**
With a treatment capacity of 300 m$^3$/d, the Luodai waste leachate treatment plant (WLTP) is located in Chengdu, China. The original treatment system includes the utilization of deep open anaerobic lagoons and aerobic shallow ponds where CH$_4$ is released directly to the atmosphere (figure 1). The influent leachate is pumped from a municipal solid waste incineration power plant with a treatment capacity of 1200 m$^3$/d. After the anaerobic effluent is further treated by the aerobic ponds, it discharges into the waterways.

![Figure 1](image)

**Figure 1.** The original treatment system and CDM project.

The municipal solid waste which is transported to the waste incineration power plant will be kept for at most seven days before incineration, so the leachate produced is a kind of young one with higher concentration of COD, BOD/COD and volatile fatty acids (VFA). Table 1 gives the details.

**Table 1.** Characteristics of the influent leachate.

| Parameter | Unit | Mean  | Maximum | Minimum |
|-----------|------|-------|---------|---------|
| pH        |      | 5.1   | 5.7     | 4.2     |
| COD       | mg/L | 68,000| 75,000  | 60,000  |
| BOD       | mg/L | 35,000| 45,000  | 25,000  |
| BOD/COD   |      | 0.52  | 0.60    | 0.43    |
| VFA       | mg/L | 11,050| 12,600  | 8,500   |
| SS        | mg/L | 4,200 | 6,000   | 2,500   |
| NH$_4^{+}$-N | mg/L | 900  | 1,300   | 780     |
| TN        | mg/L | 11,600| 14,500  | 9,300   |
| TP        | mg/L | 140   | 173     | 122     |
Schematic diagrams of baseline scenario (original treatment system) and CDM project scenario are shown in figure 1. The project activity includes the replacement of the original system with an up-flow anaerobic sludge semi-fixed filter (UASSF) and a membrane bioreactor (MBR). The biogas generated in the UASSF will be collected and utilized to substitute the fossil fuels used in electricity generation. After the primary treatment, the effluent from the UASSF will be pumped to MBR system for polishing treatment.

The UASSF reactor is cylindrical in shape whose internal diameter and overall height are 12.8 m and 15.5 m, respectively (figure 2). An up-flow velocity is kept in the reactor by using effluent recirculation pumps. The soft polyurethane belts (0.5 mm×4 cm×5 m) are suspended perpendicularly in UASSF as carrier. The upper end of the belts is fixed to a metal net and the lower end is attached to a counterbalance weight, so the semi-fixed carriers can move with the up-flow water to avoid biomass washout and clogging. In addition to a place in which microbes attach and grow, the belts are similar to a three-phase separator. The gas-carried biomass, after crashing onto the carrier, is likely to fall back down to the sludge bed, while the gas releases to the top of the reactor for biogas collection. According to the study, the COD removal of the UASSF is measured to be 80%, and the CH$_4$ generation rate is estimated to be 0.23 kgCH$_4$/kgCOD. The closed UASSF system can achieve complete recovery of biogas produced, in which the CH$_4$ content is more than 65%.

As shown in table 2, biogas from UASSF has different compositions, but in general it is mainly constituted by CH$_4$ and CO$_2$. The main sulfur compound present in biogas is H$_2$S, and other compounds in traces such as hydrocarbons, organic and inorganic acids and NH$_3$ are also contained in biogas. H$_2$S can affect gas specification for power plants and has a bad effect on the membrane bioreactor. Meanwhile, water in biogas can causes gas engine and turbine corrosion. In order to avoid damage to heat and power engines, the biogas are treated by using wet desulphurization tower and

### Table 2. Main components of biogas.

| Parameter | Unit   | Mean |
|-----------|--------|------|
| CH$_4$    | vol %  | 65   |
| CO$_2$    | vol%   | 28   |
| H$_2$S    | mg/m$^3$ | 45   |
| N$_2$     | vol%   | 4.2  |
| Dew point | ℃      | 12   |

Figure 2. Schematic diagram of UASSF.
drop catcher for H₂S and H₂O removal respectively.

The MBR system consists of the anoxic tank, nitrification tank and ultrafiltration (UF) units. Denitrification takes place in an anoxic tank followed by the nitrification tank, and receives the flow of influent and the recycled thickened sludge from UF system (figure 3). Aerators and jet pumps are equipped in nitrification tank for aeration, and the anoxic tank is furnished with a set of submerged stirrers which can be used in an emergency. N₂O generation mainly occurs during the biological nitrogen removal via nitrification and denitrification processes as both autotrophic and heterotrophic bacteria can be responsible for N₂O production. Factors affecting the efficiency of nitrification and denitrification are the major causes for N₂O emissions.

![Figure 3. Schematic diagram of MBR.](image)

Based on the combined treatment processes of UASSF and MBR, the CDM project will contribute to GHG emission reduction by recovering CH₄ gas, as well as using it to displace fossil fuels for power generation.

3. Emission calculation

In this paper, GHG emissions from leachate treatment are calculated based on the IPCC guidelines for national greenhouse gas inventories [15] and approved United Nations framework convention on climate change (UNFCCC) methodology AM0013 [16].

3.1. Baseline emissions

Baseline emissions include the CH₄ emissions from the open lagoons, the CO₂ emissions related to grid electricity generation displaced by this project and the N₂O emissions connected with the discharge of the aerobic lagoon systems.

3.1.1. CH₄ emissions from open lagoons. The baseline emissions from the lagoon system are calculated according to the COD of leachate, the maximum CH₄-producing capacity (B₀) and a CH₄ conversion factor (MCF). According to the IPCC Guidelines, the lagoon baseline emissions are calculated as follows:

\[
COD_{\text{inf}} \text{ (kg/yr)} = COD_{\text{raw}} \times \text{Capacity} \times \text{Time} \tag{1}
\]

\[
CH_{\text{demis}} \text{ (kg/yr)} = COD_{\text{inf}} \times B_0 \times MCF \tag{2}
\]

\[
E_{\text{CH₄/CO₂}} \text{ (tCO₂e/yr)} = CH_{\text{demis}} \times GWP_{\text{CH₄}} \tag{3}
\]

where \(COD_{\text{inf}}\) represents the yearly influent COD of anaerobic lagoons without the project activity, and \(CH_{\text{demis}}\) refers to the CH₄ emissions from the open lagoons. As demonstrated in equation (3), the baseline CH₄ emission is converted into CO₂ equivalent emission \(E_{\text{CH₄/CO₂}}\) by multiplying by its GWP of 0.023. More details of other parameters are shown in table 3.
Table 3. Parameters used in the calculations.

| Parameter          | Unit  | Value   | Definition                                         | Reference |
|--------------------|-------|---------|---------------------------------------------------|-----------|
| COD<sub>raw</sub>  | kg/m³ | 68      | COD concentration of raw leachate                 | Measurement |
| Capacity           | m³/d  | 300     | Leachate treatment capacity                       | Measurement |
| Time               | d/yr  | 365     | Operation time                                    | Assumption |
| B<sub>0</sub>      | kgCH₄/kgCOD | 0.21 (Anaerobic lagoon) | Maximum CH₄ producing capacity | [15] |
|                    |       | 0.23 (UASSF) |                                                | Measurement |
| MCF                | kgCH₄/kgCH₄ | 0.50 (Anaerobic lagoon) | CH₄ correction factor (fraction) | [15] |
|                    |       | 1.00 (UASSF) |                                                | [15] |
|                    |       | 0.80 (MBR) |                                                | [15] |
| GWP<sub>CH₄</sub>  | tCO₂/kgCH₄ | 0.023 | Global warming potential of CH₄ | [17] |
| R<sub>COD</sub>    | %     | 80      | COD removal rate of anaerobic system              | Measurement |
| CV<sub>CH₄</sub>   | TJ/kg | 5.5×10⁻⁵ | Calorific value of CH₄                          | [18] |
| η<sub>CH₄</sub>    | %     | 80      | Thermal efficiency of CH₄ combustion             | Assumption |
| CEF                | tCO₂/TJ<sub>oil</sub> | 77.37 | CO₂ emission factor of the fossil fuel | [15] |
| TN<sub>el</sub>    | kg/m³ | 0.82 (Aerobic lagoon) | Total nitrogen (TN) concentration of effluent | Measurement |
|                    |       | 0.15 (MBR) |                                                | Measurement |
| E<sub>F</sub>      | kgN₂O-N/kgN | 0.0531 | Percentage of TN transformed to N₂O emission from leachate treatment | [8] |

Notes: kg-Kilogram; m³-Cubic meter; d-Day; yr-Year; t-Metric ton; TJ-Trillion Joule; %-Percentage.

COD<sub>raw</sub> is directly checked by the project as the baseline activity level since the leachate that goes into the anaerobic lagoon in the baseline situation is the same as the one that goes into the UASSF in the project situation. The default IPCC value for B<sub>0</sub> is 0.25 kgCH₄/kgCOD, but a conservative value of 0.21 kgCH₄/kgCOD is used in this project due to the uncertainty of estimate. The IPCC guidelines do not give a single default factor for MCF, but provide some system MCF values. Considering the lagoon depth and the temperature, the MCF value is estimated as 0.50 in this project. The calculation results are listed in table 4.

Table 4. The results of emission calculation.

| Item                  | Emission source                                      | Emissions (tCO₂e/yr) |
|-----------------------|------------------------------------------------------|----------------------|
| Baseline emissions    | CH₄ from anaerobic lagoon                           | 17,982.1             |
|                       | CO₂ from electricity                                 | 4,740.4              |
|                       | N₂O from lagoon discharge                           | 208.8                |
| Project emissions     | CH₄ from MBR system                                  | 5,754.3              |
|                       | CH₄ from stack emission                              | 630.2                |
|                       | N₂O from MBR discharge                               | 38.2                 |
|                       | N₂O from MBR system                                  | 290.7                |
| Emission reduction    | Baseline emissions – Project emissions               | 16217.9              |

3.1.2. Electricity baseline emissions. The electricity baseline emissions are the CO₂ emissions linked to grid electricity generation which is substituted by this project. The emissions are estimated based on
CEF and $Q_{\text{CH}_4}$, and calculated by using the following equations.

\[
CH_{\text{UASSF}} (\text{kg/yr}) = (\text{COD}_{\text{inf}} \times R_{\text{COD}}) \times B_0 \times MCF
\]  
\[
Q_{\text{CH}_4} (\text{TJ/yr}) = CH_{\text{UASSF}} \times CV_{\text{CH}_4} \times \eta_{\text{CH}_4}
\]  
\[
E_{\text{CO}_2\text{CO}_2} (\text{tCO}_2/\text{yr}) = Q_{\text{CH}_4} \times CEF
\]

where $CH_{\text{UASSF}}$ is the CH$_4$ captured by UASSF, $Q_{\text{CH}_4}$ is the thermal energy that can be produced by $CH_{\text{UASSF}}$ in the project, which is equal to the energy that would be generated using fossil fuel before the project implementation. Correspondingly, $E_{\text{CO}_2\text{CO}_2}$ is CO$_2$ equivalent emission of fossil fuel without the project activity. Additionally, the $B_0$ of 0.23kgCH$_4$/kgCOD is used according to the results of measurement on site.

3.1.3. $N_2O$ emissions from aerobic lagoons discharge. $N_2O$ involves direct and indirect emissions. The former generates in treatment plants, and the latter originates from effluent after discharging into waterways, lakes or seas. Direct $N_2O$ emissions should be negligible if the treatment plants have no advanced wastewater treatment systems with nitrification and denitrification processes. Therefore, only indirect $N_2O$ emissions need to be calculated in the original systems, which can be achieved through following methods.

\[
N_{\text{ef}} (\text{kg/yr}) = TN_{\text{ef}} \times \text{Capacity} \times \text{Time}
\]  
\[
N_2O_{\text{emis}} (\text{kg/yr}) = N_{\text{ef}} \times EF_{\text{ef}} \times F_{N2O-N/N2O}
\]  
\[
E_{\text{N2OCO}_2} (\text{tCO}_2/\text{yr}) = N_2O_{\text{emis}} \times \text{GWP}_{N2O}
\]

where $N_{\text{ef}}$ is the nitrogen in the effluent discharged to aquatic environments per year, $N_2O_{\text{emis}}$ is the yearly $N_2O$ emissions, and $E_{\text{N2OCO}_2}$ refers to the CO$_2$ equivalent emission of $N_2O$, which is translated from $N_2O_{\text{emis}}$ by multiplying by its GWP of 0.296 tCO$_2$/kgN$_2O$.

This emission factor of $EF_{\text{ef}}$ is based on specific assumptions that all nitrogen is discharged with the effluent into river and that $N_2O$ production in rivers and estuaries is directly related to nitrification and denitrification. The default IPCC value for $EF_{\text{ef}}$ is in a wide range, considering the situation of the original system, a conservative value of 0.005kgN$_2O$-N/kgN is adopted.

3.2. Project emissions

Project emissions mainly include: (i) CH$_4$ emissions from the MBR system and stack release in the power generation system, (ii) $N_2O$ emissions from MBR system as well as its effluent. Other emissions, such as those associated with heat and electricity use for nitrification, pumping and auxiliary equipment, the physical leakage of the UASSF and the emissions linked with sludge treatment are assumed to be ignored.

3.2.1. CH$_4$ emissions from MBR system. After anaerobic treatment, the effluent from the UASSF will flow into the MBR system before its discharge to the waterways. The tanks of MBR system are expected to operate under anoxic and oxic conditions for denitrification and nitrification, respectively [19]. The IPCC default $MCF$ value for oxic systems is 0, so the CH$_4$ emissions from nitrification tanks are assumed to be negligible. However, owing to the uncertainty concerning the exact extent of anoxic/oxic degradation after project is carried out, the calculation of these CH$_4$ emissions is conservatively applied with the same method as for the baseline. Therefore, the CH$_4$ emissions can be calculated using equations (10) and (3).

\[
CH_{\text{emis}} (\text{kg/yr}) = COD_{\text{inf}} \times (1-R_{\text{COD}}) \times B_0 \times MCF
\]  

where the values of $B_0$ and $MCF$ are 0.21 kgCH$_4$/kgCOD and 0.8, respectively. As mentioned above, $COD_{\text{inf}}$ is the influent COD of anaerobic lagoon or UASSF system, so the expression $COD_{\text{inf}} \times (1-R_{\text{COD}})$ represents the influent COD of MBR system.
3.2.2. Stack emissions from energy generation. CH₄ may be released due to the incomplete combustion in flare or energy generation systems. However, flaring option is only an alternative during the major overhaul of the energy generation system, so the emissions from the flare system can be ignored. The stack emissions from energy generation are calculated using equation (11).

\[ E_{\text{CH4CO2}} (\text{tCO}_2\text{e/yr}) = CH_{4\text{ASSF}} \times LR_{\text{CH4}} \times GWP_{\text{CH4}} \] (11)

3.2.3. N₂O emissions from MBR discharge. The indirect N₂O emissions from MBR discharge are calculated based on equations (7), (8) and (9), which is similar to the methods used to estimate the N₂O emission from aerobic lagoons effluent. Also, the same value for \( EF_{\text{ef}} \) (0.005 kgN₂O-N/kgN) is used in these calculations. However, the effluent TN concentration of MBR system (0.15 kg/m³) is much lower than that of the aerobic lagoon (0.82 kg/m³) owing to the high separation efficiency of the membrane process. As a result, N₂O emissions from MBR discharge are only 38.2 tCO₂e/yr, which is less than 1% of total emission reductions and will be ignored if necessary [16].

3.2.4. N₂O emissions from MBR system. As an intermediate product of biological nitrification and denitrification, N₂O may increase to a high level because of inadequate organic matter for complete denitrification [8]. So the direct emissions of N₂O can occur during the leachate treatment processes with nitrification and denitrification steps, such as MBR process. These emissions are estimated using the equations (12), (13) and (9).

\[ N_{\text{inf}} (\text{kg/yr}) = TN_{\text{inf}} \times \text{Capacity} \times \text{Time} \] (12)

\[ N_{2O_{\text{emiss}}} (\text{kg/yr}) = N_{\text{inf}} \times P_{\text{TN2NO}} \times F_{\text{N2O-NN2O}} \] (13)

where \( N_{\text{inf}} \) and \( N_{2O_{\text{emiss}}} \) are the influent TN of MBR system and the direct N₂O emissions, respectively. The nondeterminacy in N₂O emission estimation is usually high, because \( P_{\text{TN2NO}} \) is based on the field test [15]. According to the results of some Chinese WLTPs with similar treatment processes to this project, a conservative value for \( P_{\text{TN2NO}} \) (0.0531%) is adopted [8].

Typically, the direct emissions of N₂O are smaller than those from effluent (indirect emissions). As for this project, however, the N₂O emissions from the plant site are calculated to be 290.7 tCO₂e/yr, which is much more than those from indirect emissions. In this case, these direct emissions should be considered as a minor source and included in project emissions.

4. Emission reductions and potential benefits

**Table 5.** Economic analysis of the project activity.

| Item                        | Value          |
|-----------------------------|----------------|
| Total investment cost       | 2,257,000 €    |
| Payback period              | 5 years        |
| Sales income of electricity | 1.13 € per ton leachate |
| Sales income of CERs        | 1.30 € per ton leachate |
| Running cost a)             | 4.12 € per ton leachate |
| Running cost b)             | 2.99 € per ton leachate |
| Running cost c)             | 1.69 € per ton leachate |
| Electricity consumption     | 2.49 € per ton leachate |

Notes: a) sales income of electricity and CERs are not included; b) sales income of CERs is not included; c) sales income of electricity and CERs are included.

Considering adjustments for leakage, emission reductions are the difference between baseline and project emissions, which is calculated to be 16,217.9 tCO₂e/yr (table 4). According to the current European Climate Exchange Carbon (www.theice.com/emissions.) trading value of 8.8 €/tCO₂e, the
total certified emission reductions (CERs) claimed arising from the project is 142,718 €/yr. In addition, electricity generated from the project activity is estimated to be 1,912,500 kWh/yr, corresponding to the sales income of 123,332 €/yr by subtracting the cost of biogas treatment. The economic analysis of the project is listed in table 5.

The results of calculations indicate that the application of anaerobic granular-sludge systems can bring substantial direct economic benefits to waste leachate treatment. These benefits resulting from electricity and CERs amount to 266,050 €/yr, which can help finance the additional cost of the environmentally advanced technologies. Even without emission trading, the running cost of the project can be reduced from 4.12 to 2.99 € per ton leachate due to the energy recovery. With carbon credits benefits, the running cost is further reduced to 1.69 € per ton leachate, which is lower than that of most WLTPs in China. Therefore, the CDM project is more economical than other alternatives lack of the benefits from the CERs and electricity. And most importantly, the project activity can reduce the anthropogenic emissions from leachate treatment significantly, which may result in good social and ecological benefits.

5. Conclusions
In addition to energy recovery, carbon credits can be obtained by using advanced anaerobic technologies in wastewater treatment. The UASSF system in the CDM project is capable of treating high strength wastewater, and renders much more carbon credits than other conventional anaerobic ones. The total emission reduction arising from the project is calculated to be 16,217.9 tCO₂/yr, which can achieve profits and finance the project. As a result, the running cost of the project is reduced significantly. Looking into the future of carbon trading, it is practical to foresee that wastewater treatment will be faced with a shift towards application of advanced anaerobic technologies in maximizing energy recovery and GHG emission reductions.

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