Reductions in greenhouse gas (GHG) generation and energy consumption in wastewater treatment plants
L. Yerushalmi, O. Ashrafi and F. Haghighat

ABSTRACT

Greenhouse gas (GHG) emission and energy consumption by on-site and off-site sources were estimated in two different wastewater treatment plants that used physical-chemical or biological processes for the removal of contaminants, and an anaerobic digester for sludge treatment. Physical-chemical treatment processes were used in the treatment plant of a locomotive repair factory that processed wastewater at 842 kg chemical oxygen demand per day. Approximately 80% of the total GHG emission was related to fossil fuel consumption for energy production. The emission of GHG was reduced by 14.5% with the recovery of biogas that was generated in the anaerobic digester and its further use as an energy source, replacing fossil fuels. The examined biological treatment system used three alternative process designs for the treatment of effluents from pulp and paper mills that processed wastewater at 2,000 kg biochemical oxygen demand per day. The three designs used aerobic, anaerobic, or hybrid aerobic/anaerobic biological processes for the removal of carbonaceous contaminants, and nitrification/denitrification processes for nitrogen removal. Without the recovery and use of biogas, the aerobic, anaerobic, and hybrid treatment systems generated 3,346, 6,554 and 7,056 kg CO2-equivalent/day, respectively, while the generated GHG was reduced to 3,152, 6,051, and 6,541 kg CO2-equivalent/day with biogas recovery. The recovery and use of biogas was shown to satisfy and exceed the energy needs of the three examined treatment plants. The reduction of operating temperature of the anaerobic digester and anaerobic reactor by 10 °C reduced energy demands of the treatment plants by 35.1, 70.6 and 62.9% in the three examined treatment systems, respectively.

Key words | biogas recovery, energy consumption, GHG emission, pulp and paper wastewater treatment plants

NOMENCLATURE

BOD  Biochemical oxygen demand
BOD_{Re}  BOD removal (%)
HRT  Hydraulic retention time (day)
\( k_{\text{max}} \)  Maximum utilization rate (kg BOD/(kg VSS·day))
\( k_d \)  Decay rate (kg/(kg·day))
\( K_s \)  Half-saturation constant (kg/m³)
S  BOD concentration (kg/m³)
SRT  Solid retention time (day)
\( S_{\text{in}} \)  Influent BOD concentration (kg/m³)
VSS  Volatile suspended solids (kg/day)
X  Biomass concentration (kg/m³)
Y  Yield coefficient (kg/kg)

INTRODUCTION

Waste management and, in particular, wastewater treatment plants (WWTPs) are among the industrial sources of greenhouse gas (GHG) emission. These industrial operations use biological and physical-chemical processes for the removal of contaminants and produce the three primary GHGs, i.e. carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O) during the treatment operation and energy generation processes. The emission of GHG in WWTPs are associated with both on-site and off-site sources, as reported previously (Bani Shahabadi et al. 2009). The on-site sources of GHG emission include liquid and solid treatment processes as well as the combustion of fossil fuels and biogas for energy generation. The off-site
sources include the production and transportation of electricity, fuel and chemicals for on-site use, as well as solid waste transportation and disposal (landfill, composting) and degradation of remaining constituents in liquid effluent.

Industrial WWTPs have considerably higher emissions of GHG compared to municipal treatment plants due to the higher strength of industrial wastewaters in terms of the concentration of organic carbonaceous contaminants and suspended solids (El-Fadel & Massoud 2001; Pickin et al. 2002). Considering the off-site emissions, the total GHG emissions from WWTPs may increase by more than 50%. The pulp and paper industry produces approximately 20–100 m³ wastewater per ton of air-dried pulp in Canada (World Bank 1999). The treatment plants of this industry commonly use activated sludge processes or aerated lagoons (Mahmood & Paice 2006). Pulp and paper mills usually deal with the low level of nutrients (nitrogen and phosphorous) in the influent (Pokhrel & Viraraghavan 2004) by adding nutrients, especially nitrogen, to increase microbial growth and activities. However, if the residual nitrogen is not removed from the effluent of the treatment plant, it may pose a significant threat to the environment. Nitrogen removal can be accomplished by nitrification/denitrification processes, producing N₂ as the predominant final gas and a small amount of N₂O during various stages of these processes (Barton & Atwater 2002). Although the Intergovernmental Panel on Climate Change (IPCC) states that N₂O emissions from WWTPs are negligible, the study of Kampschreur et al. (2009) on a laboratory-scale WWTP showed that N₂O emission has a significant impact on GHG generation of biological process.

The estimation of generated GHGs by the treatment plants requires the identification of the major sources of GHG emission. This information will also serve in the recommendation of an alternative design and operation method to reduce the generation of GHGs. GHG emission and energy consumption by on-site and off-site sources in two WWTPs that use different treatment processes have been estimated. The first plant used physical-chemical processes for the treatment of wastewater from a locomotive repair factory, while the second plant treated wastewaters of the pulp and paper industry by biological processes. The impact of alternative design and operation strategies of treatment plants on GHG generation, energy consumption and energy efficiency is presented.

**MATERIALS AND METHODS**

**Design of treatment plants**

The WWTP of the locomotive repair factory used physical-chemical processes including equalization and neutralization, sedimentation and oil separation, coagulation and flocculation, and filtration to remove the organic contaminants and suspended solids, and disinfection to disinfect the effluent before discharge into the receiving waters. The treatment plant of the pulp and paper industry used biological processes for the removal of contaminants, as presented in Figure 1. Both plants contained an anaerobic digester to treat the generated sludge. Although many existing pulp and paper WWTPs do not use anaerobic digestion processes, the addition of anaerobic digesters to municipal and industrial WWTPs is increasing due to their contribution to the reduction of total solids, which have to be incinerated or landfilled, as well as the potential for the generation of electricity, as a ‘green energy’ resource to reduce the use of coal or oil. The estimation of GHG generation and energy consumption in WWTPs of the pulp and paper industry considered three alternative plant designs using biological

aerobic, anaerobic, and hybrid processes. The hybrid process used an anaerobic reactor followed by an aerobic reactor for additional contaminant removal and effluent polishing. All examined treatment plants used coagulation/flocculation processes as tertiary treatment for the removal of residual biochemical oxygen demand (BOD), color and suspended solids. The estimation of GHG emission and energy consumption considered the removal of organic carbon and suspended solids, and nitrogenous contaminants by nitrification/denitrification processes.

Operating conditions

The average influent wastewater flow rate to the treatment plant of the locomotive repair factory was 3,200 m$^3$/day based on 252 working days per year. Pulp and paper mills generate various types of wastewaters by mechanical, chemical, and thermo-mechanical processes. Kraft mills contribute to 46% of the pulping effluents in Canada. The biological plant for the treatment of pulp and paper wastewater operated with an influent flow rate of 1,000 m$^3$/day. The operating temperatures of the aerobic and anaerobic reactors were 25 and 30 °C, respectively. The characteristics of the influent wastewater for both treatment plants are presented in Table 1.

On-site and off-site sources of GHG generation

The pertinent on-site and off-site sources of GHG generation were identified in an effort to facilitate the estimation, modelling and simulation procedure. The on-site sources of GHG production include the treatment processes for the removal of contaminants, and the combustion of natural gas for energy generation. These sources include bioreactors, anaerobic digester, biogas leakage, chemical coagulation/flocculation process unit, nitrogen removal processes and biogas combustion in recovery boilers. Off-site sources include electricity production for on-site use, fuel and material production and transportation, and landfilling of solid wastes. The major GHGs generated in the examined treatment systems are CO$_2$, CH$_4$ and N$_2$O.

Estimation of GHG generation

The estimation of GHG emission in the WWTP of the locomotive repair factory was reported previously (Wei et al., 2008). The GHG emissions associated with chemical usage, electricity generation and energy consumption were estimated from the emission factors of the chemicals used during the treatment process and corresponding emission factors of the electricity generation sources and fossil fuels, respectively. The GHG emission associated with the anaerobic digestion process was estimated by considering the generation of methane (CH$_4$) along with carbon dioxide (CO$_2$). The anaerobic digester was used for the digestion of solids separated by the sedimentation and flocculation processes. The GHGs generated due to the landfilling of the solid waste consisted only of CH$_4$, which was estimated from its global warming potential.

The estimation of GHG emission by the WWTP that used biological processes was based on the mathematical models developed from kinetic relationships and mass and energy balances around pertinent processes and activities of the treatment plants. Equations (1) and (2) were used to calculate substrate and biomass concentrations in the biological processes, leading to the estimation of CO$_2$ and CH$_4$ generation in bioreactors (Equations (3)–(6)). The calculation of GHG generation in this plant was based on the wastewater BOD values, which provide a better estimation of the amount of biodegradable material compared to the COD content of wastewater. The BOD content of wastewater BOD values, which provide a better estimation of the amount of biodegradable material compared to the COD content of wastewater. The BOD content of wastewater was readily available from the pulp and paper mills examined in this study.

$$S = \frac{K_d(1 + k_dSRT)}{SRT(Y_{K_{max} - K_d}) - 1} \quad (1)$$

$$X = \frac{SRT(Y_{S_m - S})}{HRT(1 + k_S SRT)} \quad (2)$$

$$CO_2_{,BOD\text{removal}} = Y_{CO_2} \times BOD_{Re} \quad (3)$$

$$CO_2_{,\text{decay}} = Y_{CH_4, \text{decay}} \times VSS_{\text{decay}} \quad (4)$$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Locomotive repair factory</th>
<th>Pulp and paper mill</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical oxygen demand (COD) (mg/L)</td>
<td>263</td>
<td>4,100</td>
</tr>
<tr>
<td>BOD (mg/L)</td>
<td>-</td>
<td>2,000</td>
</tr>
<tr>
<td>Suspended solid (SS) (mg/L)</td>
<td>327</td>
<td>3,600</td>
</tr>
<tr>
<td>Oil (mg/L)</td>
<td>156</td>
<td>-</td>
</tr>
<tr>
<td>Alkalinity (mg CaCO$_3$/L)</td>
<td>-</td>
<td>150</td>
</tr>
<tr>
<td>Nitrogen content (mg/L)</td>
<td>-</td>
<td>110</td>
</tr>
</tbody>
</table>
\[
CH_4, BOD_{\text{removal}} = Y_{CH_4} \times BOD_{\text{Re}}
\]  

\[
CH_4, \text{decay} = Y_{CH_4, \text{decay}} \times VSS_{\text{decay}}
\]

Equations (5) and (6) were developed for the anaerobic bioreactors. GHG emission in the anaerobic digester was estimated using the same procedure. The magnitude of \(N_2O\) emission from these processes was considered to be 0.5% of the influent wastewater nitrogen content, according to the IPCC (Kampschreur et al. 2009). The efficiency of the coagulation/floculation process was considered to be 80% using \(\text{FeCl}_3\) as the coagulant. Alkalinity, ferric chloride and methanol were transported to the WWTPs. The GHG emission from production and transportation of materials was estimated by using the emission factor of 1.74 gCO\(_2\)-equivalent/g alkalinity, 2.71 gCO\(_2\)-equivalent/g ferric chloride, and 1.54 gCO\(_2\)-equivalent/g methanol (Bani Shahabadi et al. 2009). Approximately 85% of the produced solids were assumed to be biodegradable. GHG emissions from electricity requirements of the treatment plants were calculated using the electricity requirements of different activities of WWTPs as well as the emission factor of individual electricity generation sources (Rashad & Hammad 2000). GHG emission in landfills was estimated by using the amount of residual sludge from the anaerobic digester. The emission factors for processing and production of fossil fuels were used to estimate the GHG emissions related to the fuel consumption.

**RESULTS AND DISCUSSION**

The treatment plant of the locomotive repair factory produced removal efficiencies of 97.8% oil, 82.9% COD, and 92.1% suspended solids (Wei et al. 2008). In the biological treatment plant of the pulp and paper mill, the BOD removal efficiencies were estimated to be 99, 87, and 99% for the three plants using aerobic, anaerobic, and hybrid processes, respectively. The overall GHG emission by the WWTP of the locomotive repair factory was 1,443.3 kg CO\(_2\)-equivalent/day without the recovery of biogas, and 1,234.6 kg CO\(_2\)-equivalent/day with the recovery and use of biogas. The recovery and use of biogas resulted in 14.5% reduction in the generation of GHG. The biogas generated during anaerobic digestion and anaerobic treatment processes can be recovered and used as a source of fuel to help meet the energy demands of the treatment plant, or it may be flared before discharge into the atmosphere. If biogas were released into the atmosphere without even flaring, a dangerous act rarely practiced in industrial operations, the overall GHG emission would increase by 27% due to the considerably higher global warming potential of methane, which is 23 times higher than that of CO\(_2\). Figure 2 shows the estimated values for the contribution of various wastewater treatment processes in the locomotive repair factory to the overall GHG emission without the recovery of biogas (Wei et al. 2008). Fossil fuel consumption for energy production makes the highest contribution to GHG emission, and generates close to 80% of the total GHG emission, equal to 1,150.1 kg CO\(_2\)-equivalent/day (Figure 2). This emphasizes the importance of using alternative operation strategies or energy resources to reduce the ensuing emissions.

During the treatment of pulp and paper wastewater, the overall GHG emissions by the aerobic, anaerobic, and hybrid treatment systems without the recovery and use of biogas were 3,346, 6,554 and 7,056 kg CO\(_2\)-equivalent/day, respectively, while reducing to 3,152, 6,051, and 6,541 kg CO\(_2\)-equivalent/day in the presence of biogas recovery. Based on the consumed BOD, the on-site and off-site emissions of GHG with and without the recovery and use of biogas are presented in Figure 3. This figure shows that, although the on-site emissions in the three examined plants were close and ranged from 1.0 to 1.4 kg CO\(_2\)-equivalent/kg BOD, the off-site emissions by anaerobic and hybrid treatment systems were considerably higher, and exceeded the emissions generated by the aerobic system. These results are particularly important given the higher biosolids generation during aerobic treatment processes compared to those produced during anaerobic processes for the removal of a given amount of COD. The slightly higher on-site GHG emission in the anaerobic and hybrid treatment systems results from higher CO\(_2\) emissions...
following methane combustion in biogas recovery units of these systems. Anaerobic and hybrid treatment systems generate higher amounts of biogas compared to aerobic systems due to the presence of anaerobic treatment processes, thus generating higher GHG in the form of CO₂. However, the lower generation of biosolids by anaerobic processes reduces the ensuing GHG emissions by the anaerobic digesters in anaerobic and hybrid treatment systems. Temperature affects biochemical reactions in bioreactors and controls the rate of microbial growth and activities. Decreasing the temperature of the anaerobic bioreactor leads to reduced CH₄ generation, contributing to lower GHG emission in the biogas recovery unit. Additionally, lower temperature results in lower sludge generation and consequently lowers CH₄ generation in the anaerobic digester.

As reported by Bani Shahabadi et al. (2009) the increased generation of off-site GHG results from the manufacturing and transportation of fuel and material, e.g. alkalinity, for on-site use. The requirement for alkalinity is particularly high in the anaerobic processes and makes the highest contribution to the overall material requirements. The high alkalinity requirement in anaerobic processes results from the generation of carbonic acid and volatile fatty acids. The alkalinity requirement was estimated to be in the range of 2,000–4,000 mg CaCO₃/L, and resulted in high GHG emission associated with manufacturing and production of alkalinity in the anaerobic and hybrid systems. Alkalinity is also used during the nitrification process for nitrogen removal. Accordingly, the use of nutrient removal processes that do not require external material will result in lower energy consumption and reduced GHG generation. Using the biological nitrification/denitrification processes for nitrogen removal, the emission of nitrous oxide according to Equations (7) and (8) accounted for 11 and 7% of the overall GHG emissions in the aerobic and hybrid treatment systems, respectively.

\[
\text{NH}_4^+ \rightarrow \text{NH}_2 \text{OH} \rightarrow [\text{HNO}] \rightarrow \text{NO}_2 \text{NHOH or} \\
\text{NO} \rightarrow \text{NO}_2 \Rightarrow \text{NO}_3^- \\
\text{NO}_3^- \rightarrow \text{NO}_2 \rightarrow \text{NO} \rightarrow \text{N}_2 \text{O} \rightarrow \text{N}_2
\]  

(7)  

(8)

Figure 4 presents the impact of process design and operating conditions on energy consumption and generation in the biological treatment plants. The recovery and use of biogas satisfies and exceeds the energy needs of the three examined treatment plants. The extra energy in anaerobic and hybrid systems could be used for the production of electricity and steam, which could be further utilized in various activities of pulp- and-paper mills. This figure also shows that the operation of the anaerobic digester and anaerobic reactor at lower temperatures, i.e. under mesophilic condition that uses a 10 °C lower temperature compared to the thermophilic condition, can substantially reduce energy demands of the treatment plant by 35.1, 70.6 and 62.9% in the three systems, respectively. The reduced energy demands are particularly significant in the anaerobic digester. The discharged wastewater in the pulp and paper industry has a relatively large temperature range of 25 to 70 °C, depending on the employed processes. Consequently, the energy consumption in the WWTPs of the pulp and paper industry varies as a function of the influent wastewater temperature. Since optimum operating temperatures of aerobic and anaerobic treatment systems are lower than 40 °C, most Kraft pulp and paper mills, which produce wastewaters at relatively high temperatures, take advantage of the
high temperature of wastewater to preheat the influent pulp. Consequently, these mills cover a part of the energy demands of the plants while lowering the wastewater temperature. This study suggests the inclusion of anaerobic digesters in the WWTPs, not only to reduce the amount of generated sludge but also to produce energy and cover the energy requirements of the treatment plant.

CONCLUSIONS

The estimation of GHG emission and energy consumption by WWTPs that use physical–chemical or biological treatment processes demonstrated that substantial energy savings and reductions in GHG emission can be achieved through the use of alternative designs and operation strategies of treatment plants. The manufacturing of chemicals and generation of electricity and fossil fuels for on-site consumption should use methods that generate lower amounts of GHGs. This highlights the potential benefits of using renewable energy resources that inherently produce lower GHGs to replace fossil fuels. The operation of an anaerobic reactor and an anaerobic digester at lower temperatures will reduce their energy demands and the resulting GHG generation while improving the energy efficiency of the treatment plant. The removal of nitrogen by biological processes contributes to the overall GHG emission through the generation of nitrous oxide.

REFERENCES


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