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Greenhouse gas production: A comparison between aerobic and anaerobic wastewater treatment technology

F.Y. Cakir[a], M.K. Stenstrom[b,*]

[a]Department of Environmental Engineering Sciences, University of Florida, Gainesville, FL 32611-6450, USA
[b]Department of Civil and Environmental Engineering, UCLA, LA 90095-1593, USA

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Abstract

Anaerobic wastewater treatment offers improved energy conservation with potential reduction in greenhouse gas emissions. Pitfalls exist in that the methane produced in anaerobic treatment can offset any reductions in carbon dioxide emissions, if it is released to the environment. This paper analyzes greenhouse gas emissions from both aerobic and anaerobic treatment systems, including sludge digestion and the losses of dissolved methane in digested biosolids and process effluents. There exists cross over points, ranging from 300 to 700 mg/L influent wastewater BOD_u, which are functions of the efficiency of the aerobic treatment system. Anaerobic treatment becomes favorable when treating influents higher in concentrations than the cross over values. A technology to recover dissolved methane would make anaerobic treatment favorable at nearly all influent strengths.

Keywords: Anaerobic; Carbon dioxide; Global warming; Greenhouse gas; Methane; Wastewater treatment

1. Introduction

During the last 200 years atmospheric concentrations of greenhouse gases, CO_2, CH_4 and N_2O have increased due to anthropogenic activities such as production and use of fossil fuels and other agricultural and industrial activities (El-Fadel and Massoud, 2001). To compare the effect between different gases, their global warming potentials (GWP) were estimated and referenced to CO_2. For a 100-year horizon, CO_2, CH_4 and N_2O have GWPs of 1, 21 and 310, respectively (European Commission, 2001). Wastewater treatment can contribute to greenhouse gases through production of CH_4 or CO_2 from treatment processes or from CO_2 produced from the energy required for treatment. CH_4 produced from sewage treatment was found to constitute about 5% of the global methane sources (El-Fadel and Massoud, 2001).

The objective of this paper is to estimate greenhouse gas production from domestic wastewater treatment and to investigate the differences between aerobic and anaerobic methods. In anaerobic treatment complex wastes are stabilized in three basic steps: hydrolysis, acid fermentation and methanogenesis. Anaerobic treatment processes can release CH_4 which has a greater GWP than CO_2. Aerobic treatment involves the conversion of organic waste to biomass and CO_2 by an aerobic bacterial culture, and generally does not produce CH_4 unless biosolids are digested anaerobically. One key difference between this analysis and previous analyses is consideration of anaerobic wastewater treatment technologies, such as upflow anaerobic sludge blanket (UASBs) reactors and anaerobic filters (AFs). Previous

*Corresponding author. Tel.: 310 825 1408; fax: 310 206 5476.
E-mail address: stenstro@seas.ucla.edu (M.K. Stenstrom).

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Nomenclature

AR	anaerobic reactor
ASP	activated sludge process
D	digester
E_{BIOGAS}	energy produced from biogas (kW)
$E^{ASP}_{AERATION}$	energy required for aeration (kW)
$E^{D}_{HEATING}$	energy required for digester heating (kW)
$Eff_{aeration}$	aeration efficiency (kg/kW.h)
$Eff_{electrical-conversion}$	electrical conversion efficiency
$Eff_{heat-conversion}$	heat conversion efficiency
f_s	weight fraction of sludge that is solids
f_v	weight fraction of solids that are volatile
k	maximum rate of substrate utilization per unit mass of biomass($gBOD_u/gVSS.d$)
k_d	decay rate (d^{-1})
K_H	Henry's Law constant (mg/L.atm)
O	oxygen requirement (kg/d)
θ_c	solids retention time (d)
P	sludge flow rate (m^3/d)
Pr	partial pressure of gas (atm)
PS	primary sludge
Q	wastewater flow rate (m^3/d)
RR	removal efficiency
S	substrate (mg/L)
S_s	specific gravity of sludge
SS	total suspended solids (mg/L)
$Temp$	influent wastewater temperature (^{o} C)
TSS	total suspended solids removal (kg/d)
T	greenhouse gas production (kg/d)
WB	waste biosolids
X	biomass production (kg/d)
Y_{OBS}	observed biomass yield (g VSS/g BOD_u)
Y	biomass yield (g VSS/g BOD_u)
Y_{CH_4}	CH_4 yield (kg CH_4/kg BOD_u)
Y_{CO_2}	CO_2 yield (kg CO_2/kg BOD_u)

Table 1
Process parameters used in the model

Overall facility
Flow (Q) = 37,850 m^3/d (10 MGD)
Influent BOD_u (S^{PC}_{INF}) = 100–1100 mg/L
Influent TSS (SS^{PC}_{INF}) = 49–543 mg/L
Primary clarifier
BOD_u removal ($RR^{PC}_{BOD_u}$) = 40%
TSS removal (RR^{PC}_{TSS}) = 60%
Activated sludge process
Mean effluent BOD_u (S^{ASP}_{EFF}) = 15 mg/L
SRT (θ^{ASP}_{C}) = 5, 10, 30 d
Yield (Y^{ASP}) = 0.5 g VSS/g BOD_u
Decay rate (k^{ASP}_{d}) = 0.06 d^{-1}
CO_2 yield ($Y^{ASP}_{CO_2}$) = 1.375 kg CO_2/kg BOD_u
Anaerobic reactor
Mean Effluent BOD_u (S^{AR}_{EFF}) = 28 mg/L
SRT (θ^{AR}_{C}) = 30 d
Yield Y^{AR} = 0.05 g VSS/g BOD_u
Decay rate (k^{AR}_{d}) = 0.03 d^{-1}
CO_2 yield ($Y^{AR}_{CO_2}$) = 0.6875 kg CO_2/kg BOD_u
CH_4 yield ($Y^{AR}_{CH_4}$) = 0.25 kg CH_4/kg BOD_u
Anaerobic digestion
SRT (θ^{D}_{C}) = ˜12 d
Yield (Y^{D}) = 0.04 g VSS/g BOD_u
Decay rate ((k^{D}_{d})) = 0.015 d^{-1}
CH_4 yield ($Y^{D}_{CH_4}$) = 0.25 kg CH_4/kg BOD_u
Energy
Heat conversion efficiency ($Eff_{heat-conversion}$) = 0.83
Electrical conversion efficiency ($Eff_{electrical-coversion}$) = 0.5
Aeration efficiency ($Eff_{aeration}$) = 2 kg O_2/kWh
CO_2 production in power generation ($Y^{Power\_Generation}_{CO_2}$) = 0.96 kg CO_2/kWh

analyses have usually considered only aerobic wastewater treatment and anaerobic sludge treatment (El-Fadel and Massoud, 2001; Monteith et al., 2003). The greenhouse gases, CO_2, CH_4 and N_2O can all be produced in wastewater treatment but only CO_2 and CH_4 are included in this analysis, while N_2O is neglected.

2. Methodology

The approach taken in this analysis is to model two different types of treatment systems that use aerobic and anaerobic technology to achieve secondary treatment effluent standards (30 mg/L BOD_5 and 30 mg/L total suspended solids). Most secondary treatment plants consist of primary clarification, aerobic biological treatment such as the activated sludge process, or an anaerobic treatment technology such as a UASB reactor, and anaerobic digestion for biosolids treatment. Three cases were considered for the aerobic technology: a conventional activated sludge process with a solids retention time (SRT) of 10 days, an extended aeration activated sludge process with a SRT of 30 days and a high-rate activated sludge process with a SRT of 5 days. The anaerobic technology was assumed to have an SRT of 30 days, which requires that biomass can be accumulated in the reactor, as occurs with a UASB or AF. The influent wastewater temperature was assumed to be 20 °C which is reasonable for subtropical and tropical regions. The anaerobic technology considered here would not be suitable for cold regions. Henry's coefficients and other temperature dependent coefficients were calculated for 20 °C. The seasonal temperature variations were not included in the analysis. The

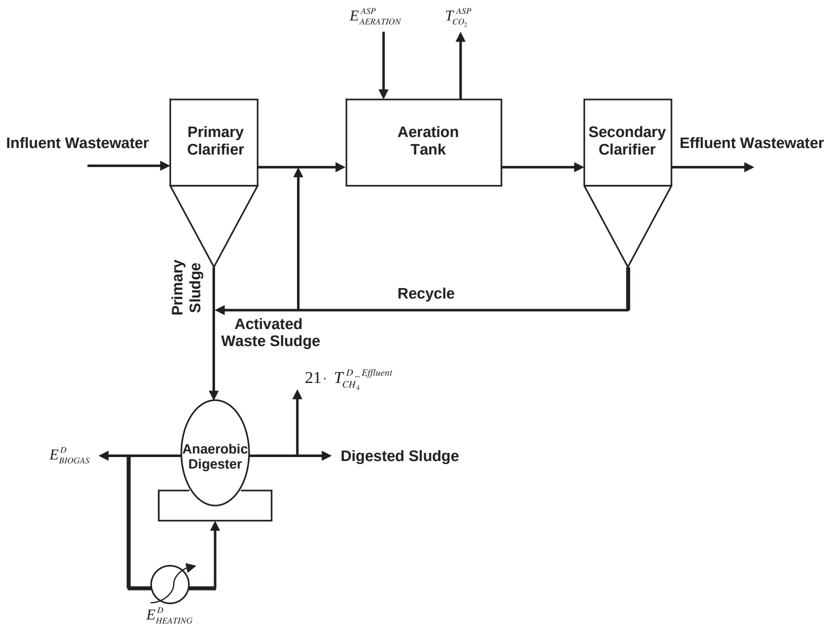

Fig. 1. Aerobic treatment plant layout.

process parameters used in the model are shown in Table 1.

The energy produced from digester and anaerobic reactor biogas is used for digester heating and power generation. Eq. (1) shows the net energy calculation to be used for the greenhouse gas production from power generation. For the anaerobic case the energy required for aeration is zero and for the aerobic case the energy production from reactor biogas is zero. The greenhouse gas production from methane combustion is calculated. The total greenhouse gas production is calculated from each part of the system as shown below in Eq. (2), using equivalence factors for the greenhouse potential of CH_4:

$$E^{\text{ASP\_or\_AR}}_{\text{NET}} = E^{\text{ASP}}_{\text{AERATION}} - Eff_{\text{electrical-conversion}} \times (E^{\text{AR}}_{\text{BIOGAS}} + E^{\text{D}}_{\text{BIOGAS}} - E^{\text{D}}_{\text{HEATING}}) \quad (1)$$

$$T^{\text{Equivalent}}_{\text{CO}_2} = T^{\text{ASP\_or\_AR}}_{\text{CO}_2} + T^{\text{Methane\_Burning}}_{\text{CO}_2} + T^{\text{Power\_Generation}}_{\text{CO}_2} + 21 \times T^{D\text{\_Effluent}}_{\text{CH}_4} + 21 \times T^{AR\text{\_Effluent}}_{\text{CH}_4}. \quad (2)$$

Fig. 1 shows the aerobic treatment system, and the model includes CO_2 production from biological oxidation of substrates in the wastewater, biomass decay and CO_2 production from anaerobic digestion and biogas combustion. The CO_2 production from power consumption is included, and the reduction in CO_2 production from energy conservation by using digester gas for heating and power generation is also considered. Fig. 2 shows the anaerobic treatment system and the model includes CO_2 contributions that are similar to the aerobic case, as well as CH_4 production from anaerobic wastewater treatment and dissolved CH_4 in the treatment plant effluent. Also for both technologies the dissolved CH_4 in the digester effluent is included.

The model equations are included in Fig. 3 Subscripts and superscripts are used for simplicity and clarity of understanding. Subscripts show what the variable stands for and the superscripts show the process (Benefield and Randall, 1980; Cakir and Stenstrom, 2003; Gujer et al., 1999).

3. Results and discussion

The treatment efficiency of the aerobic and anaerobic technology can be seen in Fig. 4. Influent wastewater concentrations ranged from 100 to 1100 mg/L BOD_u (BOD_u ~COD) for both technologies. The activated sludge plant had a mean effluent concentration of 15 mg/L BOD_u compared to 28 mg/L BOD_u for the anaerobic reactor. The treatment efficiency for aerobic and anaerobic treatment was 75–98% and 51–96%, respectively. The anaerobic treatment might require some post treatment to achieve discharge limits, depending on where it is located.

A key difference in this analysis and previous analyses is the impact of the CH_4 contained in treated wastewaters. For anaerobic digesters, this term is generally small, because anaerobic digesters treat low flows of concentrated biosolids. For anaerobic wastewater

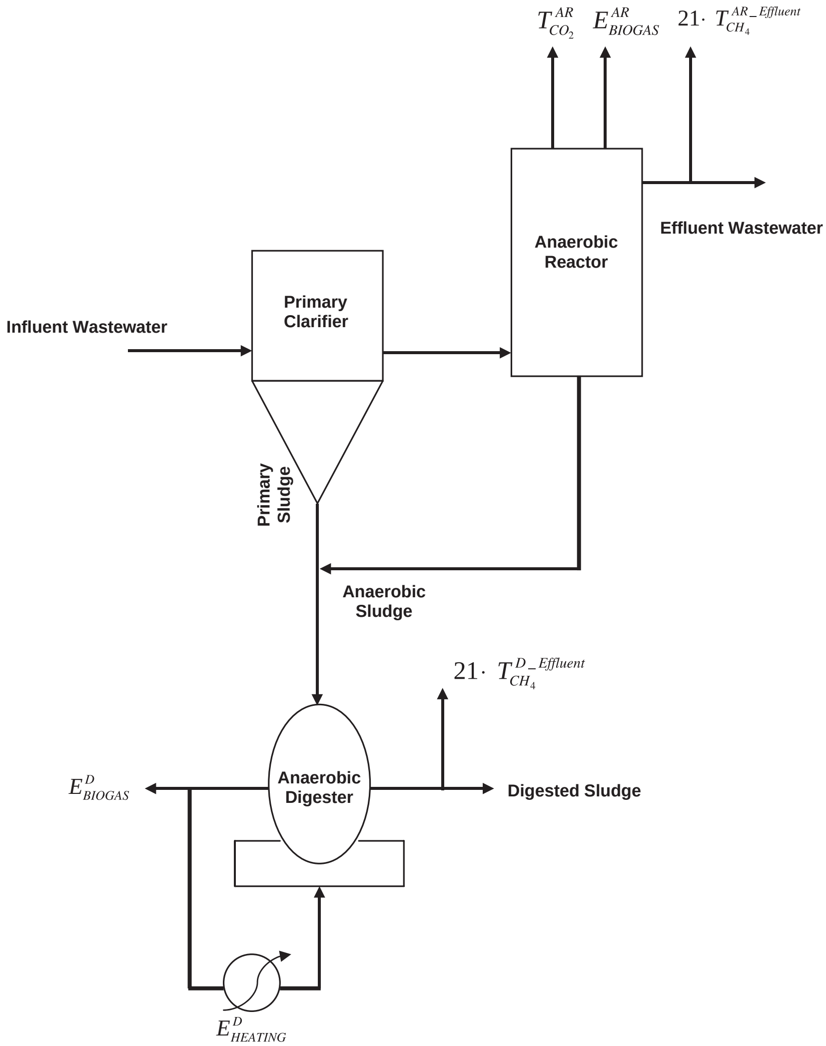

Fig. 2. Anaerobic treatment plant layout.

treatment, the mass of dissolved CH_4 in the process effluent can be as large as the recovered CH_4, especially for low strength wastewaters. Previous analyses have generally ignored dissolved CH_4. For example for an influent concentration of 100 mg/L BOD_u, mass of CH_4 in digester effluent is 0.01 t/day which is very small compared to 3.27 t/day of CH_4 in anaerobic reactor effluent (Cakir and Stenstrom, 2003). CH_4 dissolved in the anaerobic reactor effluent is a major contributor for greenhouse gas production especially for low strength wastewaters.

The dissolved CH_4 in the anaerobic effluents is calculated using Henry's Law and the partial pressure of CH_4 in the anaerobic reactor gas. The CH_4 partial pressure in the anaerobic reactor biogas ranged between 0.18 and 0.76 atm and increased with increasing influent strength. The CH_4 in the digested sludge effluent is calculated assuming 0.65 atm CH_4 partial pressure. The treatment efficiency and methane partial pressures in the anaerobic reactor are calculated using the authors' previously developed mathematical model (Cakir and Stenstrom, 2003).

Fig. 5 shows digester gas composition for previously published studies treating low-to-medium strength wastewaters (Donovan et al., 1979; Koon et al., 1979; Kobayashi et al., 1983; Abramson, 1987; Noyola et al., 1988; Barbosa and Sant'Anna, 1989; Vieira and Garcia, 1992; Singh et al., 1996; Agrawal et al., 1997; Chua et al., 1997; Lomas et al., 1999; Lacalle et al., 2001). The results are for a variety of temperatures and conditions, but show the trend of increasing CH_4 concentration with increasing wastewater strength. The high N_2

$$E_{AERATION}^{ASP} = \frac{O^{ASP}}{24\times Eff_{aeration}}$$

$$E_{BIOGAS}^{AR} = 0.145\times O^{AR}$$

$$T_{CO_2}^{ASP\_or\_AR} = Y_{CO_2}^{ASP\_or\_AR}\times O^{ASP\_or\_AR}$$

$$Y_{OBS}^{ASP\_or\_AR} = \frac{Y^{ASP\_or\_AR}}{1+k_d^{ASP\_or\_AR}\times\theta_C^{ASP\_or\_AR}}$$

$$X^{ASP\_or\_AR} = \frac{Y_{OBS}^{ASP\_or\_AR}\times Q\times\left(S_{INF}^{ASP\_or\_AR}-S_{EFF}^{ASP\_or\_AR}\right)}{1000}$$

$$O^{ASP\_or\_AR} = \frac{Q\times\left(S_{INF}^{ASP\_or\_AR}-S_{EFF}^{ASP\_or\_AR}\right)}{1000}-1.42\times X^{ASP\_or\_AR}$$

$$TSS_{PS}^{ASP\_or\_AR} = \frac{RR_{TSS}^{PC}\times Q\times SS_{INF}^{PC}}{1000}$$

$$TSS_{WB}^{ASP\_or\_AR} = \frac{X^{ASP\_or\_AR}}{f_{V_{WB}}}$$

$$P_{PS}^{ASP\_or\_AR} = \frac{TSS_{PS}^{ASP\_or\_AR}}{S_{s_{PS}}\times 1000\times f_{S_{PS}}}$$

$$P_{WB}^{ASP\_or\_AR} = \frac{TSS_{WB}^{ASP\_or\_AR}}{S_{s_{WB}}\times 1000\times f_{S_{WB}}}$$

$$S_{PS}^{ASP\_or\_AR} = \frac{RR_{BOD_u}^{PC}\times Q\times S_{INF}^{PC}}{P_{PS}^{ASP\_or\_AR}}$$

$$S_{WB}^{ASP\_or\_AR} = \frac{1.42\times X^{ASP\_or\_AR}\times 1000}{P_{WB}^{ASP\_or\_AR}}$$

$S_{INF}^{ASP\_or\_AR}$

$S_{EFF}^{ASP\_or\_AR}$

$$T_{CH_4}^{AR\_Effluent} = \frac{Q\times K_{H_{CH_4}}^{AR}\times \mathrm{Pr}_{CH_4}^{AR}}{1000}$$

$$P = P_{PS}^{ASP\_or\_AR} + P_{WB}^{ASP\_or\_AR}$$

$$S_{INF}^{D} = \frac{S_{PS}^{ASP\_or\_AR}\times P_{PS}^{ASP\_or\_AR} + S_{WB}^{ASP\_or\_AR}\times P_{WB}^{ASP\_or\_AR}}{P}$$

$$Y_{OBS}^{D} = \frac{Y^D}{1+k_d^D\times\theta_C^D}$$

$$X^D = \frac{Y_{OBS}^D\times P\times\left(S_{INF}^D - S_{EFF}^D\right)}{1000}$$

$$O^D = \frac{P\times\left(S_{INF}^D - S_{EFF}^D\right)}{1000}-1.42\times X^D$$

$$T_{CH_4}^{D\_Effluent} = \frac{P\times K_{H_{CH_4}}^{D}\times \mathrm{Pr}_{CH_4}^{D}}{1000}$$

$$S_{EFF}^D = \frac{K_S^D\times\left(1+k_d^D\times\theta_C^D\right)}{\left(\theta_C^D\times\left(Y^D\times k^D - k_d^D\right)-1\right)}$$

$$E_{BIOGAS}^{D} = 0.145\times O^{D}$$

$$E_{HEATING}^{D} = \frac{0.0678\times P\times(35-Temp)}{Eff_{heat-conversion}}$$

$$T_{CO_2}^{Methane\_Burning} = Y_{CO_2}^{AR}\times\left(O^{AR}+O^{D}\right)$$

Fig. 3. Equations used in the model (wastewater treatment reactor, activated sludge process or anaerobic reactor, top; anaerobic digester, bottom).

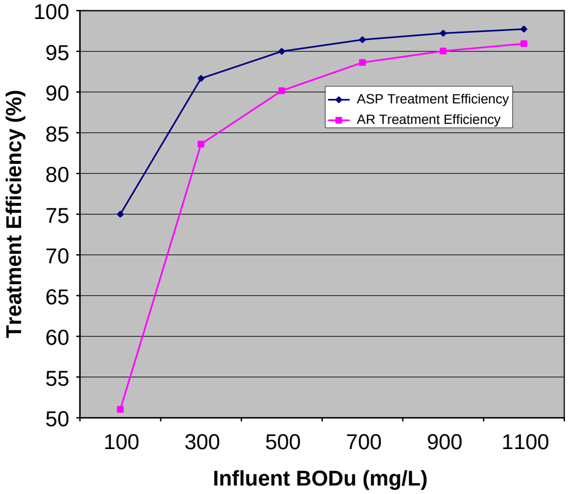

Fig. 4. Treatment efficiency versus influent BOD_u.

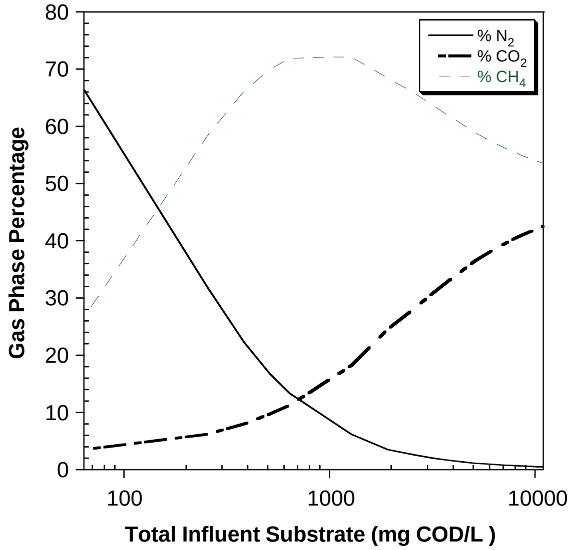

Fig. 6. Simulated gas composition vs. influent substrate concentration.

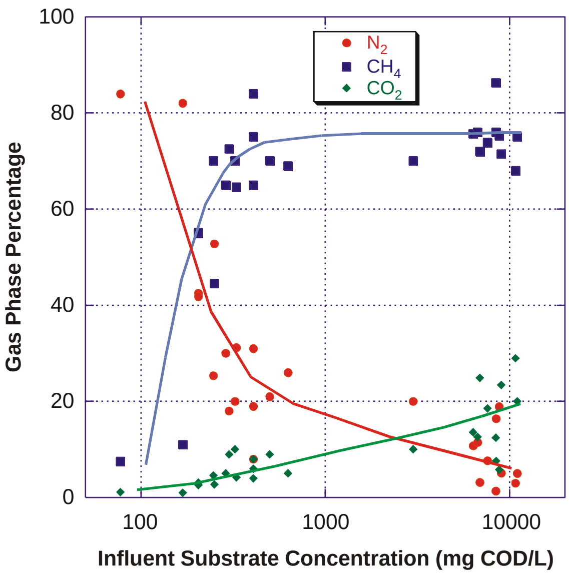

Fig. 5. Gas composition vs. influent substrate concentration (literature references).

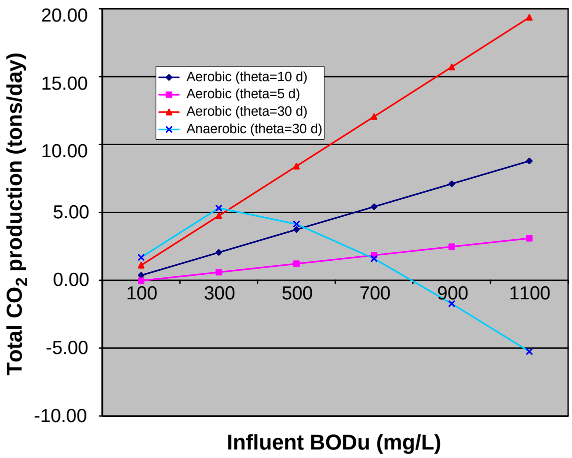

Fig. 7. Total equivalent CO_2 production vs. influent BOD_u.

concentration at low strength is from dissolved nitrogen in the influent; at higher wastewater strengths there is sufficient CO_2 and CH_4 production to reduce the nitrogen concentrations to the low levels usually observed in anaerobic digesters. Fig. 6 shows the model prediction of biogas composition for the same range of influent wastewater strengths. The trends are quite similar but the exact values are different due to the wide range of conditions for the literature data. The high N_2 concentration and low CH_4 concentration at low strengths is an additional challenge for economical gas recovery.

The equivalent CO_2 production from aerobic and anaerobic wastewater treatment is shown in Fig. 7. At higher influent concentrations, the anaerobic process produces “negative” CO_2 due to biogas combustion that supplies energy that would have otherwise required fossil fuel combustion. Cross over points for extended aeration, conventional and high-rate activated sludge process are about 300, 500 and 700 mg/L BOD_u, respectively. For influent wastewater concentrations above cross over points, anaerobic technology becomes a feasible technology for wastewater treatment that produces lower greenhouse gas emissions. A technique to capture CH_4 lost in the anaerobic reactor effluent so that it could be used as a fuel gas would make the anaerobic treatment more favorable even for very low influent wastewater strengths.

There exist significant differences between this analysis and previous analyses. El-Fadel and Massoud (2001) considered a variety of treatment systems but did not assume that CH_4 produced from anaerobic sludge digestion is routinely combusted. In the United States and other developed countries methane from anaerobic digestion is combusted to produce energy at large treatment plants and is at least flared and converted to CO_2 at smaller plants (Monteith et al., 2003). El-Fadel and Massoud's analysis will overestimate CH_4 release from many treatment plants. Monteith et al. (2003) considered anaerobic sludge digestion and combustion of the biogas, but did not consider anaerobic wastewater treatment. Keller and Hartley (2003) considered anaerobic wastewater treatment, but assumed that the dissolved CH_4 in the effluent is captured and not released to the environment. It is not clear how this can be economically achieved for all processes.

4. Conclusions

This paper compares greenhouse gas production by aerobic and anaerobic treatment systems, including anaerobic wastewater treatment by processes such as the upflow anaerobic sludge blanket reactor. Methane recovery as well as methane losses in process effluents and digested biosolids are considered. The analysis shows that for very low strength wastewaters (less than 300 mg/L BOD_u), aerobic processes will emit less greenhouse gas. At higher strengths, anaerobic wastewater treatment is more favorable, and the cross over point depends upon the relative efficiency of the aerobic system. A technology to economically recover dissolved CH_4 from process effluents could make anaerobic wastewater treatment more favorable in reducing greenhouse gas emissions at all influent strengths. One possible approach is to use an aerobic post treatment step that could biologically oxidize the dissolved methane. This would have an added benefit of polishing the anaerobic effluent. The net greenhouse gas reduction will depend upon the energy consumption of the added oxidation process.

References

Abramson, S.D., 1987. A predictive model for anaerobic filters treating low strength domestic wastewaters. J. Environ. Systems 16 (3), 201.

Agrawal, L.K., Ohashi, Y., Mochida, E., Okui, H., Ueki, Y., Harada, H., Ohashi, A., 1997. Treatment of raw sewage in a temperate climate using a UASB reactor and the hanging sponge cubes process. Water Sci. Technol. 36 (6–7), 433.

Barbosa, R.A., Sant'Anna Jr., G.L., 1989. Treatment of raw domestic sewage in an UASB reactor. Water Res. 23 (12), 1483.

Benefield, L.D., Randall, C.W., 1980. Biological Process Design for Wastewater Treatment. Prentice-Hall, New Jersey, USA.

Cakir, F., Stenstrom, M.K., 2003. A dynamic model for anaerobic filter. J. Environ. Sci. Health (Part A) 38 (10), 2069.

Chua, H., Hu, W.F., Yu, P.H.F., Cheung, M.W.L., 1997. Responses of an anaerobic fixed-film reactor to hydraulic shock loadings. Bioresource Technol. 61, 79.

Donovan, E. J., Mulligan, T. J., Mueller, J. A., Husband, J., Salotto, V., 1979. Treatment of high strength wastes with an anaerobic filter. Presented at the AIChE 86th National Meeting, Houston, TA.

El-Fadel, M., Massoud, M., 2001. Methane emissions from wastewater management. Environ. Pollut. 114 (2), 177.

European Commission, 2001. Environmental pressure indicators for the EU, Eurostat, Data 1985–98. Office for official publications of the European Communities, Luxembourg, ISBN 92-894-0955-X.

Gujer, W., Henze, M., Mino, T., van Loosdrecht, M., 1999. Activated sludge model No. 3. Water Sci. Technol. 39 (1), 183.

Keller, J., Hartley, K., 2003. Greenhouse gas production in wastewater treatment: process selection is the major factor. Water Sci. Technol. 47 (12), 43.

Kobayashi, H.A., Stenstrom, M.K., Mah, R.A., 1983. Treatment of low strength domestic wastewater using the anaerobic filter. Water Res 17 (8), 903.

Koon, J. H., Davis, G. M., Genung, R. K., Pitt, W. W., 1979. The feasibility of an anaerobic upflow fixed-film process for treating small sewage flows. Presented at the Energy Optimization of Water and Wastewater Management for Municipal and Industrial Applications Conference, New Orleans, LA.

Lacalle, M.L., Villaverde, S., Fdz-Polanco, F., Garcia-Encina, P.A., 2001. Combined anaerobic/aerobic (UASB + UBAF) system for organic matter and nitrogen removal from a high strength industrial wastewater. Water Sci. Technol. 44 (4), 255.

Lomas, J.M., Urbano, C., Camarero, L.M., 1999. Evaluation of a pilot scale downflow stationary fixed film anaerobic reactor treating piggery slurry in the mesophilic range. Biomass Bioenergy 17, 49.

Monteith, H. D., Sahely, H. R., MacLean, H. L., Bagley, D. M., 2003. A Life-cycle approach for estimation of greenhouse gas emissions from canadian wastewater treatment. In Proceedings of WEFTEC Conference, Los Angeles, CA.

Noyola, A., Capdeville, B., Roques, H., 1988. Anaerobic treatment of domestic sewage with a rotating-stationary fixed-film reactor. Water Res. 22 (12), 1585.

Singh, K.S., Harada, H., Viraraghavan, T., 1996. Low-strength wastewater treatment by a UASB reactor. Bioresource Technol. 55, 187.

Vieira, S.M.M., Garcia Jr., A.D., 1992. Sewage treatment by UASB-reactor: operation results and recommendations for design utilization. Water Sci. Technol. 25 (7), 143.