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Contribution of On-Site and Off-Site Processes to Greenhouse Gas (GHG) Emissions by Wastewater Treatment Plants

Laleh Yerushalmi, Fariborz Haghighat and Maziar Bani Shahabadi

***Abstract*—**The estimation of overall on-site and off-site greenhouse gas (GHG) emissions by wastewater treatment plants revealed that in anaerobic and hybrid treatment systems greater emissions result from off-site processes compared to on-site processes. However, in aerobic treatment systems, on-site processes make a higher contribution to the overall GHG emissions. The total GHG emissions were estimated to be 1.6, 3.3 and 3.8 kg CO_2-e/kg BOD in the aerobic, anaerobic and hybrid treatment systems, respectively. In the aerobic treatment system without the recovery and use of the generated biogas, the off-site GHG emissions were 0.65 kg CO_2-e/kg BOD, accounting for 40.2% of the overall GHG emissions. This value changed to 2.3 and 2.6 kg CO_2-e/kg BOD, and accounted for 69.9% and 68.1% of the overall GHG emissions in the anaerobic and hybrid treatment systems, respectively. The increased off-site GHG emissions in the anaerobic and hybrid treatment systems are mainly due to material usage and energy demand in these systems. The anaerobic digester can contribute up to 100%, 55% and 60% of the overall energy needs of plants in the aerobic, anaerobic and hybrid treatment systems, respectively.

***Keywords*—**On-site and off-site greenhouse gas (GHG) emissions, wastewater treatment plants, biogas recovery

I. Introduction

GLOBAL warming and climate change have moved to the forefront of political and economic agenda in recent years, mainly due to their impact on the environmental, energy and economic sectors. This underlines the significance and urgency of climate change and highlights international efforts for sustainable development, while demanding the implementation of reliable srategies to address these issues. According to the Intergovernmental Panel for Climate Change (IPCC), the excessive generation of greenhouse gases (GHGs) notably carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) by human activities such as deforestation, production and consumption of fossil fuels, and industrial and agricultural activities has been partly responsible for global warming and climate change [1]. Greenhouse gases absorb thermal radiation reflected from the surface of the earth and reduce the amount of energy that escapes to the atmosphere, thus leading to an increase in the global mean surface temperature. The contribution of a greenhouse gas to global warming is commonly expressed by its global warming potential (GWP) which enables the comparison of global warming impact of the gas and that of a reference gas, typically carbon dioxide. On a 100 year basis, the GWP of carbon dioxide, methane and nitrous oxide are 1, 23 and 296, respectively [2].

Wastewater treatment plants (WWTPs) have been recognized as a source of GHG emission in the commercial sector since they produce CO_2, CH_4, and N_2O during the treatment processes and CO_2 from the energy demand of the plant [3]. The imposition of regulations, obligatory limitations, carbon taxes and penalties in response to international treaties and protocols that restrict the emissions of GHGs by industrial operations will have a major impact on the design and operation of WWTPs, particularly those that treat high-strength wastewaters. Therefore, the source of GHG emissions by WWTPs must be identified before any meaningful mitigation strategy could be designed and implemented.

The estimation of GHG emissions by WWTPs have commonly been associated with on-site emissions which are due to liquid and solid treatment processes as well as biogas and fossil fuel combustion for energy generation. The Off-site GHG emissions resulting from the production of electricity for plant, production and transportation of fuel and chemicals for on-site usage, degradation of remaining constituents in the effluent, as well as transportation and disposal of solids are traditionally allocated to the energy or industrial sectors. This practice has resulted in serious underestimation of emissions associated with wastewater treatment plants. In addition, most studies have focused on municipal wastewater treatment plants using aerobic treatment combined with anaerobic sludge digestion operations and ignored alternative designs such as anaerobic or hybrid treatment systems with nutrient removal [4]-[9].

L. Yerushalmi is an Adjunct Professor at the Department of Building, Civil and Environmental Engineering at Concordia University and Vice President Research and Development of BioCAST systems Inc. in Montreal, Canada (laleh@encs.concordia.ca).
F. Haghighat is a Professor at the Department of Building, Civil and Environmental Engineering at Concordia University in Montreal, Canada (haghi@bcee.concordia.ca)
M. Bani Shahabadi is a Ph.D. student at the Department of Building, Civil and Environmental Engineering at Concordia University in Montreal, Canada (m_banish@encs.concordia.ca)

The present study used a comprehensive mathematical model developed by Bani Shahabadi et al. [10] to estimate the overall on-site and off-site GHG emissions by WWTPs. The application of the developed model in the estimation of GHG emissions by biological treatment systems that treat food processing wastewaters and use three alternative designs is demonstrated. The contribution of individual processes to the generation of GHGs was identified, facilitating the development and implementation of strategies to reduce these harmful atmospheric emissions.

II. Methodology

The on-site and off-site GHG emissions by wastewater treatment plants of food-processing industry using aerobic, anaerobic and hybrid, aerobic/anaerobic biological processes were estimated by using an elaborate mathematical model that addressed the removal of organic carbon, suspended solids as well as nitrogenous contaminants by nitrification/denitrification processes [10]. The model estimates GHG emissions by biological treatment as well as energy generation, chemical manufacturing and solid disposal processes. Only carbon dioxide and methane emissions were considered in this study and nitrous oxide emissions were excluded due to the lack of accurate data during full-scale and pilot-scale operations of wastewater treatment plants [11]. Table 1 presents the characteristics of wastewater used in this study. The process parameters used in the model were based on the literature-cited values [8], [12]-[13].

TABLE I
CHARACTERISTICS OF THE FOOD-PROCESSING WASTEWATER

Symbol	Parameter	Value
Q_i	Flow rate	1000 m^3/d
S_{i0}	BOD_u	2000 g BOD/m^3
N	Nitrogen	100 g N/m^3
X_i	VSS	1000 g VSS/m^3
T	Temperature	25 °C

The on-site emissions associated with treatment processes were estimated from mass balances and kinetics and stoichiometric relationships, while the emissions associated with heating energy needs and electricity consumption were estimated from emission factors as recommended by the Intergovernmental Panel for Climate Change (IPCC) [2], [14]. Fig. 1 presents the generation of carbon dioxide and methane by aerobic and anaerobic processes in biological treatment systems.

Two scenarios were considered for the fate of the generated biogas; first, flaring of biogas, and second, recovery and use of biogas as fuel.

On-site biological processes produce similar amounts of GHG which are 0.88, 0.85 and 1.02 Kg CO_2-e/kg BOD in the three examined treatment systems, as presented in Fig. 3. However, the contribution of GHG emissions from material usage and energy demand in the anaerobic and hybrid treatment systems results in considerable increases in off-site GHG emissions in these systems, well above the corresponding values in the aerobic treatment system.

The off-site greenhouse gas emissions associated with the generation and transportation of energy, electricity and chemicals for on-site use as well as solid waste transport and disposal were estimated by using the corresponding emission factors [15]-[16]. It was assumed that natural gas was imported to the plant to satisfy the energy needs.

The emissions related to the use of chemicals, particularly carbonate to support the alkalinity needs of treatment processes, and methanol which was used as the external carbon source to support nitrogen removal processes were estimated by using the emission factors of 1.74 g CO_2e/g alkalinity and 1.54 g CO_2e/g methanol.

The electricity consumption rate of 0.3 kWh/m^3 WW for hybrid treatment and 0.2 kWh/m^3 WW for aerobic and anaerobic treatment systems were used as suggested by Sahely et al. [9] The electricity demand for aeration was calculated from the oxygen requirements of the aerobic reactor and an aeration efficiency of 7.2 g O_2/kJ [4]. The electricity generation mix in Canada was used to estimate the upstream (off-site) GHG emissions due to electricity generation. The concentration of dissolved methane in the effluent of anaerobic reactor and anaerobic digester was determined by using the Henry's Law constant and the partial pressure of methane in the corresponding reactor.

III. Results and Discussion

The overall on-site and off-site GHG emissions by the three different types of treatment systems examined in this study are presented in Fig. 2.

The aerobic treatment system produced the least amount of GHG emissions compared to hybrid and anaerobic treatment systems when considering the overall on-site and off-site GHG emissions.

In the anaerobic and hybrid treatment systems, the off-site GHG emissions which are due to material usage during the treatment process, off-site energy generation, and off-site degradation of carbonaceous material are substantially higher than the GHG emissions resulting from the treatment process itself. However, in the aerobic treatment system, the on-site emissions are higher than the off-site emissions and contribute to 65.3% and 59.8% of the overall GHG emissions with and without the recovery and use of biogas, respectively. In anaerobic and hybrid treatment systems, the off-site GHG emissions accounted for 69.9% and 68.1% emissions without biogas recovery and use, and 70.8% and 69.2% with the recovery and use of biogas, respectively. The recovery of generated biogas and its use as fuel reduced the off-site GHG emissions by 28.8%, 11.0% and 12.0% in the aerobic, anaerobic and hybrid treatment systems, respectively. In fact, the generated biogas covers the total energy needs of treatment plants for aeration, heating and electricity for all three types of operations.

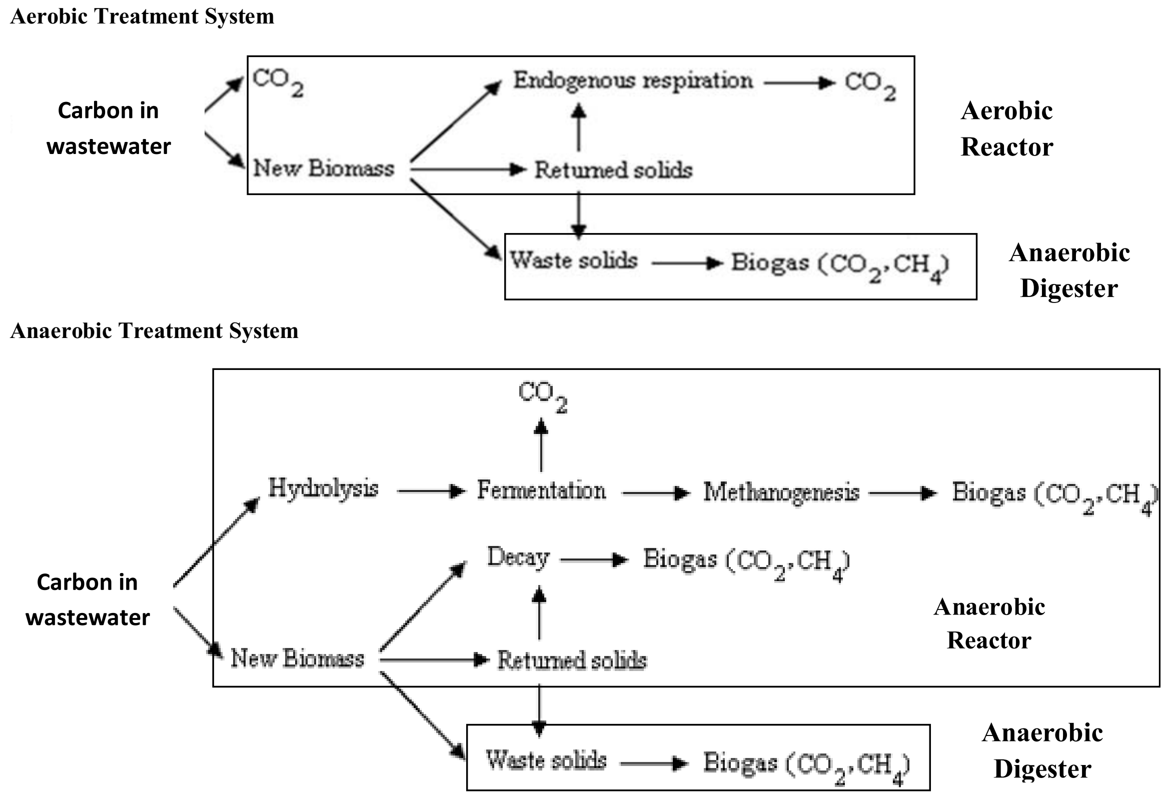

Fig. 1 Greenhouse gas (GHG) generating processes in aerobic and anaerobic biological treatment systems

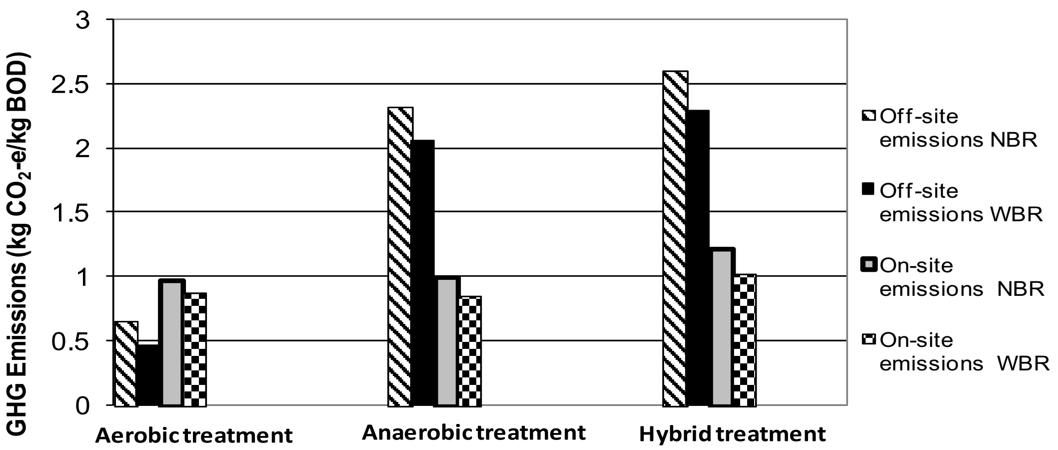

Fig. 2 On-site and off-site greenhouse gas (GHG) emissions by the three treatment systems examined. NBR = No biogas recovery, WBR = With biogas recovery

This suggests that the manufacturing of chemicals and generation of electricity and fossil fuels for on-site consumption should use methods that generate lower amounts of GHGs, thus reducing the overall GHG emissions of the plant. The total GHG emissions were estimated to be 1.6, 3.3 and 3.8 kg CO_2-e/kg BOD in the aerobic, anaerobic and hybrid treatment systems, respectively.

Fig. 3 also shows that the GHG emissions due to solid disposal are small compared to biological processes and material usage.

Pervious studies had suggested that anaerobic treatment generates the least amount of GHGs [6]. However, the present study showed that when off-site GHG emissions are also taken into consideration, anaerobic and hybrid treatment systems produce considerably more GHGs compared to the aerobic treatment system.

The contribution of various processes to the generation and consumption of energy in the three treatment systems are examined in Fig. 4. Anaerobic digester is the most energy producing process, contributing to 100%, 55% and 60% of the overall energy needs of plants in the aerobic, anaerobic and hybrid treatment systems, respectively, while anaerobic reactor contributes to 45% and 40% of the energy needs of plants in the anaerobic and hybrid treatment systems, respectively.

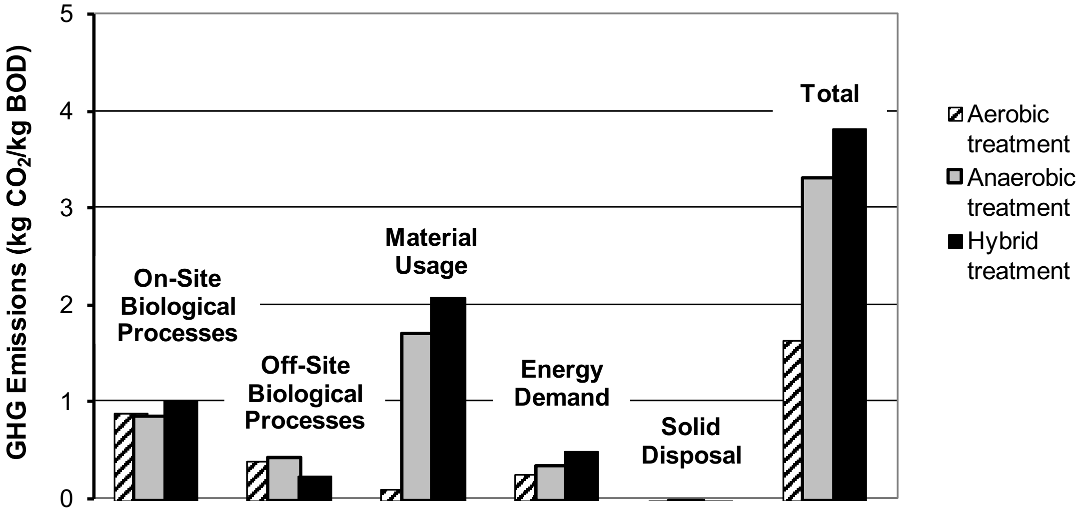

Fig. 3 Greenhouse gas (GHG) emissions by the individual on-site and off-site processes in the three treatment systems examined

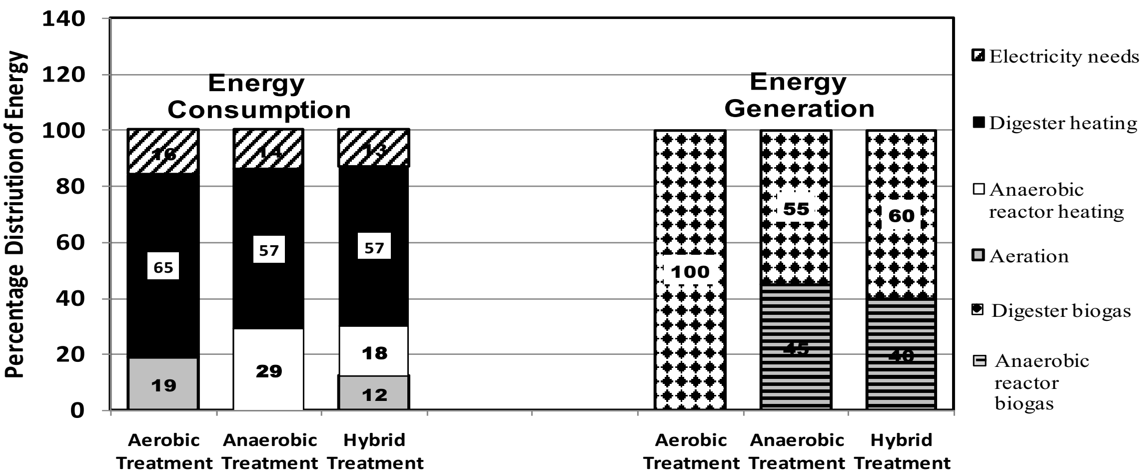

Fig. 4 Percentage contribution of various processes to energy consumption and generation in the three treatment systems examined

Digester heating consumes the highest amount of energy and accounts for 65%, 57% and 57% of total energy consumption in the three treatment systems, respectively. This implies that efficient digesters with less heating needs and a higher degree of sludge stabilization will reduce energy needs of the treatment plant and increase biogas production, leading to an overall GHG reduction of the WWTPs.

This study showed that aerobic treatment systems combined with anaerobic solid digestion generate the least GHG emissions compared to anaerobic or hybrid treatment systems. On-site biological processes are the major source of GHG generation in the aerobic treatment system, while material usage is the major source of GHG generation in the anaerobic and hybrid treatment systems.

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