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A Comparative Study of the Various Methodologies for Estimation of Green House Gas Emission from Wastewater Treatment Systems (A Review)

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ABSTRACT

Various methodologies have been adopted for estimation of greenhouse gas (GHG) emission from wastewater treatment systems. Intergovernmental Panel on Climate Change (IPCC), World Resources Institute and the U.S. Environmental Protection Agency have provided general guidelines for estimation of CH_4 and N_2O based on per capita total waste loads. Bridle Consulting, (2007) has identified five distinguished parts where greenhouse gases are emitted, namely the bio-treatment, sludge treatment, chemical usage, power consumption and biogas production and proposed an empirical static model for estimation of GHGs. Monteith et al., (2005) suggested a rational procedure for estimation of GHGs from municipal treatment plant. A comprehensive mathematical model was proposed by Shahabadi et al., (2009 & 2010) that estimates GHG emission from on-site and off-site activities. Detailed mechanistic models that dynamically describe the behaviour of wastewater treatment plants have been developed by Ashrafi et al., (2013).

The present work is dedicated to briefly describe the various important methodologies and models available for the estimation of GHGs emission from wastewater treatment plant. A comparative study will also be conducted to identify their usefulness and their accuracy in estimation GHGs as extended work of the present study.

Keywords: Wastewater treatment, greenhouse gas, climate change, static and dynamic model.

INTRODUCTION

The Earth is the only planet in the solar systems that supports life due probably presence of water, oxygen – rich atmosphere, and a suitable temperature. Only Earth is known to have an atmosphere of the proper depth having suitable chemical composition, which are probably essential requirements for suitable condition to nurture various forms of lives on the planet. Most of it is nitrogen

(78%), comprises inert part of the atmosphere; about 21 % oxygen, essentially required for respiration activities in all lives forms; and only a small fraction (0.036 %) is made up of CO_2 which plants require for photosynthesis[1]. The atmosphere is critically responsible for trapping sufficient amount of energy released from the Sun and thus maintaining life sustaining environment on the Earth. If all this energy were to be retained by the atmosphere completely, the Earth would gradually become hotter and hotter. But actually the Earth both absorbs and simultaneously releases it in the form of infrared waves. All this rising heat is not lost to space, is partly trapped by some gases present in very small quantities in the atmosphere [2]. These gases are known as Green House Gases (GHGs). The GHGs mainly comprises of CO_2, CH_4, N_2O, water vapour, O_3 remit some of this heat to the Earth surface. If these gases would not be present in the atmosphere, most of the heat energy received from the Sun would escape leaving the Earth cold (about 18°C) and thus unfit to support life[3]. Several man-made gases, which are generally more potent than the previous GHGs such as chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF6) etc, have also been introduced to the atmosphere. In the recent years the manmade activities have significantly added quantities of GHGs to the atmosphere resulting in elevated mean average temperature of the Earth commonly known as Global Warming.

Sources of GHGs emission

The main sources of GHGs due to following human activities :

- Burning of fossil fuels and deforestations leading to higher CO_2 concentration in air. The deforestations accounts for up to one third of total anthropogenic CO_2 emissions.
- Industrialisation adds CO_2, CH_4 and other GHGs to the atmosphere.
- Fermentation, manure management, rice farming, land use and wetland changes, covered vented landfill emissions, vented septic systems waste and wastewater management are sources of atmospheric methane.
- Use of CFC in refrigeration and in fire suppression system.
- Agricultural activities lead to higher N_2O concentrations.

Sector wise global GHGs emission

Global GHGs emissions by various economic activities/sources for the year of 2004 are presented in Table 1. :

GHG emission from wastewater treatment

Wastewater treatment plants are employed for the destruction of the causative agents of water related diseases, conversion of waste into reusable resources; conserve water and nutrients and prevention of pollution of water bodies as well land. WWTPs use energy for lifting wastewater as well used in different processes. The energies supplied to WWTPs is responsible for emission of GHGs at the source of its generation. Besides this, the WWTPs emit GHGs at different stages of wastewater treatment process. The materials used in contraction as well operation and maintenance of WWTPs also emit GHGs at the stage of production of materials. Due to the above facts the WWTPs are recognised as one the larger minor sources of GHGs emission[5,6].

Methodologies for Estimation of GHG Emission

In the recent years, the awareness about emission of GHG emission has increased worldwide due to increasing concern of Global warming having adverse effect on climate change. The GHGs have different Global Warming Potential (GWP). A small quantity of gas emitted with a high GWP has a greater effect on the atmosphere than a gas with low GWP. One kg of N_2O and CH_4 will have the same heat trapping potential as 296 and 23 kg of CO2 respectively. The WWTPs emit considerable amount of GHGs during on-site and off-site activities. Efforts have been made by various pollution control authorities as well various organisations/research groups working in the field and laboratories to estimate/inventories the GHGs emissions. There are different types of methodologies and models available. On the one hand there are methodologies available for inventories of GHGs emission with help of emission factors[6,7,8] and on the other hand empirical static models[9,10] and detailed dynamic model[11] are available for inventories and estimation of GHGs. Major methodologies and models are described as under:

Methodology for estimation of GHG emission by Intergovernmental Panel on Climate Change (IPCC)

The Intergovernmental Panel on Climate Change (IPCC) is a leading international body jointly established by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) for the assessment of climate change and its potential impacts on environmental and socio-economic development[12]. IPCC has probably suggested first detailed methodology for estimation of green house gas emission in 1997. Further in 2006 a modified guideline known as "2006 IPCC Guidelines for National Greenhouse Gas Inventories" was published in five volumes. Detailed information about these is available on www.ipcc-nggip.iges.or.jp/public/2006gl/index.html[13]. The fifth volume of the said document is titled as "Waste". In this volume, a detailed procedure for estimation of GHG emission from various categories of wastes such as Solid waste disposal, Biological treatment of solid waste, Incineration and open burning of waste, and Wastewater treatment and discharge are described by IPCC 2006[7]. The sixth chapter on the "Waste" is dedicated for "wastewater treatment and discharge" related to GHG emission.

A wastewater treatment (domestic / industrial) system produces gases which are well known for their direct global warming potential such as CO_2, CH_4 and N_2O. IPCC 2006 has not included CO_2 emission as GHG due to its biogenic origin and thus only CH_4 and N_2O could be estimated[7]. Emission of NH_3 is also indirect source of N_2O; still IPCC does not provide any methodology for its estimation.

Methodology for estimation of CH_4

GHG emission from the wastewater treatment system is primarily due the content of organic matter present in the wastewater. Besides this, there are several other factors which govern the GHG emission. These are climatic conditions; availability, type and condition of sewerage system; type of treatment process; efficiency of the treatment process employed, economical status of the region etc. For the estimation of GHG emission several data related to wastewater characteristic, coverage and type of sewerage, degree of treatment employed, final disposal of effluent to the receiving bodies etc. Depending upon availability of data, IPCC 2006 suggests three tier methods as described below[7]:

Tier 1 method: This method is application with limited availability of data and hence, specific emission factors are considered for estimation of GHG emission.

Tier 2 method: This method also considers country specific emission factor and country specific activity data in addition to default values as taken in Tier 1 for estimation of GHG emission.

Tier 3 method: This method is applicable where most of the desired data are available.

Variation in wastewater treatment system and final effluent disposal pathway is very common for rural and urban areas. This variation can also be observed country to country, region to region. Considering these issues, IPCC 2006 has prepared an inventory table "(Table 6.5)" which suggests factors to be incorporated, values for various degree of urbanisation, degree of utilisation of treatment or discharge pathway or method for several income groups. Besides these, several other default values are also recommended by IPCC 2006[7].

Methodology for estimation of N_2O

Possibility of Nitrous oxide (N_2O) emissions is grouped in two categories. First category includes the emission that come directly from treatment plants and termed as direct emission. The second category encompasses all the emissions taking place after discharge of effluent (treated wastewater from a wastewater treatment plant) and known as indirect emission. The indirect emission may occur during the transportation of treated wastewater or at place where it is finally disposed off into aquatic environment such as lake, river, wetland, sea etc.

Direct emissions from nitrification and de-nitrification in wastewater treatment process may be considered as a minor source, because the emissions are generally much smaller than those from the effluent disposal including its pathway. The suggested overall emission factor to estimate N_2O emissions from a wastewater treatment plants is 3.2 g N_2O/person/year. For the estimation of indirect N_2O emission from the effluent disposal and its pathway suitable equations are also suggested by IPCC 2006[7]:

Methodology for estimation of GHG emission adopted by World Resources Institute, USA

World Resources Institute, Washington DC, USA, recommends the methodologies for estimation of GHG emission[8]. To make estimation simpler and user friendly an analysis tool—the Climate Analysis Indicators Tool (CAIT) is made available through its website "http://cait.wri.org" free of cost[14]. CAIT has several products having its own importance. Some of the products are discussed below:

CAIT (online) is web-based interface software which provides sector wise *country*-level GHG emissions data for 186 countries.

Three additional modules of CAIT, incorporating different data and indicators are as under:

CAIT-UNFCCC is a basic interface for viewing and analyzing official GHG emissions data submitted by UNFCCC signing Parties to the Convention Secretariat.

CAIT-U.S. is an interface for viewing data and indicators pertaining to U.S. *states*.

CAIT-V&A is an interface for viewing data and indicators related to country's vulnerability and adaptive capacity.

The data base of CAIT software was prepared from various sources such as Carbon Dioxide Information Analysis Center (CDIAC), U.S. Environmental Protection Agency (EPA), International Energy Agency (IEA), Energy Information Administration (EIA), etc. However for waste sector most of the methodology/data were procured from US EPA.

Methodology for estimation of GHG emission adopted by Water Environment Federation[15]

Water Environment Federation has issued a Technical Practice Update (TPU) for the estimation of GHG emission particularly from wastewater treatment facilities. Brief discussions on protocols developed by several important organisations involved in prescribing voluntarily, GHG emission reporting standards are summarised. These organisations are The World Resources Institute/World Business Council for Sustainable Development (WRI/WBCSD) GHG Protocol (2005), The Climate Registry (TCR), and The Organization of International Standards (ISO) 14064 GHG standard 2006 etc. Information from the protocols and other relevant field observations are collected by WEF to develop improved estimating methods and emissions factors that can be used to more accurately characterize local facility-level emissions based on specific operating parameters. In all cases the same procedure was followed for the preparation of GHG emission inventory. The methodology involves selecting a base year, establishing inventory boundaries, identifying and categorizing facility GHG emissions sources and finally quantifying the emissions in term of CO_2 equivalent.

Methodology for estimation of GHG emission adopted by U.S. Environmental Protection Agency (US EPA)

Methodology prescribed by US EPA for the estimation of GHG (CH_4 and N_2O) from domestic wastewater treatment process are listed in two separate head namely first for CH_4 estimation and second for N_2O estimation. Similar to IPCC, there is no place for CO_2 emission considering it as biogenic source. CH_4 may be released from both onsite treatment facilities such as septic system and from off-site centralised treatment system such as publicly owned treatment works (POTWs) under following four categories:

i. Septic system
ii. Centrally Treated Aerobic Systems
iii. Centrally Treated Anaerobic Systems
iv. Anaerobic Digester

The total emission from domestic wastewater sector is the summation of all four as listed above.

N_2O Emission Estimation from Domestic Wastewater Treatment: US EPA follows the similar methodology as prescribed by IPCC,2006.

The above mentioned methodologies adopt procedure to inventories the region wise / country wise GHGs emissions based on various emission factors to predict over all emission. The country or the region considered for GHGs inventories have wide diversity in terms of climatic and geographical conditions, waste generation potential, other social and cultural practices. These factors have bearing on GHGs emissions but not taken care of in GHGs inventories. For example in India the conditions in Laddakh and Kashmir are very different in condition in Rajsthan. However country specific emission factor taken for India will not be giving real picture of overall GHGs inventories. These methods do not consider in depth various physical, chemical, biological, microbial processes involved in wastewater pathway, wastewater treatment and effluent disposal system hence do not estimate realistic GHG emissions from wastewater. More specifically the IPCC approach does not incorporate the strategies to reduce GHG emission at wastewater treatment plants[9] The GHG emissions inventories based on above methods serve only the guiding factor to access and plan for control of GHGs emission. Thus, they are more dedicated for the calculation or estimation of national/regional level GHG inventories than the plant or process specific estimation. In this regard Yerushalmi *et al*. 2011[16] also supported the above statement. One of the most important limitations associated with the assumption is not to include CO_2 emission coming from degradation of biomass or food waste etc in wastewater treatment plant due to its biogenic origin[7,17]. Thus the above methods may not be applicable for calculating GHG emission produced by a given wastewater treatment plant. It is worthwhile to mention that without use of fossil fuel, biomass or food are rarely produced. Thus CO_2 emission due to degradation of organic waste from wastewater may be included in total GHG emission. Use of energy and materials in WWTPs does have GHGs emissions at its production as well in transmission and transportation to the treatment sites. However the inventories suggested by above said methodologies do not include GHGs emission for waste sector for energy and material related consumption. Hence the prediction of the GHGs emission through above inventories does not give the realistic picture for the sector.

Wastewater treatment plants emit GHGs through different processes involving treatment techniques. Kyoto and subsequent protocols considered the wastewater treatment plant as highly vulnerable to impose taxes and penalties on GHGs emission. The wastewater treatment plant should be based on the abatement strategies to reduce generation of GHGs and avoid possible carbon GHGs taxes. The wastewater treatment plants may adopt treatment techniques which can reduce carbon footprints and claim carbon credit. The process parameters and operating conditions of the WWTPs can be optimised by identifying the key process parameters that control GHG emissions. Keeping above in view many researchers have tried to suggest optimization of process parameters and operating condition to reduce the overall GHG emission from WWTPs[9].

Besides the above major methodologies for estimation of GHGs emission from wastewater and wastewater treatment plant, following are the methods adopted by various researchers. The researchers have tried to study the actual processes responsible for GHGs emissions based actual plant studies as well process studies. These methods can be utilised not for only GHGs emissions but also for controlling the emissions from wastewater and its treatment and disposal. The researchers have tried to develop static and dynamic models on laboratory/ field observations for estimation of GHGs emissions. These methods are briefly described as under:

Methodology for estimation of GHGs emission adopted by Bridle Consulting(2007)[10]

According to Bridle (as described in Snip (2010)[18]), following five segments namely bio-treatment, sludge treatment, chemical usage, power consumption and biogas production are GHG emitting in a wastewater treatment system. For each segment an empirical individual model was proposed for estimation of GHGs. For the bio-treatment, Bridle has proposed comprehensive model, which consists of three processes namely endogenous biomass decay, BOD oxidation, and nitrogen removal, where GHG production can take place. The comprehensive model also includes the emissions due to the use of chemicals. The GHG's can be realistically estimated with the model. The most GHG are produced during anaerobic digestion and sludge reuse. The N_2O emission can be modelled dynamically and in more detail. This gives a more realistic view of the N_2O production during the treatment of wastewater and the generation.

Table 1: Sector wise global GHG emission[4]

S. No.	Sector	% Emission	Remarks
1	Energy Supply	26	Due to fossil fuel burning
2	Industry	19	Emission from energy use excluded
3	Land Use, Land-Use Change, and Forestry	17	Decay of peat soil included, CO_2 removal by ecosystem not included
4	Agriculture	14	Biomass burning included
5	Transportation	13	Fossil fuel burning included
6	Commercial and Residential Buildings	8	Only includes on-site energy production and burning of fuel for heating purposes
7	Waste and Wastewater treatment	3	CO_2 emission from incineration of fossil fuel based (waste) products included.

Methodology for estimation of GHGs emission adopted by Monteith *et al*., (2005)[9]

Montheith *et al*., (2005)[9] developed a rational procedure for estimation of GHG emission from municipal wastewater treatment plant. The procedure can be used either with plant – specific data or more general regional data to estimate a facility's carbon-based GHGs emissions per cubic meter of treated wastewater for different processes. The principal GHGs gases emit from municipal wastewater treatment plant to be CO_2 with very little methane CH_4. The procedure was evaluated using full-scale data from 16 Canadian Wastewater treatment facilities and the applied to 10 Canadian Provinces. The procedure identifies the opportunities to reduce GHG emissions at municipal wastewater treatment plant.

For use of the procedure, an appropriate system boundary and inputs required for the system were identified. The GHGs producing processes within the systems were identified and approaches for determining GHG emissions were developed for the cases where plant-specific data are and are not available. The GHG emissions calculation using plant specific data were compared to the serialised calculations developed for use in the absence of plant level data. The method estimates the carbon based GHG emissions that is mainly CO_2 and CH_4. This method has not considered the emission of N_2O, a component of GHG from wastewater treatment plant. However the author has suggested additional work to conduct N_2O estimation at treatment facilities looking over the potency of N_2O as GHG. The estimation of carbon based GHG emission is limited to onsite treatment processes under system boundary. The results of this methods shows that the predominant GHG emitted from facilities in Canada is CO_2. Methane produced during anaerobic digestion of solids is combusted to produce CO_2 hence reduce the potency CH_4 as compared to CO_2. This method does not include the GHG emissions of off-site electricity generation used for treatment plant, off-site transportation and degradation of solids, off-site chemical production and degradation of treated effluent disposal.

Methodology for estimation of GHG emission adopted by Shahabadi *et al*., (2009 & 2010)[19, 20]

A comprehensive mathematical model was proposed by Shahabadi *et al*., (2009 & 2010)[19,20] that estimate over all GHG emission from on-site and off-site activities of wastewater treatment plant considering different types of treatment processes including aerobic, anaerobic and hybrid - anaerobic/ aerobic processes. The emission estimation procedure estimate on-site and off-site CO_2 and CH_4 production only and do not estimate N_2O emission due to unavailability of relevant data. The off-site GHG emissions based on electricity consumption for mixing of liquid in the reactors, illumination of plants and operation of electrical devices. For this purpose the emission factor for the source of electricity generation has been considered for CO_2 emission based on electricity demand in the plant.

The off-site GHGs emission due to degradation of remaining bio-solids in the effluent of digesters has been estimated. They have also tried to estimate impact on GHG emissions due to recovery of biogas and its use. They further have studied on impact of GHGs emissions due to nutrient removal. The overall on-site GHGs emission expressed in terms of CO_2 equivalent per day was found more than off-site emission in case of aerobic treatment system. However the results found in case of anaerobic as well hybrid treatment system was different than the aerobic treatment system. It means the off-site overall GHG emission was more than on-site emission in case of anaerobic and hybrid treatment systems. Based on the results obtained, the authors have also suggested GHG mitigation strategies based on recovery and use of biogas for energy generation to replace fossil fuel combustion. Authors have recommended psychrophilic treatment instead of mesophilic and thermophilic treatments in digester to minimise the consumption of energy in digester. For GHGs reduction, the authors have recommended strategies to use alternative nutrient removal processes such as the anaerobic process, anammox that removes nitrogen with a lower consumption of energy and lower carbon use.

Yerushalmi *et al*., (2011)[16] has studied the effects of major process parameters in the wastewater treatment process as considered by Shahabadi *et al*., (2009 & 2010)[19, 20] that are aerobic, anaerobic and hybrid on the overall on and off-site GHGs emissions. The key process parameters considered identified as the under flow rate in primary clarifier, SRT and temperature of reactors and sludge digesters. The operating temperature of anaerobic sludge digester has highest effect on GHGs generation in the aerobic treatment system. Based on the study the authors have recommended strategies for the reduction of GHGs emissions in different types of treatment process systems. In aerobic treatment process, minor GHG emission can be achieved by reduction in the removal ratio of VSS and increase removal ratio of BOD in primary clarifier. In anaerobic treatment system reduction is GHG emission will be achieved by reducing wasting ratio of anaerobic reactor. In hybrid treatment system GHGs reductions are accomplished by reductions in the VSS and BOD removal ratios of primary clarifier, increase of SRT and decrease of wasting ratio of anaerobic reactor and decrease of SRT in the anaerobic digester.

Methodology for estimation of GHG emission adopted by Ashrafi *et al.*, (2013)[11]

Ashrafi *et al*., (2013)[11] have developed dynamic model for estimation of GHG emission as well energy consumption in WWTPs. Considerable variation in the GHGs emissions by on-site and off-site activities in various treatment processes such aerobic, anaerobic and hybrid processes have been observed because of varying process parameters including influent substrate concentration, inflow rate and temperature. The dynamic model developed by Ashrafi *et al*., (2013)[11] has showed more realistic estimation of GHGs emissions as it is based on actual variation of process parameters. Hybrid biological process has showed more fluctuation as compared to aerobic and anaerobic biological process. Though the prediction by dynamic model is bit difficult as it involves consideration varying process parameters but its prediction is more accurate compare to static model.

CONCLUSIONS

WWTPs are responsible for GHGs emission during various stages of processes. Hence quantification and inventories of GHGs emissions are warranted. For this purpose several methodology and static/dynamic mathematical models are proposed by various pollution control authorities, other related organisations and research groups. IPCC has probably suggested first detailed methodology/guidelines for estimation of green house gas emission in 1997 and subsequently in 2006[4,5]. Depending upon availability of data, IPCC 2006 suggests three tier (tier 1, tier 2 and tier 3) methods. To make the estimation simpler and user friendly World Resources Institute (WRI) USA has provided web based interface software which calculates sector wise country level GHG emission[8]. Water Environment Federation has also issued a Technical Practice Update (TPU) for the estimation of GHG emission particularly from wastewater treatment facilities. Information from the other organisation such as (WRI/WBCSD) GHG Protocol (2005), The Climate Registry (TCR), and The Organization of International Standards (ISO) 14064 GHG standard 2006 etc including relevant field observations are incorporated by WEF (2009)[15] to develop improved estimating methods and emissions factors that can be used to more accurately characterize local facility-level emissions based on specific operating parameters. US EPA has also suggested mathematical equations for the estimation of GHG (CH_4 and N_2O) from domestic wastewater treatment process are listed in two separate head namely first for CH_4 estimation and second for N_2O estimation. The method prescribed by US EPA is very similar to IPCC methodology. None of the above organisations suggests any methodologies for the estimation of CO_2 emission released due to decomposition of organic wastes in WWTPs because of it biogenic origin. Moreover these methodologies are found limited application in estimating plant specific GHG estimation. To improve plant specific estimation procedure several research groups come forward and suggested several static and dynamic models[9,11,16,19,20]. Ashrafi *et al*., (2013)[11] after studying the actual processes responsible for GHGs emissions during WWTPs operations. These methods can be utilised not for only GHGs emissions but also for controlling the emissions from wastewater treatment and disposal.

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