ABSTRACT

India is a fast developing nation witnessing rapidly expanding industrialization, increasing economic income, rising transport along with population growth. These factors are side by side contributing in anthropogenic emissions of greenhouse gases (GHG), which pose a serious threat of climate change. Recognizing the seriousness of the climate change issues, India is engaged actively in multilateral negotiations under the United Nations Framework Convention on Climate Change (UNFCCC). India has launched its National Action Plan to deal with the climate change. Under this action plan, a National Mission on Sustainable Habitat was also launched to make habitat sustainable by the incorporation of energy efficiency buildings, management of solid waste, etc. besides other elements. The municipal solid waste (MSW) is normally dispose off in landfills, which, if not scientifically managed, will lead to emissions of GHGs like CH$_4$, CO$_2$, N$_2$O and volatile organic compounds (VOCs).

In India, the landfills have been estimated to contribute about 604.5 Gg of CH$_4$ by the India’s Second National Communication (SNC) submitted to UNFCCC by the government of India in 2010. The SNC has also estimated the compound annual growth rate (CAGR) of CH$_4$ emission from the waste sector as 7.3% during the period of 1999 to 2007, which indicates the significance of this sector in the emission of national GHG. However, information of a large number of factors like waste generation quantities, waste composition, collection of waste, recycling efficiencies, biochemical processes in the landfills, etc. are not available in India, and therefore, there exists large uncertainties in GHG mission estimation from MSW. There is an urgent need to address these issues by developing quality information on GHG emission from waste sector and help in identification required mitigation action.

The research work presented in this thesis aims at addressing these issues by carrying out field measurement of GHG missions in the three existing landfills of Delhi and estimating the CH$_4$ emissions from landfills using different models like IPCC default method (IPCC-DM), first order decay (IPCC-FOD) and modified triangular method (MTM). The CH$_4$ emission estimates from the MSW in India have also been developed using FOD method in both bottom up and top down approaches and associated
uncertainties in these estimations have also been assessed. The measurement and theoretical estimations have also helped in determining the country specific decay constant ($k$) and oxidation potential (OX) which is critical parameters in modeling studies of CH$_4$ emissions from landfills. Laboratory studies have also been carried out through incubation experiments on MSW soils for assessing the landfill gas (LFG) generation potential and effects of limiting factors on LFG generation. Finally, an assessment of energy generation potential of Delhi’s MSW has also been carried out to assess the variability of different waste to energy (WTE) technologies.

All these measurements were conducted at the three landfills of Delhi’s namely, Ghazipur (28° 37’ 22.4” N, 77° 19’ 25.7” E); Bhalswa (28° 44’27.16” N, 77° 9’ 27.92” E); and Okhla (28° 30’ 42” N, 77° 16’ 59” E) during the period of 2008 to 2011. Based on the average municipal corporation of Delhi (MCD) records, daily MSW dumping was estimated to be about 2200, 1500, 1200 t from Ghazipur (GL), Bhalswa (BL) and Okhla (OL) respectively. The types of MSW received at GL include waste from household, animal waste from poultry, fish market and slaughter houses. BL receives waste, mainly from households, vegetable market, besides construction and demolition (C&D) waste. OL receives households, street sweeping waste along with C&D waste.

The field measurement carried during the year 2008-2011 periods yielded the CH$_4$ emission fluxes at GL, BL, OL as 1494±893, 1576±746 and 961±322 mg m$^{-2}$ h$^{-1}$ respectively. Using the measured CH$_4$ emission and the quantity of MSW disposed in each of the three landfills during these years, average CH$_4$ emission factors (EFs) have been computed as 5.6±3.5, 4.4±1.9 and 4.2±1.4 g kg$^{-1}$ for GL, BL and OL, respectively. CO$_2$ emission fluxes have been found to be 7520± 3401, 8005±3907 and 5066±1985 mg m$^{-2}$ h$^{-1}$ in GL, BL and OL respectively. The corresponding CO$_2$ EFs have been computed as 20.0±7, 23.3±9 and 16.3±4.7 g kg$^{-1}$ for GL, BL and OL, respectively. N$_2$O emission fluxes have been found to be 1210±329, 998±298 and 944±339 μg m$^{-2}$ h$^{-1}$ in GL, BL and OL as respectively. The N$_2$O EFs have been computed as 3.8±0.1, 2.5±0.2 and 3.1±0.3 mg kg$^{-1}$ for GL, BL and OL, respectively. The measurements reveal high temporal and spatial variability in the LFGs emissions from landfills.

The CH$_4$ emissions from landfills have also been estimated using IPCC default method (DM), IPCC first order decay (FOD) and modified triangular method (MTM).
The DM estimation showed CH$_4$ emission from GL, BL and OL as 23.0, 22.8 and 18.7 Gg respectively for the year 2013. The FOD method yielded the CH$_4$ emission values GL, BL and OL as 17.7, 14.5 and 11.4 Gg respectively for the year 2013. The MTM showed in CH$_4$ emission values from GL, BL and OL as 21.0, 15.9 and 16.8 Gg respectively for the year 2013. Therefore, the total CH$_4$ emission has been estimated as 64.5, 53.7 and 43.5 Gg respectively from landfills in 2013 by DM, FOD and MTM respectively. The average CH$_4$ EFs have been computed as 15±7, 19±11 and 31±5 g kg$^{-1}$ using FOD, MTM and DM method respectively. It is evident from these estimations that the DM yields the highest emission values followed by MTM and FOD methods. It is, therefore, important to use CH$_4$ EFs developed through in-situ measurements which captures the site specific circumstances for reduction of uncertainties in CH$_4$ emission estimation.

The IPCC FOD methodology recommends the use of decay rate constant ($k$) and oxidation factor (OX). However, such values were not available for Indian MSW. In view of this an effort has been made to generate country specific decay constant based on the studies carried out for $k$ value and OX Delhi’s landfills. The present study reveals that the OX values of 20% for GL & BL and 23% for OL is associated with $k$ values of 0.09, 0.07 and 0.07 y$^{-1}$ for the GL, BL and OL respectively moderate degradability, yields CH$_4$ emission as 8.2, 4.4 and 3.3 Gg from GL, BL and OL respectively by FOD method. The CH$_4$ emission values are close to measured CH$_4$ emissions. Therefore, these OX and $k$ values seem to represent the landfill specific values. However, further research is required to develop country specific OX and $k$ values by undertaking experiments in other landfill in various region of the country.

The national CH$_4$ emissions for the year 2011 from the landfills in India using IPCC-FOD method has been developed using both bottom up and top down approaches. The bottom up approach that include development of city/town wise CH$_4$ emission estimation incorporating available information on various input parameters like state wise per capita MSW generation rate ($W_{pt}$), increasing rate in per capita MSW generation ($W_i$), MSW collection efficiencies ($C_f$), fraction of recyclable materials ($R_f$), waste composition (F), decay constant ($k$), CH$_4$ correction factor (MCF), degradable organic carbon (DOC), fraction of degradable organic carbon (DOC$_f$), fraction of CH$_4$ in LFG ($M_f$), MSW treatment facilities, etc. In addition, IPCC-FOD method has also been
employed to estimate national CH$_4$ emissions from MSW in India for the year 2011 using top down approach. Monte Carlo simulation was conducted with different input parameters to the IPCC-FOD method to estimate the total input uncertainty in the CH$_4$ emission estimates developed using top down approach and also to assess the relative strength of different parameters influencing the uncertainties in emission estimation. City-wise CH$_4$ emission estimations from landfills of 7863 cities of India have been generated using the IPCC FOD method incorporating the city level values of input parameters in a bottom up approach. The summing up the city wise emission estimation yielded the total CH$_4$ emission from MSW in India as 572 (± 206) Gg for the year 2011. The top down approach has resulted in national CH$_4$ emission as 531 (± 297) Gg from MSW in India in the year 2011. Monte Carlo analysis of all the input parameters to the IPCC-FOD method in the top down approach indicates uncertainties in the parameters like $W_{pt}$, $F$, $k$, MCF, DOC and $M_f$ account to about 42%, 43%, 46%, 25%, 23% and 19% respectively while the uncertainty in the parameters like $W_i$, $R_f$, $C_f$, and DOC$_f$ accounts to 4%, 2%, 5% and 5% respectively in the CH$_4$ estimation using the IPCC-FOD.

The degradability of MSW has been determined through incubation experiments. During these experiments the initial concentrations of OC, N, S, O, H in MSW have been found as 19.1, 1.39, 0.34, 23.0, and 4.8%, respectively, which at the end of the experiment; reduced to 9.7, 0.54, 0.11, 11.3 and 1.0% for OC, N, S, O, and H respectively. The inorganic carbon (IC) has been found as < 1% in the total carbon content at the beginning, which was found to be almost unchanged at the completion of the experiment. By molar composition, the chemical formula of MSW has been found as C$_{12.5}$H$_{29.7}$O$_{9.8}$N. The experiment revealed that the loss of substrate (i.e. decay) in the early period of the experiment was rapid (exponential loss) followed by slow decay for a long period of time. The decay rate ($k$) has been calculated as 0.27 y$^{-1}$ which is representing fast degradability of organic waste. Depending upon the $k$, the half life ($t_{1/2}$) of the MSW samples has been calculated as 2.6 years.

Finally an assessment of energy generation potential of Delhi’s MSW also been carried out assess the viability of different waste to energy (WTE) technologies. The MSW to energy market in India is expected to grow at a compound annual growth rate (CAGR) of 9.7% by 2013 and the technology can array for mitigation of GHG emission
from MSW. Hence there is a need to assess the appropriateness of different technologies for their use for Indian MSW. In the present study, the energy generation potential of MSW reaching to three landfills of Delhi under different technological options available for waste to energy (WTE) generation has been assessed. For these purpose, the total MSW (i.e. bulk MSW) and segregated MSW (after removal of recyclable materials) have been considered in association with their calorific value. The WTE generation potential of different technologies like biomethanation, incineration, refused derived fuel (RDF), pyrolysis/gasification and plasma arc gasification have been assessed. The plasma arc gasification technology showed the highest energy generation potential ranging from 17-35, 16-32 and 11-28 MWd\(^{-1}\) from the MSW of GL, BL and OL respectively as compared to the other technologies like gasification/pyrolysis technology (17-32, 16-29 & 11-25 MW d\(^{-1}\) from GL, BL and OL respectively), incineration process (17-32, 16-29 & 11-25 MW d\(^{-1}\) from GL, BL and OL respectively), RDF process (9-19, 8-18 & 6-15 MW d\(^{-1}\) from GL, BL and OL respectively), biomethanation process (3-10, 3-8, 2-8 MW d\(^{-1}\) from GL, BL and OL respectively). Thus, the plasma arc gasification seems to have highest energy generation potential, but a number of other factors like installation cost, handling of by-products, environmental regulations, etc. are required to be considered for identifying the most viable technology for WTE which can also help in emissions mitigating the GHG.

The study shows that landfills in Delhi are a significant contributor in anthropogenic GHG emission in India. Perhaps, higher organic carbon content, moisture and poor landfill management practice pushed to higher emission to GL than BL and OL. The IPCC-DM, FOD and MTM model based CH\(_4\) emission estimations was found 6.3, 3.6 and 5.6 times higher than field estimation. CO\(_2\) emissions in the LFG have been found to be higher by about as 20-23% than the reported values. Using these oxidation factors, decay constant (\(k\)) estimated as 0.09, 0.07 and 0.07 for the GL, BL and OL respectively. National CH\(_4\) emission estimations from MSW was found to be 572 Gg by the bottom up while 531 Gg by top down approach in the year 2011. By the degradability of MSW assessment in the laboratory it was found that \(k\) value as 0.27 y\(^{-1}\) while \(t_{1/2}\) as 2.6 years. In the energy generation potential of MSW assessment of different technologies, plasma arc gasification seems to have highest energy generation potential.