Technical Note

National Municipal Solid Waste Energy and Global Warming Potential Inventory: India

Ankur Choudhary[1]; Ashish Kumar[2]; and Sudhir Kumar[3]

Abstract: In this study, the municipal solid waste methane emission, energy, and global warming potential inventory for 2005–2030 is estimated at both national and state level for India using the Intergovernmental Panel on Climate Change (IPCC) default method, IPCC first-order decay methods, the Landfill Gas Emissions Model (LandGEM) with state specific values, LandGEM with default inventory values, and LandGEM with Clean Air Act values. Simulations made by LandGEM with state specific values show that India will be emitting 1,084 Gg methane in 2020 and expected to reach 1,969 Gg in 2030 if the existing scenario does not change in India. If suitable measures, such as the conversion of open dumps into sanitary landfills with landfill gas collection mechanisms, take place, an amount equal to 1,387 MW of energy in the year 2030 (using LandGEM state specific values) can be conserved. The study concludes that efforts in the direction of scientifically managed landfill with proper landfill gas collection mechanisms can turn the table in India's favor in the future and help to achieve the nation's quest for the development of renewable energy. **DOI: 10.1061/(ASCE)HZ.2153-5515.0000521**.

Author keywords: Municipal solid waste; Energy; Global warming potential; Open dump; Greenhouse gases; Landfill gas.

Introduction

In the last few years, the generation of municipal solid waste (MSW) has been a function of population, urbanization, and economic growth (Du et al. 2017). A recent report submitted by the central pollution control board (CPCB) stated that urban India is currently generating approximately 135,198 t of MSW every day (CPCB 2017) and the generation of MSW is further expected to increase in coming years. Owing to insufficient budget allocation and less awareness among local bodies, almost every municipal corporation is disposing of 75%–80% of the total MSW on open dumps without further treatment (Chakraborty and Kumar 2016). The MSW in the open dump is subjected to natural anaerobic degradation, where emissions of carbon dioxide (CO_2), methane (CH_4), hydrogen sulfide (H_2S), and other gases occur, in which CH_4 and CO_2 constitute approximately 80%–90%. (Choudhary et al. 2020; Ramani et al. 2012). Moreover, both the gases are greenhouse gases (GHGs); in fact, CH_4 has 28–36 times more global warming potential (GWP) than CO_2 and is hence more hazardous to the environment than CO_2 (US EPA 2016). Nevertheless, researchers have found it more useful because it can work as a green fuel for the generation of electricity and heat and for many other uses, if it is successfully collected from landfills. Certainly, properly managed landfills with efficient landfill gas (LFG) collection systems can capture the landfill gas and convert it into heat or electricity onsite or pipe it to industries and landfill projects can be made more attractive from an economic point of view. Hence, this scenario creates a win-win situation for both investors and the environment. So, in this direction, before the implication of any landfill process, quantification of methane generated during the landfill process becomes important and can be estimated with the help of various methods.

A large number of studies have been conducted in several cities or regions of different developed and developing countries for the quantification of methane and other gases. In this context, the IPCC developed analytical methods, such as the default and first-order decay method (IPCC 2006). In addition, the US Environmental Protection Agency (USEPA) developed the Landfill Gas Emissions Model (LandGEM), in which default inventory, Clean Air Act, and region or state specific input parameters can be used (USEPA 2005). A gap has been formed in the corpus of published research, however, because researchers have taken the default input parameters e.g., degradable organic carbon (DOC), half-life (k), and methane production capacity (L_0) suggested by IPCC (2006) or USEPA (2005) for their analyses rather than taking region-specific parameters, leading to further uncertainties and overestimation of GHG emissions, energy potential, and GWP. Moreover, in a study of the literature, it was found that the results of studies in India are lacking in state and national inventories. Hence, inventory of GHG emissions, energy potential, and GWP at state and national level can be prepared with the help of these models which will initiate the research in the field of carbon sequestration and energy potential of MSW in India. The objectives of this study are as follows: (1) to compute the extent of methane emissions from MSW landfills in India from 2005 to 2030; (2) to identify changes in emissions among all states in India; (3) to examine the correlation between GWP from MSW landfills, gross domestic product (GDP), and population, as well as make suggestions for decision-makers in India. This study also evaluates income abilities from MSW disposed of in landfills in India. Moreover, it reviews the current state of production, collection, characterization, and treatment of MSW in India.

[1]Ph.D. Student, Dept. of Civil Engineering, Jaypee Univ. of Information Technology, Waknaghat, Solan, Himachal Pradesh 173234, India. ORCID: https://orcid.org/0000-0001-6202-6714. Email: ankur.ankur5901@gmail.com

[2]Professor, Dept. of Civil Engineering, Jaypee Univ. of Information Technology, Waknaghat, Solan, Himachal Pradesh 173234, India (corresponding author). Email: ashish.fce@gmail.com

[3]Professor, Dept. of Biotechnology and Bioinformatics, Jaypee Univ. of Information Technology, Waknaghat, Solan, Himachal Pradesh 173234, India. Email: sudhir.syal@juit.ac.in

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Methodology

The year 2005 is assumed as the base year and investigation is carried out for the following 25 years. To compute state-wise methane emission, energy potential, and GWP, state-wise MSW generation is a key parameter. The data on state-wise MSW generation for this study are taken from CPCB (2005). In India, the average state-wise MSW generation growth is computed to be 6.68% per year, using data obtained from CPCB (2010) and CPCB (2015) and further used in the analysis (Table 1). To estimate methane emissions, energy potential, and GWP from MSW of all the states and union territories, several methods have been utilized. The detail of each method is given next.

Methane Emission, GWP, and Energy Estimation

IPCC 1996 Default Method ($IPCC_{DM}$)

This method was recommended by IPCC in 1996 and named the IPCC default method for the determination of methane emissions from landfills (IPCC 2006). For any particular landfill site, the methane emitted from total waste deposited up to that instant of time is calculated as (IPCC 2006)

$$CH_4 \text{ emissions} = MSW_t \times MSW_f \times MCF \times DOC \times DOC_f \times F \times \left(\frac{16}{12} - R\right) \times (1 - OX) \quad (1)$$

where MSW_t = total waste generated (Mg/year); MSW_f = fraction of total MSW disposed on landfill (80%); MCF = Methane correction factor; DOC_f = fraction of DOC dissimilated (0.77); F = fraction of methane in total LFG (0.5); R = recovered CH_4 (Mg/year) (default value = 0); OX = Oxidation factor (default value = 0). The values of MSW_f, DOC_f, F, R, and OX are used following the data of Chakraborty et al. (2011) and Ghosh et al. (2019). The values of MCF and DOC are computed using the method suggested by IPCC (2006). State-wise MCF and DOC values are shown in Table 1.

First-order Decay Method ($IPCC_{FOD}$)

This method can be used with site-specific data, i.e., waste generation, population, DOC, DOC_f, the decay rate of waste (k), MCF, or waste composition, or a combination of these, or with default values. Unlike $IPCC_{DM}$, $IPCC_{FOD}$ assumes that organic matter decays slowly by biochemical and microbiological activities and continues for decades; the decay produces LFGs, primarily CO_2 and CH_4 (IPCC 2006). The values used in the analysis are shown in Table 2. Computation of k is achieved by a method suggested by Mohsen et al. (2019) while L_0 is computed by a method suggested by Staley and Barlaz (2009). The methane emissions are calculated using (IPCC 2006)

$$A = \sum_{y-b}^{T-1} \{Q_x L_0 (e^{-k(T-y-1)} - e^{-k(T-y)})\} \quad (2)$$

where A = methane production per year (Mg/year); y = year of waste disposal; b = beginning year of inventory; T = year for which the emission is to be determined; Q_x = waste quantity (Gg); and L_0 = methane production capacity (m^3/Mg); and k = the decay rate of waste ($year^{-1}$).

US EPA's LandGEM

The USEPA has developed an automated tool for the simulation of LFG due to the degradation of total annual disposed MSW within and even after the operation of the site. This method is best suitable for those landfills for which composition or characterization of MSW is not available because the processing of this tool does not require any composition or characterization. LandGEM can be used with land or state specific data ($LandGEM_{SSV}$), default parameters, i.e., inventory ($LandGEM_{inventory}$), or default parameters, such as values obtained from the Clean Air Act ($LandGEM_{CAA}$). The state specific parameters used for these equations are shown below in Table 2. The general equation suggested by US EPA (USEPA 2005) is

$$A_{CH_4} = \sum_{t=1}^{m} \sum_{p=0.1}^{1} kL_0 \left(\frac{N_i}{10}\right) e^{-kX_{ip}} \quad (3)$$

where A_{CH_4} = CH_4 production per (Mg/year); i = increment in time (1 year); m = (calculation year) minus (initial year of waste dumping); p = 0.1 year time increment; N_i = mass of waste accepted in the ith year (Mg); and X_{ip} = age of the pth section of waste mass N_i accepted in the ith year.

Estimation of GWP

To determine the GWP of India due to MSW, $LandGEM_{SSV}$, $LandGEM_{inventory}$, and $LandGEM_{CAA}$ are used. Among various GHGs, only CO_2 and CH_4 were utilized for GWP estimation; this is because only CO_2 and CH_4 are produced in significant quantities at landfills during the anaerobic digestion process. Based on these two models, simulations were run for CO_2 and CH_4 and further utilized in GWP estimation. In accordance with the definition, the GWP potency of CO_2 was taken as one. The GWP potency of CH_4 is 28–36 (US EPA 2016); here it was taken as 31 for analysis purposes. So, in this study, the total GWP (CO_2-eq) was estimated using Eq. (4), as suggested by (US EPA 2016):

$$\text{GWP in Gg}(CO_2 - eq) = CO_2 \text{ emissions in Gg} \times 1(CO_2 - eq) + CH_4 \text{ emissions in Gg} \times 31\ (CO_2 - eq) \quad (4)$$

Results and Discussion

Current Scenario of Sanitary Landfill Facilities and Energy Generation in India

In India, approximately 82% of the waste is collected. Of the collected waste only 20%–25% of waste is treated, while 75%–80% of the waste is openly dumped (CPCB 2015). A significant part of India lacks sanitary landfill sites and LFG collection mechanisms. In fact, today there are only 179 landfills in operation across the India out of which, there are only 12 landfills from which LFG is captured (CPCB 2015). The captured LFG can be utilized as a source of renewable energy. At present, across the country, only 151 MW of heat or other energy is generated using this captured LFG. However, the current and future energy potential from MSW is much greater and should be estimated by researchers. In addition to this, landfills with LFG collection mechanisms should be proposed by the policymakers in the country. The current (2020) and future (2030) energy potential across all the states and union territories has been computed in this study and is shown in the Table 1. Based on the analysis, Haryana is the state with maximum energy potential, i.e., 288 MW in 2030, followed by Maharashtra (198 MW) and Uttar Pradesh (150.9 MW). Further, in the analysis, it was found that all the states collectively have a huge energy potential, i.e., 764 and 1,387 MW in 2020 and 2030, respectively.

Table 1. State-wise MSW generation scenarios and parameters used in various models

States	MSW generation (2005–2006)[a]	Per year growth in MSW (%)	MSW generation (2030)	No. of landfills in operation (2015–16)[a]	DOC	MCF	L_0 (m^3/Mg)	K ($year^{-1}$)	Waste to energy potential in 2020 (MW)	Waste to energy potential in 2030 (MW)
Andaman Nicobar	70	8	210	—	—	0.4	—	0.102	0.8	1.4
Andhra Pradesh	6,440	0	6,440	2	0.112	0.8	31.7	0.038	15.4	21.7
Arunachal Pradesh	13	18.2	72	0	0.138	0.4	58.2	0.097	0.2	0.5
Assam	7,920	−8.6	7,920	0	0.138	0.4	58.2	0.096	60.8	72.4
Bihar	1,670	0	1,670	0	0.128	0.4	41.2	0.045	5.8	8.1
Chandigarh	370	−2.1	370	1	0.118	0.8	31.3	0.021	0.5	0.8
Chhattisgarh	2,245	12.9	9,257	0	0.150	0.4	61.6	0.051	25.4	48.5
Daman Diu	85	21.4	541	—	—	0.4	—	0.074	1.5	2.9
Delhi	9,620	2.7	16,173	4	0.128	0.8	33.7	0.021	18.5	31.4
Goa	450	−1.0	450	6	0.157	0.8	63.1	0.098	3.8	4.5
Gujrat	10,480	5.0	23,603	3	0.130	0.8	37.7	0.041	44.0	75.4
Haryana	4,837	109.98	137,841	10	—	0.8	—	0.021	113.2	288.0
Himachal Pradesh	276	−0.2	276	—	0.194	0.4	70.6	0.032	1.3	1.9
Jharkhand	3,570	21.7	22,985	0	—	0.4	—	0.047	45.7	95.0
Jammu and Kashmir	1,634	0	1,634	2	0.124	0.8	48.0	0.050	7.2	9.7
Karnataka	8,842	7.0	24,376	134	0.137	0.8	46.0	0.038	47.5	86.1
Kerala	1,339	−16.3	1,339	—	0.141	0.4	52.1	0.095	9.1	10.9
Nagaland	344	8.7	1,094	—	0.138	0.4	58.2	0.065	3.7	6.5
Lakshadweep	21	0	21	—	—	0.4	—	0.065	0.1	0.2
Madhya Pradesh	6,678	2.5	10,974	—	0.152	0.4	44.4	0.035	25.3	40.8
Maharashtra	21,867	7.9	65,227	5	0.147	0.8	41.5	0.037	107.0	198.0
Manipur	176	11.1	666	—	0.138	0.4	58.2	0.066	2.1	3.9
Mizoram	552	17.6	552	—	0.138	0.4	58.2	0.133	4.8	5.4
Meghalaya	187	−1.1	187	0	0.138	1	58.2	0.096	1.4	1.7
Orissa	2,574	1.9	3,844	0	0.128	0.4	83.7	0.053	23.5	35.1
Punjab	4,456	8.5	13,993	0	0.112	0.4	36.0	0.025	14.6	28.2
Puducherry	513	6.0	1,289	1	0.181	0.8	95.5	0.041	5.7	10.0
Rajasthan	5,037	0	5,037	—	0.133	0.4	40.9	0.026	11.4	17.0
Sikkim	49	4.0	104	—	0.138	0.4	58.2	0.095	0.5	0.8
Tamil Nadu	230	3.2	416	0	0.137	0.4	39.8	0.041	0.9	1.5
Telangana	6,628	3.0	11,599	1	0.136	1	40.4	0.036	23.7	38.8
Tripura	414	2.6	684	1	0.144	0.8	93.5	0.116	6.8	9.2
Uttarakhand	917	6.9	2,508	0	0.136	0.4	97.7	0.057	13.8	23.8
Uttar Pradesh	15,192	13.1	64,990	9	0.128	0.8	39.1	0.030	74.3	150.9
West Bengal	9,500	−6.1	9,500	—	0.139	0.4	44.2	0.060	43.0	56.2
Total or average	135,196	+6.7	447,849	179	0.139	0.6	54.1	0.058	764	1,387

[a]Source: Data from CPCB (2015).

Estimation of MSW Methane Emissions and Energy Potential

A comparison of cumulative methane emissions from all the states of India at the end of 2030 is shown in Fig. 1. Using $\text{LandGEM}_{\text{SSV}}$ it was found that Haryana (3,820 Gg) has maximum methane emission potential, followed by Maharashtra (3,354 Gg) and Uttar Pradesh (2,377 Gg). The temporal variation of methane emissions for the period 2005–2030 is shown in Fig. 2(a). In Fig. 2, it is also very interesting to notice the behavior of emissions patterns for all the models. In the very first year of the study, $\text{LandGEM}_{\text{SSV}}$, $\text{LandGEM}_{\text{inventory}}$, $\text{LandGEM}_{\text{CAA}}$, and IPCC_{FOD} have predicted zero emissions but IPCC_{DM} has predicted certain emissions. This is attributed to the fact that, with the exception of IPCC_{DM}, the models assume that methane emissions do not start in the same year of waste dumped. In fact, models start predicting emissions after a period of approximately 12–13 months (based on first-order decay kinetics); conversely, IPCC_{DM} utilizes a zero-order equation and assumes that emissions are produced in the same year that the waste was disposed of. Of all the models, $\text{LandGEM}_{\text{CAA}}$ has predicted the maximum cumulative methane emissions for the period 2005–2030. In fact, the results obtained using $\text{LandGEM}_{\text{CAA}}$ are 4.60, 4.72, 2.00, and 1.03 times the simulations made by IPCC_{FOD}, IPCC_{SSV}, $\text{LandGEM}_{\text{inventory}}$, and IPCC_{DM}, respectively. For this duration, the total cumulative methane emissions from India are estimated as 24,541, 56,520, 109,693, 112,913, and 23,936 Gg/year from IPCC_{FOD}, $\text{LandGEM}_{\text{inventory}}$, IPCC_{DM}, $\text{LandGEM}_{\text{CAA}}$, and $\text{LandGEM}_{\text{SSV}}$, respectively. Based on $\text{LandGEM}_{\text{SSV}}$, in 2020 and 2030, the total MSW energy potential in India is 764 and 1,387 MW, respectively. A state-wise MSW energy potential is shown in Table 1. The MSW energy inventory of states shows that Haryana, Maharashtra, and Uttar Pradesh, are among the most

Table 2. Economic and environmental benefits of methane produced from Indian MSW

Parameter	2020	2025	2030
[a]Methane potential (Gg)	1,084	1,511	1,969
[a]GWP CO_2-eq (Gg)	36,599	50,989	66,443
[b]Revenue from carbon credit (million USD)	483	673	877
[c]Equivalent electricity generation (GWh)	6,692	9,324	12,150
[c,e]Equivalent electricity generation (MW)	305	425	554
[d]Revenue from electricity sale (billion USD)	478	666	867

[a]Estimated using $\text{LandGEM}_{\text{SSV}}$.
[b]USD 13.2/t of equivalent emission.
[c]Based on the methane calorific value 55,530 kJ/kg.
[d]Price of electricity 1 kW·h/5 INR and assuming 1 USD = 70 INR.
[e]Calculated assuming 40% efficiency of LFG.

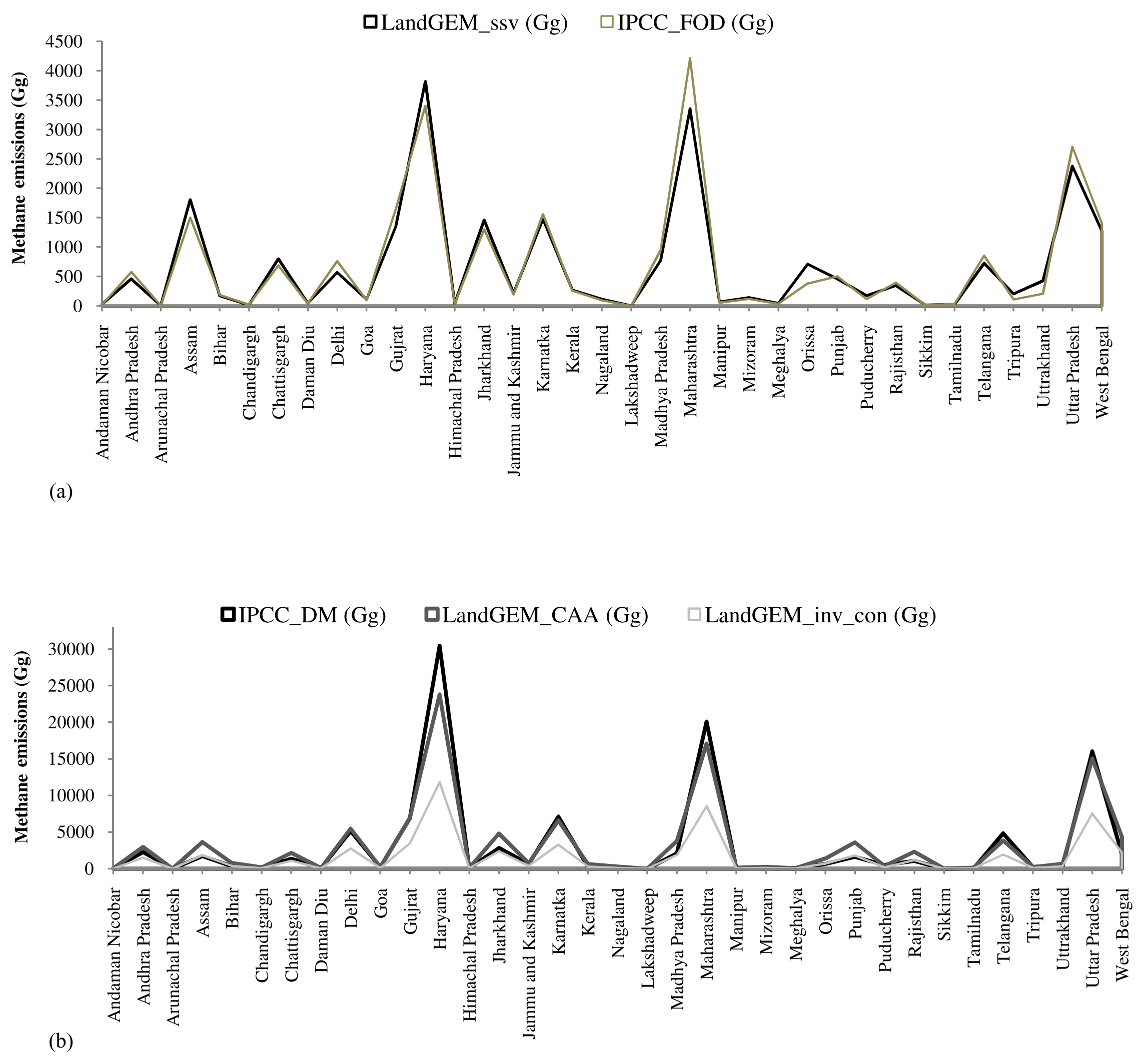

Fig. 1. Comparison of various models used in methane emissions from all the states of India at the end of 2030 by using: (a) $\text{LandGEM}_{\text{SSV}}$ and IPCC_{FOD}; and (b) $\text{LandGEM}_{\text{inventory}}$, $\text{LandGEM}_{\text{CAA}}$ and IPCC_{DM}.

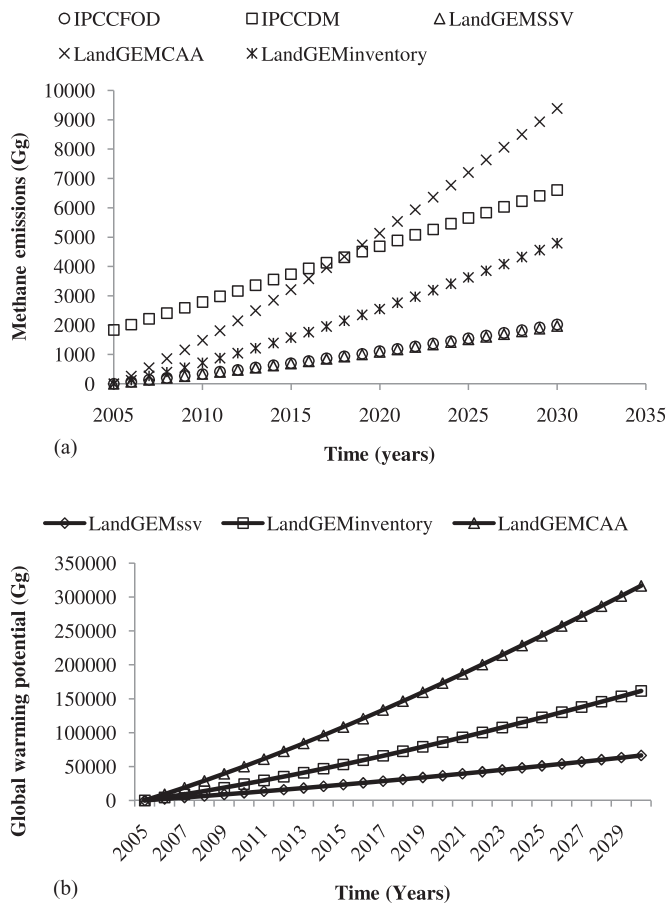

Fig. 2. (a) Temporal distribution of methane emissions; and (b) GWP of India.

heavily CH_4-emitting states and contribute about 20.7%, 14.2%, and 10.8% of total Indian CH_4 emissions, respectively. In estimates produced using these models, there exist various uncertainties. A study found that uncertainties associated with the input parameters can influence the outcomes; 10% uncertainty in the parameters leads to 20% uncertainty in the outcomes (Du et al. 2017).

MSW GWP, Association of Methane with GDP, Environmental, and Economic Benefits of Methane Capture

Simulation from the models shows that GWP is increasing with the passage of time; see Fig. 2(b). The analysis from $\text{LandGEM}_{\text{SSV}}$ shows a GWP of 36,599, 50,989, and 66,443 Gg CO_2-eq in 2020, 2025, and 2030, respectively. This study determined correlation of CH_4 emissions with GDP (Fig. 3). It is found that MSW CH_4 emissions are significantly correlated with GDP (R^2 = 0.998) and hence GDP is also a major factor affecting CH_4 emissions. These results lead to the conclusion that higher GDP indicates higher human activity, leading to the production of much greater volumes of MSW.

The economic and environmental advantages of methane capture through the LFG collection system are shown in Table 2. Under clean development mechanism programs, or any other renewable energy practices, if methane emitted from landfills is captured, it could attract a revenue of 483, 673, and 877 million USD in 2020, 2025, and 2030 through carbon credit from carbon reduction based on the rate of USD 13.20/t of CO_2. Moreover, a gas engine with an efficiency of 40%, as suggested by Shin et al. (2005) can produce 305, 425, and 555 MW of energy in 2020, 2025, and 2030, respectively. Assuming 5 INR/kW·h, the electricity thus generated can be sold to attract a revenue of up to 478, 666, and 867 million USD in 2020, 2025, and 2030, respectively.

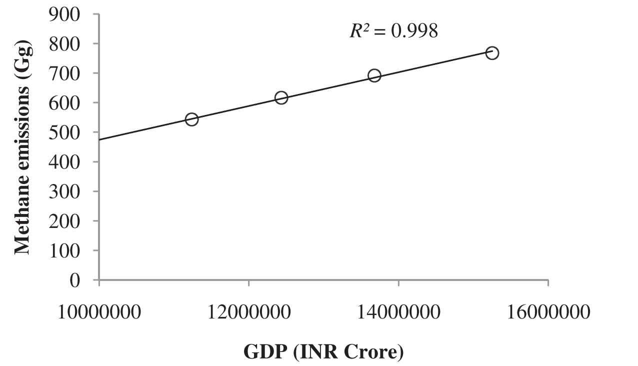

Fig. 3. Regression curve for MSW methane emissions and GDP over the period 2011–2017

Conclusion and Recommendations

This study reports the CH_4, global warming, and energy potential of MSW in India for the period 2005–2030. The analysis shows that, across the country, a substantial number of open dumps are emitting GHG in the absence of an appropriate LFG system, therefore, resulting in adverse effects for people in the vicinity. GHG has a huge potential of energy, and, if captured through a LFG collection system, will not only curtail GHG emissions but also becomes a source of revenue from the landfills; in a nutshell, this is a win-win situation for the environment and investors. This study shows that revenue equal to 867 billion USD can be attained by selling electrical energy produced from MSW by the year 2030. The study also concludes that population and GDP in the last few years is dependent on GHG emissions. In the future, a huge population and significant economic development will lead India to become a major GHG emitter across the globe. Nevertheless, by minimizing waste generation, along with appropriate recycling, reuse with proper LFG collection system can help to achieve the nation's quest for the development of renewable energy.

Data Availability Statement

All the models, i.e., the IPCC default method, IPCC first-order decay method, and LandGEM, used in this study are described in the methodology section in the manuscript with their references. Data generated during simulations are available from the corresponding author on request.

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