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APPLICATION OF LANDGEM MATHEMATICAL MODEL FOR THE ESTIMATION OF GAS EMISSIONS FROM CONTAMINATED SITES. A CASE STUDY OF A DUMPING SITE IN LAHORE, PAKISTAN

Decomposition of organic waste in dumping sites and landfills prompts the uncontrolled emission of greenhouse gases which enhances global warming and related issues. The present investigation estimated the total landfill gas, methane, carbon dioxide and non-methane organic compounds emissions from Mahmood Booti dumping site located at Lahore, Pakistan from 1996 to 2045. LandGEM 3.02 model was utilized to evaluate the gas emission with the volumetric methane 50%, production potential (170 m^3/Mg), and methane generation rate (0.050/year). The findings demonstrated that organic and food wastes had the maximum quantity in the solid waste stream (63.46%). Methane measured from solid waste was 1.150E+03 (Mg/year) in 1997 in the first year after waste was accepted by landfill while the maximum methane generation rate happened from 2014 to 2018,

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i.e., from 4.049×10^4 to 4.654×10^4 Mg/year, respectively. The study finding highlighted that all gases emissions have an increasing/rising trend up to 2021 and then gradually their level will decrease because most of the organic fractions of solid waste would degrade with time. The findings of this study can be used to identify the impacts and contribution of MBODS in the global emission of greenhouse gases. The study concludes that proper management of landfill gas will not only decreases greenhouse gas emissions, diminishing adverse impacts on public health but can also be used as a sustainable energy source.

1. INTRODUCTION

In developing countries like Pakistan, solid waste is usually dumped in open dumping areas/landfill sites without any proper treatment. These dumping areas are not systematically designed. Inappropriate management of waste disposal sites (including leachate) and the absence of qualitative and quantitative assessment have led to several serious problems all over the world [1, 2]. Municipal solid waste (MSW) usually decomposes in landfills, therefore generating methane (CH_4), carbon dioxide (CO_2) and traces of non-methane organic compounds (NMOCs) [3]. The emitted methane greatly depends on the composition and quantity of wastes, pH, moisture content, and waste management practices. Generally, methane generation escalates with high moisture and organic content in landfills. Methane is the chief constituent of landfill gas (LFG) and it has 21 times more probability of global warming as compared to carbon dioxide [4]. Modelling and prediction of greenhouse gases (GHGs) are essential in planning landfills for energy production. Estimating methane emissions from landfills will facilitate in determining Pakistan's contribution towards the global production of GHGs. There are several methods for estimating methane productions including field testing, site assessment, and mathematical modelling [5].

MSW is usually dumped in dumping sites or landfills and gases from these sites are released into the environment. Dumping sites are considered to be the main concern because of greenhouse gases production and its impact on health as these are the main basis of atmospheric irritation in residential communities [6]. Decomposition of organic waste under anaerobic conditions generates large quantities of landfill gases including 60% methane, 40% carbon dioxide and volatile organic compounds due to microbial action [7]. Methane gas is one of the main components in landfill gas that greatly contributes to the greenhouse effect [8]. In the majority of dumping sites/landfills waste is typically covered by 10–15 cm of the soil cover to reduce the gas and smell dispersion, but still, a considerable level of these gases escapes into the atmosphere continuously. It is complicated to measure and analyze the gas emissions from landfills [9].

Numerous studies have measured and assessed the landfill gas from disposal sites, since then several models have been established to measure landfill gas production, oxidation, and emissions. Unluckily, the use of simulation software for designing, operating and monitoring is not as extensive in the domain of landfills as compared to other domains of environmental engineering [10]. In a landfill modelling scenario, the importance of factors like waste configuration, dumping procedure and protection methods, makes the model's development applicable to various landfill amenities [11]. Calibration of modelling software mainly depends on data observed in a definite landfill or related facilities, that does not develop into real prediction tools. However, these models are still useful for approximate estimations when other advanced procedures are not accessible. Various authors have described modelling procedures that emphasize the biological and chemical waste degradation, which leads to the emission of gases. Among these integrated models, LandGEM modelling software was established for estimating gas emissions from landfills [12]. The LandGEM model was developed by United State Environmental Protection Agency (USEPA) and it provides an estimation of landfill gases and methane quantities generated over several projected years. It is an automatic estimation and assessment tool for modelling landfill gas emissions from MSW. This approach uses a first-order equation for modelling landfill gas (LFG).

Estimation of gases from waste disposal sites is important because emitted gases contain harmful chemicals that greatly damage nearby natural and anthropogenic environments. Literature review shows that several studies used the LandGEM model for gas estimation worldwide but very few studies exist in Pakistan's context. The present study was conducted to determine the emission rate of gasses in a contaminated site, i.e., dumping site, for the time duration of 50 years (from 1996 to 2046). Thus, this study aimed to estimate the total emission of landfill gas and its components including CH_4, CO_2, NMOCs from the Mahmood Booti Dumping site, Lahore using the LandGEM model as this model is reliable and configured on a simple approach to assess the emissions from dumping and landfill sites. Estimation of gases from dumping sites is helpful in risk assessment and management.

2. MATERIALS AND METHODS

Study area. Mahmood Booti Open Dumping Site (MBODS), Lahore, Pakistan was selected as a study area for LFG estimation because it is considered as one of the main and oldest municipal waste disposal and contaminated site of Lahore located between 31°36033.00N and 74°2310.2400E. It was an authorized dumping site in Lahore owned by City District Government Lahore (CDGL) since 1997, having an area of 32 ha (Fig. 1).

Selection of computer-aided model. Several computer-aided models are being used for gas estimation like GasSim, GasSimLite, etc., but they are quite expensive to use and not easily available. LandGEM model was selected because it is reliable, easy and free to avail. Moreover, it calculates landfill gas emissions comprehensively and effectively. LandGEM model consists of nine Microsoft Excel worksheets (Fig. 2). This model has great benefits in that it estimates the produced gases as per specific landfill conditions and in case, field data is not available, default information of the database can help. Default information depends on the following landfill criteria: 1. *Clean Air Act (CAA) including New Source Performance Standards/Emission Guidelines (NSPS/EG) and National Emission Standards for Hazardous Air Pollutants (NESHAP).* 2. The other criterion is based on Agency's Compilation of Air Pollutant Emission Factors (AP-42), called EPA.

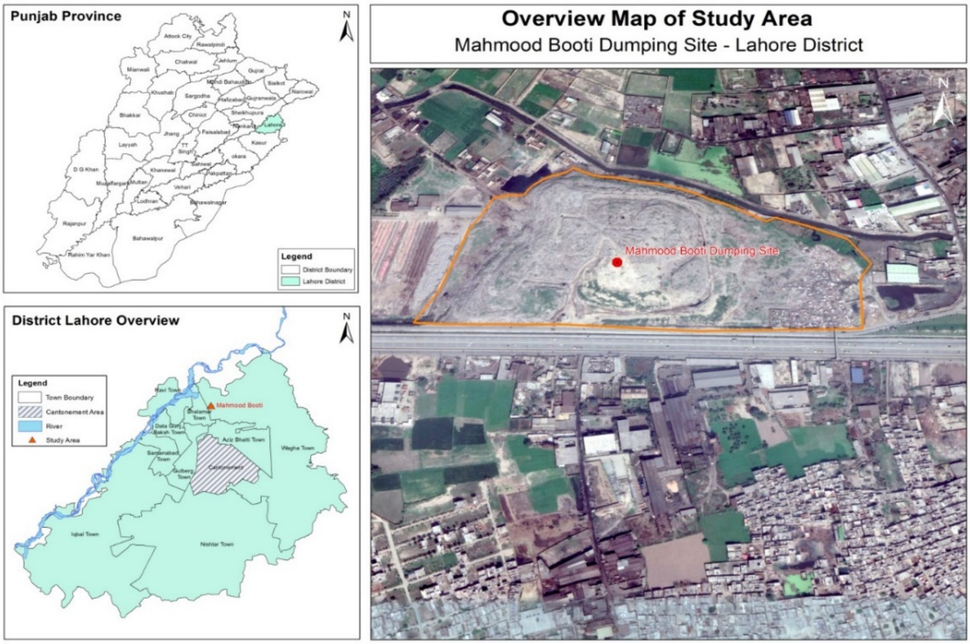

Fig. 1. Map of study area (Mahmood Booti Dumping Site, Lahore City, Pakistan)

Data input and use of LandGEM model in current scenario: Landfill open year, landfill closure year, waste design capacity (Mg) and waste acceptance rates (Mg/year) are the main input parameters in the LandGEM model. In the present study, data required for LandGEM was collected from the relevant department (Lahore Waste Management Company) and field visits. Waste quantity per year was calculated based on the waste amount received per day at the site and on the population rate. Model calculation primarily depends on methane yield (L_0) and methane generation rate (k). It was illustrated that NMOCs does not have any impact on calculation as the model assumes that methane and carbon dioxide, both gases that make up 100% of the total pollution and all other pollutants are considered under less than 1% category [13]. For the implementation of the model, 1996 was chosen as a start year for MSW disposal at MBODS and the closing year was 2016 as it reached its maximum capacity. Though 2016 was chosen as a closing year LFG will continue to emit for several years. LandGEM model estimates the emissions in Megagram (Mg) and it is a unit of mass equal to 1 000 000 g.

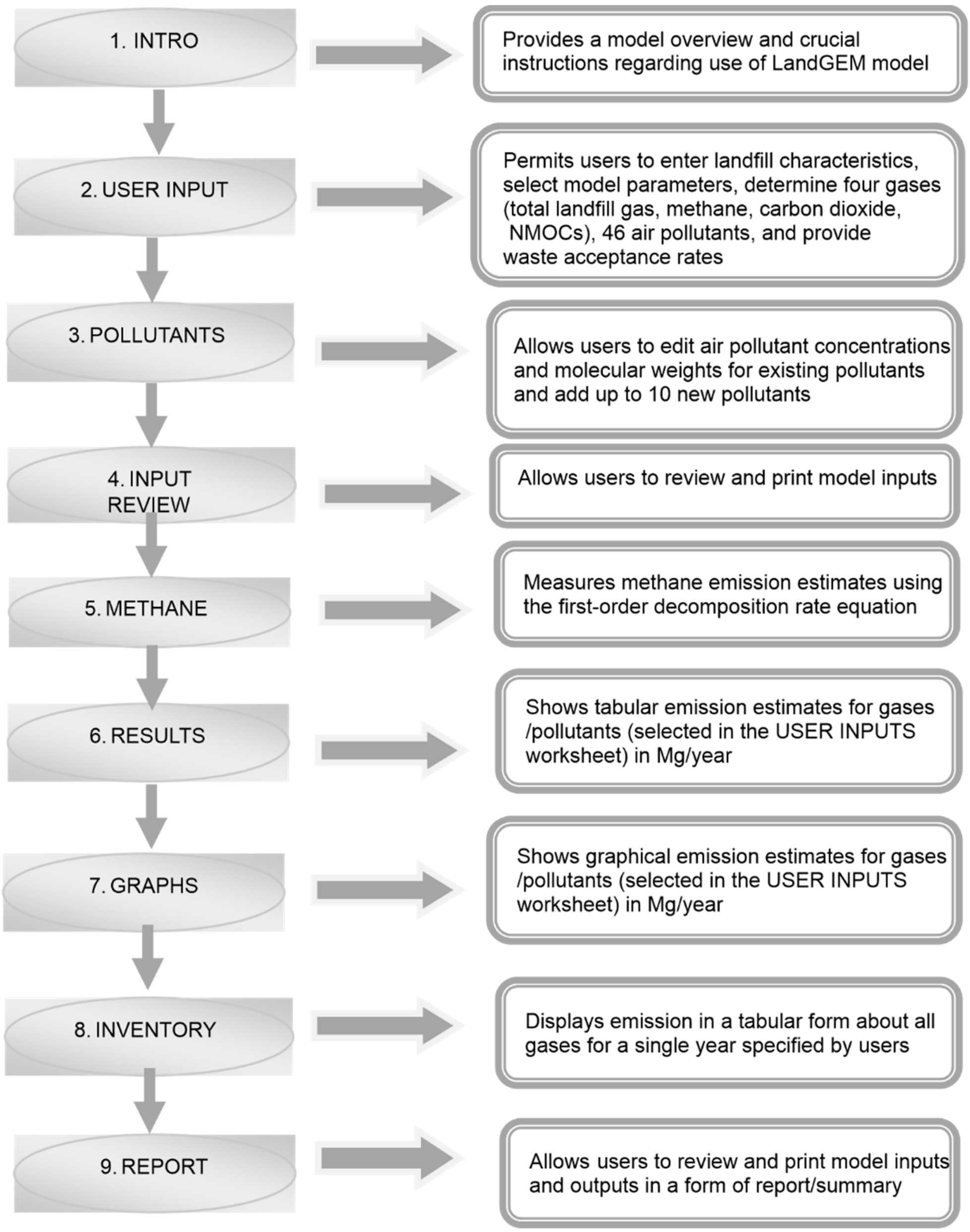

Fig. 2. Design of LandGEM model and its nine Excel sheets

First order decay decomposition equation. The model uses the first-order decomposition rate equation to measure the emission over a specific time. The model parameters k and L_0 used by the following decomposition equation

$$Q_{\mathrm{CH}_4} = \sum_{i=1}^{n} \sum_{j=0.1}^{1} k L_0 \left(\frac{M_i}{10} \right) \mathrm{e}^{-kt_{ij}}$$

where Q_{CH_4} is annual methane generation, m^3/year, i one year time increment, n year of the calculation – initial year of waste acceptance, j 0.1 year time increment, k methane generation rate, 1/year, L_0 potential methane generation capacity, m^3/Mg, M_i weight of waste accepted in the ith year, Mg, t_{ij} age of the jth section of waste M_i accepted in the ith year (decimal years, e.g., 3.2 year)

3. RESULTS AND DISCUSSION

3.1. COMPOSITION AND QUANTITY OF THE SOLID WASTE

The generation of landfill gas mainly depends on the solid waste composition. The composition of solid waste in the study area has been shown in Table 1. As per data biodegradable waste like food waste has the maximum quantity in the solid waste (over 63.46%) that decomposes rapidly and produces gas. A high amount of organic and food waste could accelerate the gases production and emission from landfills. The composition of solid waste greatly depends on lifestyle ad consumption patterns. Hosseini et al. [14] illustrated that high quantities of food and organic waste could expedite the gas generation from landfills.

Table 1

Composition of solid waste at the study area

Waste component	Weight average [%]	Waste component	Weight average [%]
Biodegradable	63.46	Tetrapak	0.94
Metals	0.04	Textile	7.05
Non-combustibles	1.82	Combustibles	3.69
Paper Cardboard	3.84	Diaper	6.75
Pet	0.18	Electronics	0.02
Naylon	9.77	Glass	0.85
Plastics	0.66	Hazardous	0.91

Landfill characteristics and LandGEM model parameters are shown in Table 2. Model parameters were based on *Clean Air Act (CAA) Regulations* and in the present study model projected LFG emissions for 50 years. Methane generation rate (k) indicates methane production rate, thus enhancing the decomposition of the organic matter. As the production rate is directly proportional to decomposition. According to CAA and LandGEM model, the approximate value of k is 0.05/year depending on the climate of the area.

Table 2

Supplementary input data to run the LandGEM model

Landfill parameter	Value
Landfill open–closure years	1996–2016
Methane generation constant (k), y^{-1}	0.050
Potential methane generation capacity (L_0), m^3/Mg	170
NMOC concentration as hexane, ppmv	4000
Methane content, vol. %	50

Table 3

Quantity of disposed waste in the study area [Mg/year]

Year	Waste accepted	Waste-in-place	Year	Waste accepted	Waste-in-place
1996	207 386	0	2022	0	12 655 877
1997	326 177	207 386	2023	0	12 655 877
1998	332 814	533 564	2024	0	12 655 877
1999	376 282	866 377	2025	0	12 655 877
2000	400 836	1 242 659	2026	0	12 655 877
2001	441 318	1 643 495	2027	0	12 655 877
2002	481 136	2 084 814	2028	0	12 655 877
2003	497 727	2 565 950	2029	0	12 655 877
2004	550 486	3 063 677	2030	0	12 655 877
2005	590 305	3 614 164	2031	0	12 655 877
2006	613 864	4 204 468	2032	0	12 655 877
2007	631 450	4 818 332	2033	0	12 655 877
2008	666 291	5 449 782	2034	0	12 655 877
2009	696 818	6 116 073	2035	0	12 655 877
2010	746 591	6 812 891	2036	0	12 655 877
2011	763 182	7 559 482	2037	0	12 655 877
2012	797 359	8 322 664	2038	0	12 655 877
2013	862 727	9 120 023	2039	0	12 655 877
2014	878 323	9 982 750	2040	0	12 655 877
2015	1 020 341	10 861 073	2041	0	12 655 877
2016	774 464	11 881 414	2042	0	12 655 877
2017	0	12 655 877	2043	0	12 655 877
2018	0	12 655 877	2044	0	12 655 877
2019	0	12 655 877	2045	0	12 655 877
2020	0	12 655 877	2046	0	12 655 877
2021	0	12 655 877			

Methane production potential (L_0) depends on the type and composition of landfills' waste, e.g., the more the amount of cellulose in the waste, the greater the potentiality for methane production. Depending on the type of climate, proposed by CAA, for arid and semi-arid regions, methane production potential equals 170 m^3/ton. NMOC concentration of landfill gas depends on the type of waste in landfills along with different anaerobic decomposition reactions on waste. NMOC concentration is measured in parts per million volume (ppmv). According to CAA, its default value equals 4000 ppmv, like that of hexane.

Table 3 represents the quantity of solid waste being disposed of in the study area (MBODS, Lahore). The total quantity of disposed waste was 12,655,877 Mg at the site by 2016. This illustrates the fact that the increase in population and industrial revolution leads to more volume of municipal and industrial waste. Rafiq et al. [15] also supported the fact that the population of Pakistan has tremendously increased which results in high solid waste generation. In the developing world, the waste generation rate is 500–900 g per capita per day as per United Nations' report [16]. Similarly, according to a solid waste management survey in eight main cities of Pakistan, the waste production rate is 450 g per capita per day [15].

3.2. METHANE PRODUCTION

Years from 2014 to 2018 were considered as peak years for methane emissions. The methane emission rate between 2014 and 2018 was 4.049×10^4 Mg/year and 4.654×10^4 Mg/year, respectively, and these rates will decrease to around 1.207×10^4 Mg by 2045.

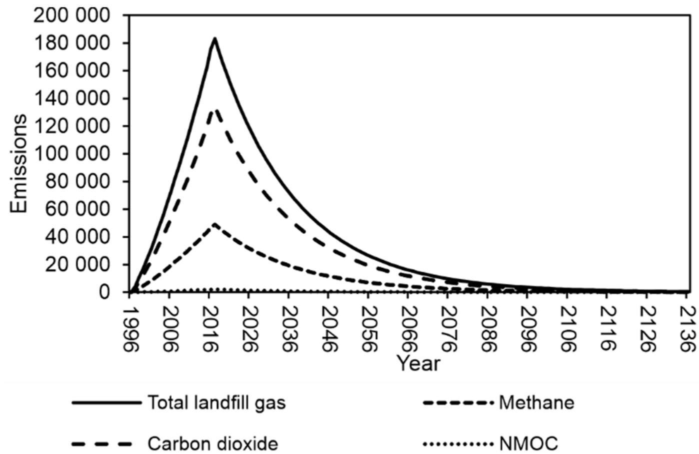

Fig. 3. Landfill gases emissions from MBODS

The reduction in methane rate production is due to the decline in biological activity and reduced organic waste content [17]. Methane generation in landfills depends on the decomposition of organic content – the higher the organic matter, the higher the concentration of CH_4 gas would be. Factors that are considered essential for methane emissions are topography, waste composition, pH, air temperature and microbial interactions. Landfill gas components are strongly correlated with rainfall and ambient temperature [18]. Figure 3 is a chart showing an overall trend of TLG, CH_4, CO_2 and NMOC from the Mahmood Booti Open Dumping site. NMOCs gases are responsible for tropospheric ozone which act as a greenhouse gas pollutant. These compounds have different chemical structures but similar behaviour in the atmosphere. Figure 3 represents the levels of NMOC gases, although the total amount of these gases (about 1%) is much less than methane and carbon dioxide still these are having more harmful impacts on human health. A number of these substances are known as the main causes of cancer [16].

Table 4

Annual trends of gases production from dumpsite[Mg/year]

Year	TLG	CH_4	CO_2	Year	TLG	CH_4	CO_2
1996	0	0	0	2021	1.500×10^5	4.006×10^4	1.099×10^5
1997	4.305×10^3	1.150×10^3	3.155×10^3	2022	1.427×10^5	3.811×10^4	1.046×10^5
1998	1.087×10^4	2.903×10^3	7.964×10^3	2023	1.357×10^5	3.625×10^4	9.946×10^4
1999	1.725×10^4	4.607×10^3	1.264×10^4	2024	1.291×10^5	3.448×10^4	9.461×10^4
2000	2.422×10^4	6.468×10^3	1.775×10^4	2025	1.228×10^5	3.280×10^4	8.999×10^4
2001	3.136×10^4	8.376×10^3	2.298×10^4	2026	1.168×10^5	3.120×10^4	8.560×10^4
2002	3.899×10^4	1.041×10^4	2.857×10^4	2027	1.111×10^5	2.968×10^4	8.143×10^4
2003	4.708×10^4	1.257×10^4	3.450×10^4	2028	1.057×10^5	2.823×10^4	7.746×10^4
2004	5.511×10^4	1.472×10^4	4.039×10^4	2029	1.005×10^5	2.685×10^4	7.368×10^4
2005	6.385×10^4	1.706×10^4	4.680×10^4	2030	9.563×10^4	2.554×10^4	7.009×10^4
2006	7.299×10^4	1.950×10^4	5.350×10^4	2031	9.097×10^4	2.430×10^4	6.667×10^4
2007	8.218×10^4	2.195×10^4	6.023×10^4	2032	8.653×10^4	2.311×10^4	6.342×10^4
2008	9.128×10^4	2.438×10^4	6.690×10^4	2033	8.231×10^4	2.199×10^4	6.032×10^4
2009	1.007×10^5	2.689×10^4	7.377×10^4	2034	7.829×10^4	2.091×10^4	5.738×10^4
2010	1.102×10^5	2.944×10^4	8.078×10^4	2035	7.448×10^4	1.989×10^4	5.458×10^4
2011	1.203×10^5	3.214×10^4	8.819×10^4	2036	7.084×10^4	1.892×10^4	5.192×10^4
2012	1.303×10^5	3.481×10^4	9.551×10^4	2037	6.739×10^4	1.800×10^4	4.939×10^4
2013	1.405×10^5	3.753×10^4	1.030×10^5	2038	6.410×10^4	1.712×10^4	4.698×10^4
2014	1.516×10^5	4.049×10^4	1.111×10^5	2039	6.098×10^4	1.629×10^4	4.469×10^4
2015	1.624×10^5	4.338×10^4	1.190×10^5	2040	5.800×10^4	1.549×10^4	4.251×10^4
2016	1.757×10^5	4.692×10^4	1.287×10^5	2041	5.517×10^4	1.474×10^4	4.044×10^4
2017	1.832×10^5	4.893×10^4	1.343×10^5	2042	5.248×10^4	1.402×10^4	3.846×10^4
2018	1.742×10^5	4.654×10^4	1.277×10^5	2043	4.992×10^4	1.333×10^4	3.659×10^4
2019	1.657×10^5	4.427×10^4	1.215×10^5	2044	4.749×10^4	1.268×10^4	3.480×10^4
2020	1.577×10^5	4.211×10^4	1.156×10^5	2045	4.517×10^4	1.207×10^4	3.311×10^4

The components of the solid waste stream were the most important influencing factors on gas emission rate. Table 4 shows the annual trend of total landfill gas, methane and carbon dioxide production from the study area (MBODS) during 1996 –2046. Results display that all gas emissions have an increasing trend up to 2021 and then gradually their level will decrease. The emissions level has decreased after the first 20 years because most of the organic fractions of solid waste would degrade during this time. There was no gas collection and treatment system present at MBODS site, gases were directly emitted into the ambient surrounding air. Bogner et al. [19] explained that disposal sites without gas collection systems are responsible for a considerable amount of methane emissions to the environment, with the expectation of a large spatial and seasonal variability.

Waste pH, temperature, decomposition rate and moisture content are four parameters that are mainly responsible for landfill gas generation rate. A large amount of moisture in the solid waste may enhance the gas generation rate [20]. Lahore (study area) has a sub-tropical and sub-arid climate and dumping sites are fully saturated during monsoon rains. Aerobic decomposition of solid waste in the study area may be higher because of higher moisture and temperature that has a positive impact on CH_4 generation. Rainfall rate is recognized as another essential factor because a substantial amount of organic carbon cleans out or removed during rain which lowers methane production. Factors that greatly contribute to the uncertainties in GHG generation estimation from landfills are variation in a waste amount reaching a landfill site, paper and textile because of industrialization, the oxidation rate of methane in the upper layer of landfill and net emission to the atmosphere [14, 21].

The LandGEM model is considered a screening tool because it will provide better gas estimates if there is accurate data input. Frequently, there are restrictions with the accessible data such as waste composition and quantity, fluctuation in design and operating methods with time, and alterations happening over time that affect the emissions capacity [18]. Landfill operation under moist conditions via leachate recirculation or other liquid accumulations will result in more gas production at a rapid rate. Landfill gas is a product of the degradation of biodegradable waste and direct volatilization of organic compounds from waste components. CH_4 and CO_2 are the main constituents of landfill gas. Trace components include aromatic volatile organic compounds, halogenated volatile organic compounds, ammonia and hydrogen sulfide. Carbon dioxide may enhance groundwater acidity [22]. Methane may migrate and lead to explosions in the nearby built environment and surrounding spaces. Literature reported several explosions due to methane from landfills [23]. Gases are mainly responsible for odors around waste sites and may pose health hazards under specific conditions [24] and the air is considered a crucial atmospheric receptor. The Occupational Safety and Health Administration (OSHA) has no allowable exposure level for CH_4 and landfill gases, but according to National Institute for Occupational Safety and Health's (NIOSH) maximum recommended safe methane concentration for workers during 8 hours is 1000 ppm (0.1%). Methane is an asphyxiant at extremely high concentrations and can displace oxygen in the blood.

Modelling and prediction of greenhouse gases (GHGs) are essential in planning landfills for energy production [5]. Gas emissions have a great potential for energy generation. According to the previous studies, the gas emission rate per ton of MSW is in the wide range of 120–300 m^3. Every cubic meter of landfill gas emission can generate 5.9 kW/h energy, which is equivalent to 66% of energy gained from a similar amount of natural gas. After recycling and modification of properties, landfill gas may be directly utilized in industries and for supplying energy to gas turbines and electricity generators [25]. Estimating methane emissions from landfills will facilitate in determining Pakistan's contribution towards the global production of GHGs. Moreover, the establishment of a landfill gas collection system may help in the recovery of energy, generate electricity and facilitate the combined heat and power generation (CHP). A gas collection system can play a crucial role in reducing carbon dioxide emission and other GHGs [26].

4. CONCLUSIONS

The emission of landfill gases from the Mahmood Booti Open Dumping Site has been estimated by using the LandGEM model. This dumping site started operation in 1996 to receive municipal solid waste from nearby areas till 2016. The generated amount of methane from solid waste was 1.150×10^3 Mg/year in the first year (1997) right after waste was accepted by the dumping area, while the peak of methane generation was observed during 2014–2015 with a production rate from 4.049×10^4 Mg/year to 4.654×10^4 Mg/year). The potential of rapidly degradable organic compounds for gas emission would be higher than that of slowly degradable organic compounds. The results of this study can be applied in a variety of ways including serving as a source of scientific information that can be utilized at the decision-making stage in sustainable waste management projects in developing countries. The results are valuable for both researchers and landfill operators, by indicating waste fractions that could emit CH_4 at modern or conventional landfills, Pakistan's landfills greenhouse gasses contribution to global emissions and concentration assessment at the risk assessment stage for estimating the greenhouse gases production and its impact on the environment.

Additionally, the outcome of the present study can be usefully applied in planning for energy production such as methane as an alternative energy source and other applications in landfill sites including efficient designing of methane collection systems to prevent an explosion. It is recommended to improve landfill management, establish leachate and gas collection systems, take post-care actions for the closed dumping sites and use appropriate cover materials (impermeable covers) which capture maximum methane amounts. The mitigation of the GHGs emissions from the open dumping site in Lahore is proposed to be addressed in the context of integrated waste management. Implementation of strategies that encourage landfill methane recovery and reduction of the quantity of landfilled biodegradable waste is important and will bring environmental and economic benefits.

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