



Article

Environmental Sustainability Enhancement of Waste Disposal Sites in Developing Countries through Controlling Greenhouse Gas Emissions

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Abstract: Sustainable management of municipal solid waste is one of the major challenges for authorities in developing countries. Current waste disposal methods in Pakistan and other developing countries are not meeting standards of any proper waste management system opted for in the developed world. This mismanagement of waste is leading to serious environmental problems at local as well as global levels. This study aims to investigate the methane emissions from waste dumpsites in the city of Karachi, Pakistan, and to propose an effective approach to enhance their environmental sustainability. The methane emissions from waste disposal sites were assessed by simulating four different landfill situations during the landfill simulation reactor experiment. The residual methane reduction potential of each waste disposal approach was assessed by a biochemical methane test of waste after the experiment. It is estimated that in the present situation, about 11,500 tons of CO₂-eq methane is released annually from waste disposal sites in Karachi. The convectional anaerobic landfill with methane capturing facilities and post-aeration operation was found to be the most environmentally sustainable approach with controlling 65% of residual methane emissions in comparison with the present scenario. For the development of new landfill sites, we recommend the bioreactor landfill approach with methane recovery and post-care (in-situ aeration).

Keywords: environmental sustainability; greenhouse gas; waste disposal sites; methane; landfill; in-situ aeration; MSW; developing countries; Karachi



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1. Introduction

Sustainable management of municipal solid waste (MSW) is one of the major challenges municipal authorities are facing in developing countries [1–3]. Sustainable management of waste can be defined as the handling of waste generated by the means of collection, transfer/transport, re-use, re-cycling, disposing and landfilling concurrently, and considering the costs and effects on public health and the ecosystem [4,5]. Open disposal and uncontrolled burning of MSW is commonly practiced in developing countries [6]. Landfills and waste disposal sites are some of the key contributors in anthropogenic emissions of methane globally [7,8]. In comparison with other human-caused greenhouse gases (GHGs), methane (CH₄) has the second highest potential for a climate change effect after carbon dioxide (CO₂) [9]. The GHG emissions from the waste sector in developing countries are anticipated to increase in coming years [10]. The global emissions of non-CO₂ GHGs (N₂O and CH₄) rose by up to 10% during the period of 1990–2005, and are estimated to increase by up to 43% till 2030 [11]. The Climate Watch [12] stated that, in 2016, the worldwide waste sector accounted for 1560 million tons of carbon dioxide equivalent (Mt CO₂-eq) (3.1% of global GHG emissions) of which 91% was methane (CH₄). According to a report by the Intergovernmental Panel on Climate Change (IPCC) [13], if no step is taken to control

the continuously rising GHG emissions, the global temperature will rise by 6.4 °C in the 21st century.

Developing countries were responsible for 29% of global GHG emissions in the year 2000, and this percentage is estimated to increase by up to 64% and 76% by the year 2030 and 2050, respectively, with waste landfills as a key contributor in these emissions due to uncontrolled waste disposal [14]. The latest GHG inventory of waste sectors, reported by different developing countries, is given in Table 1.

Table 1. Greenhouse gas (GHG) inventory of municipal solid waste sectors in developing countries.

Country	Total GHG Emission	GHG Emissions from the MSW Sector	Share of the MSW Sector in GHG Emissions	Reporting Year	Reference
	Mt CO ₂ -eq	Mt CO ₂ -eq	(%)		
Pakistan	329.5	12.45	2.2	2015	[15]
India	2607.49	14.86	0.57	2014	[16]
China	11,186	104	1	2014	[17,18]
Bangladesh	190	18.28	10	2012	[19]
Sri Lanka	45	12.47	28	2011	[20]
Malaysia	290.23	34.32	12	2011	[21]
Indonesia	2161	64.7	3	2013	[22]
Thailand	318.66	11.82	3.7	2013	[23]
Russia	2297.15	53.41	2.33	2012	[18,24]
Brazil	1357.18	45.52	3.4	2014	[25]
South Africa	542.58	15.76	2.9	2015	[26]
Colombia	224	13.71	6.1	2010	[27]
Turkey	527.27	9.1	1.72	2017	[28]
Egypt	325.61	13.19	4	2015	[29]
Mexico	665.3	30.9	4.6	2013	[30]
Cambodia	51.67	0.39	0.7	2013	[31]
The Philippines	157.6	10.4	7	2012	[32]
Worldwide	49,360	1560	3.1	2016	[12]

To control the GHG emissions from waste sectors, various waste management technologies have been developed, including composting, incineration with energy recovery, anaerobic digesters, landfill bioreactors, landfill gas (LFG) capturing, refuse-derived fuels (RFD), and combustion in cement burners [33,34].

Pakistan is a developing country and lacks any sustainable waste disposal mechanism or technologies [35]. Pakistan accounted for 0.81% in global GHG emissions in the year 2016 [12]. The latest reported national GHG inventory of Pakistan is summarized in Table 2.

Table 2. National GHG inventory of Pakistan for the year 2015 [15].

Sector	Energy	Industry	Agriculture	Wastes	Land-Use Change and Forestry (LUCF)
GHG emissions (Mt CO ₂ -eq)	184.0	21.85	174.56	15.65	10.39

The per capita GHG emission in Pakistan was 0.85 tons of CO₂-eq in 2016 [36], which was much less than China (6.65 tons of CO₂-eq) and India (1.65 tons of CO₂-eq) [37]. Pakistan accounted for more than 650 million tons of CO₂-eq in 2020 containing 54% CO₂, 36% CH₄, 9% NO_x, 0.7% CO, and 0.3% other volatile organic carbons (VOCs) [36]. The waste sector in Pakistan adds 3.9% to the GHG inventory of the country [15]. The share of different sectors in the greenhouse gas inventory of Pakistan is shown in Figure 1.

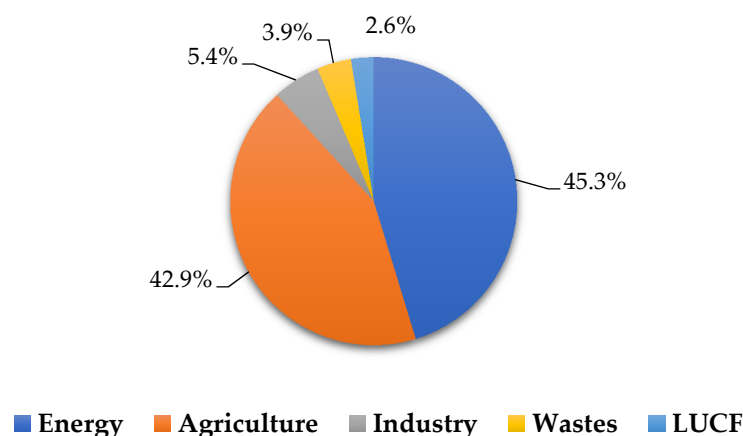


Figure 1. Share of GHG emissions by sector in Pakistan [15].

Karachi is the most populous and largest city of Pakistan, producing about 15,000 tons of MSW every day [38,39]. In Karachi, 60% of MSW is being collected and openly disposed of in waste dumpsites [40]. The open dumping and burning of municipal solid waste is a widespread method of waste disposal in Pakistan [35,38,41].

This study has been conducted to estimate the GHG (methane) emissions from waste disposal sites in Karachi, and propose suitable and environmentally sustainable waste disposal options to control methane emissions. This study was conducted through simulating conditions (by considering climate and waste composition) prevailing at MSW dumpsites in the city. In parallel to the existing situation, three different scenarios were simulated for comparison. The comparison of environmental sustainability in each scenario is made on the basis of a reduction in residual methane formation potential by conducting a biochemical methane potential (BMP₂₁) assessment of waste after the experiment.

2. Materials and Methods

2.1. Municipal Solid Waste Sample Preparation

Model waste sample representing MSW composition in Karachi (reported by [42]) was prepared in the laboratory at the Institute of Environmental Technology and Energy Economics, Hamburg University of Technology, Hamburg, Germany. The composition of synthetic MSW sample used in this study is given in Table 3.

Table 3. The composition of synthetic MSW sample used in this landfill simulation experiment [42].

MSW Component	Food Waste	Green Waste	Paper	Glass	Metal	Plastic	Fines	Nappies Textile	Tetra Pack	Wood	
Fraction (%)	26.1	17	8	5.6	1.1	8	3.7	9.8	7.6	10	3.1

The synthetic MSW sample was modeled by collecting and mixing all of the waste components according to their fraction as reported in Table 2 [43]. For lab-scale small landfill simulation reactors used in this experiment, the size of waste components was reduced and waste mixture was shredded to <25 mm in order to load representative samples of MSW in the reactors [39,43]. Various other landfill simulation studies [44,45] used shredded waste samples in the reactors. The initial moisture content of waste sample was noted as 42.7%. The moisture content of waste mixture was optimized by adding 10 L of tap water and rigorously mixing the waste specimen (for equal moisturization of waste material) [43]. The physicochemical properties of the synthetic MSW sample are reported in Table 4.

Before and after the loading of waste samples in landfill simulation reactors, all reactors were weighed to determine the waste quantity loaded in each reactor [43]. Table 5 shows the basic data of waste samples loaded in the reactors.

Table 4. Physicochemical properties of the synthetic MSW sample. [39,43].

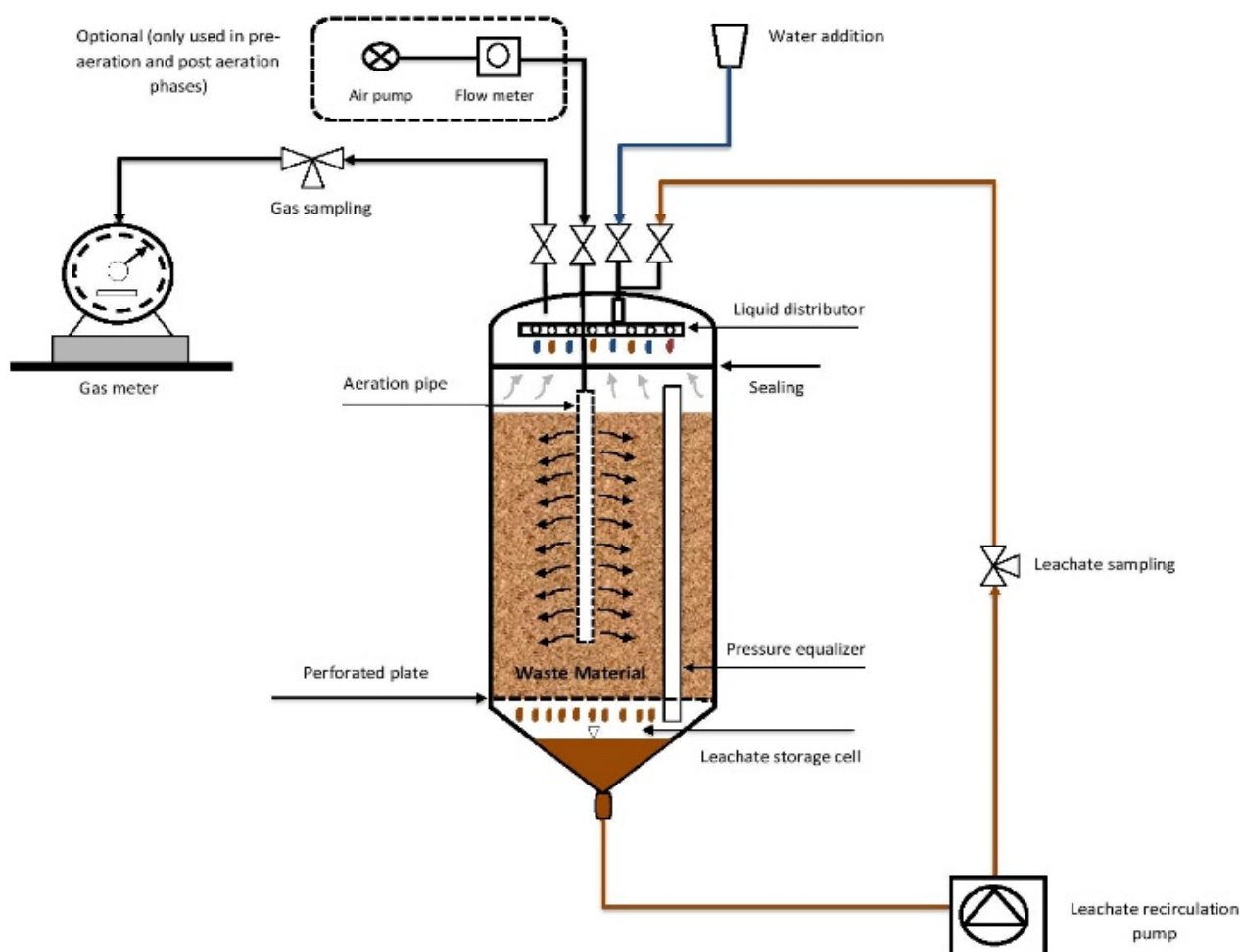
Sample	Moisture Content	Volatile Solids (VS)	Total Organic Carbon (TOC)	Particle Size
	(% Fresh mass, FM)	(% Dry mass, DM)	(% DM)	(mm)
Fresh MSW	55.5	83.1	41.2	~25

Table 5. Basic data of waste loaded in the landfill simulation reactors [43].

Waste Loading Data	Unit	R1	R2	R3	R4
Fresh mass	(kg)	2.8	3	3.4	2.8
Dry mass	(kg)	1.24	1.33	1.51	1.24
Organic dry mass	(kg)	1.03	1.10	1.25	1.03
Volume	(L)	4.52	4.16	4.65	4.26
Wet density	(L/kg)	0.62	0.72	0.73	0.66
Dry density	(L/kg)	0.28	0.32	0.32	0.29

2.2. Landfill Simulation Experiment

In order to simulate different landfill conditions, including the existing situation at waste disposal sites in Karachi city, four glass reactors (with an average height and diameter of 38.6 cm and 14.7 cm, respectively) were used and operated under controlled climate conditions at $36 \text{ }^{\circ}\text{C} \pm 1$ [43]. The illustration of the landfill simulation reactor setup is shown in in Figure 2.

**Figure 2.** Schematic and setup of landfill simulation reactors modified from [43].

At the start of the landfill simulation experiment, a brief pre-aeration phase was realized for 2 weeks in all reactors to avoid a long lag phase and acid accumulation due to the high organic fraction in waste samples [43,46]. The landfill simulation reactors (LSRs) were operated under anaerobic conditions to simulate the landfill ecosystem. Two reactors (R1 and R2) simulating actual conditions of waste disposal sites in Karachi were operated under limited water additions of 56 mL/week to realize the annual rainfall of 176 mm in the city [43,47]. The remaining two reactors (R3 and R4) were operated under highly moisturized conditions with leachate recirculation to simulate bioreactor landfill conditions [43].

Thereafter, post-aeration was realized in two reactors (R1 and R3) to compare the impact of post-aeration under the respective operational conditions. The summary of landfill simulation reactor operations is given in Table 6. The biogas/off-gas quantity was measured (by milli-gas counters in the anaerobic phase and drum gas meters in the post-aeration phase) and quality was analyzed (by Gas Chromatography) on a weekly basis till the end of the experiment.

Table 6. Summary of landfill simulation reactor (LSR) operations.

LSR#	Landfill Approach	Operation Time (An-Aerobic/Aerated)	Average Water Addition	Leachate Recirculation	Aeration Rate
		(days)	(mL/week)	(daily)	(L/h)
R1	Con. An-A with post-aeration	448 (252/196)	56	-	0.45
R2	Existing Situation	448	56	-	-
R3	BRL with post-aeration	364 (252/112)	165	Twice	0.42
R4	BRL without post-aeration	364	165	Twice	-

Con. An-A, Conventional anaerobic; BRL, Bioreactor.

2.3. Biochemical Methane Potential (BMP_{21}) Test

Environmental sustainability assessment of applied approaches was analyzed by a BMP_{21} test of solid waste samples acquired from landfill simulation reactors after completion of the experiment. The BMP_{21} test of waste samples was conducted in accordance with the protocol given by the association of German Engineers VDI 4630 2016 [48]. The experimental procedure followed the BMP_{21} test as reported in a research article [39]. The schematic diagram of the biochemical methane potential (BMP_{21}) test experiment setup is shown in Figure 3.

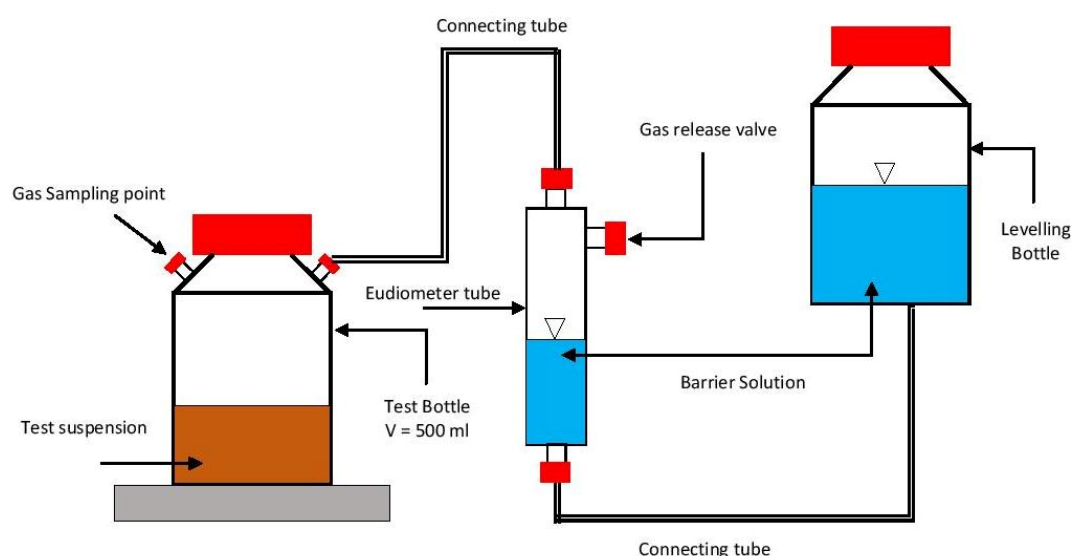


Figure 3. Schematic diagram of the biochemical methane potential (BMP_{21}) test setup modified from [39].

The quantity of waste sample used in the BMP₂₁ test was calculated according to a substrate-to-inoculum ratio (SIR) of 1:2 as reported in [48]. The quality and quantity of waste samples used in the BMP₂₁ test is reported in Table 7.

During the BMP₂₁ assessment, the volume of biogas produced during the test was measured by the displacement method through the mean of the eudiometer tube as shown in Figure 3 and reported in [39]. The biogas composition (CH₄ and CO₂) was analyzed at the time of every measurement of the gas volume. The details of other analytical methods used to examine different parameters of solid waste samples are summarized in Table 8.

Table 7. Quality and quantity of waste samples used for the BMP₂₁ test after the LSR experiment.

LSR	Total solids (TS)	VS	TOC	Quality of Waste	
#	(% FM)	(% DM)	(% DM)	(g FM)	(g VS)
R1	33.24	56.74	30.34	9.54	1.8
R2	36.03	74.09	39.65	6.74	1.8
R3	26.7	62.34	36.42	10.81	1.8
R4	26.04	69.54	40.06	9.94	1.8

Table 8. Summary of parameters and analytical methods.

Parameter	Analytical Method/Standard	Material	Reference
Total solids (TS)	DIN 38 414-S 2	Solid waste	[43]
Volatile solids (VS)	DIN 38 409-H 1-3	Solid waste	[43]
Total organic carbon (TOC)	Difference between TC and TIC (TC-TIC)	Solid Waste/Leachate	[49]
Total carbon (TC)	DIN EN 15936 Multi EA 4000 Analyzer	Solid waste	[49]
Total inorganic carbon (TIC)	DIN EN 15936 Multi EA 4000 Analyzer	Solid waste	[49]
Biogas composition (N ₂ , O ₂ , CO ₂ , CH ₄)	Gas Chromatography (HP-5890), Agilent	Landfill/Off-gas	[39]

3. Results and Discussion

The estimations for methane emissions from different MSW landfilling scenarios designed in this study were made by considering the MSW management situation (generation, composition, and disposal rate) and climate conditions in Karachi. The basic data used for estimation of methane emissions and power generation from waste disposal sites in the city are given in Table 9.

Table 9. Basic MSW data used for estimation of methane emissions and power generation from waste disposal sites in Karachi.

Data	Unit	Value	Reference
MSW generation	(tons/day)	15,220	[39]
MSW landfilled	(%)	60	[41]
MSW landfilled, FM	(tons/day)	9132	
Organic fraction in MSW	(%)	58.2	[43]
Organic mass landfilled, FM	(tons/day)	5310.3	
Dry mass (DM) content	(%)	44.4	
Organic dry mass (ODM) content in MSW	(%)	83.1	[43]
Dry mass landfilled	(tons/day)	4056.4	
Annual rainfall rate in Karachi	(mm/year)	176	[47]
Density of methane	(g/m ³)	660	[50]
Calorific value of methane	(Mj/ton)	55,526	[39]
Global warming potential of methane	(CO ₂ -eq)	23	[51]
1 kWh =	(Mj)	3.6	
Electric efficiency (η)	(%)	35	[52]
Methane recovery rate (r)	(%)	75	[51,52]

During the anaerobic operation mode of the landfill simulation reactors, lower methane emissions were recorded from the reactor (R2) simulating existing conditions of waste disposal sites in Karachi. The methane production rate from reactor R2 was calculated as 0.24 L/kg DM/d and in reactors R1, R3, and R4 the methane production rate was 0.38 L/kg DM/d, 0.37 L/kg DM/d and 0.19 L/kg DM/d, respectively, as shown in Table 9. After 252 days of operation, the anaerobic phase in reactors R1 and R3 was ended when the weekly landfill gas (LFG) generation rate in reactors decreased to 0.3% and 0.06% of the cumulative LFG production, respectively. In comparison, the landfill gas production rate in R2 and R4 decreased to 0.23% and 0.09% of the cumulative LFG production, respectively, at the end of the experiment, after 448 days in R2 and 364 days in R4.

It can be observed from the results that the LFG gas production rate in the reactors simulating bioreactor landfill conditions (R3 and R4) reached lower values in less time than R1 and R2. This rapid LFG production was due to the accelerated waste biodegradation process in the result of leachate recirculation [53,54]. Table 10 provides the detailed calculations for estimation of methane emissions analyzed in existing situations of waste disposal sites and other scenarios developed in the study.

Table 10. Calculation of methane emissions in different landfill approaches and existing MSW situations in Karachi.

LSR Experiment Result Analysis	Landfill Approach	Conventional with Post-Aeration	Existing Situations	Bioreactor with Post-Aeration	Bioreactor without Post-Aeration
	Scenario	Case-1	Case-2	Case-3	Case-4
	Unit	R1	R2	R3	R4
Cumulative methane production	(L/kg DM)	95.0	108.0	93.3	68.0
An-A operation duration	(days)	252	448	252	364
Methane production rate	(L/kg DM/d)	0.38	0.24	0.37	0.19
Volume of methane produced	(m ³ /year)	558,162.2	356,930.0	547,997.7	276,392.0
Quantity of methane produced	(tons/year)	368.4	235.2	361.7	182.4
Methane emissions	(tons of CO ₂ -eq/year)	8472.9	5418.2	8318.6	4195.6

The test results of the BMP₂₁ assessment of the waste samples were analyzed with the data of MSW generated in Karachi (as given in Table 9) to know the total methane emissions potential of MSW disposed in waste dumpsites in the city. The BMP₂₁ test results were also used to observe the residual methane reduction efficacy of different landfill approaches simulated in this study.

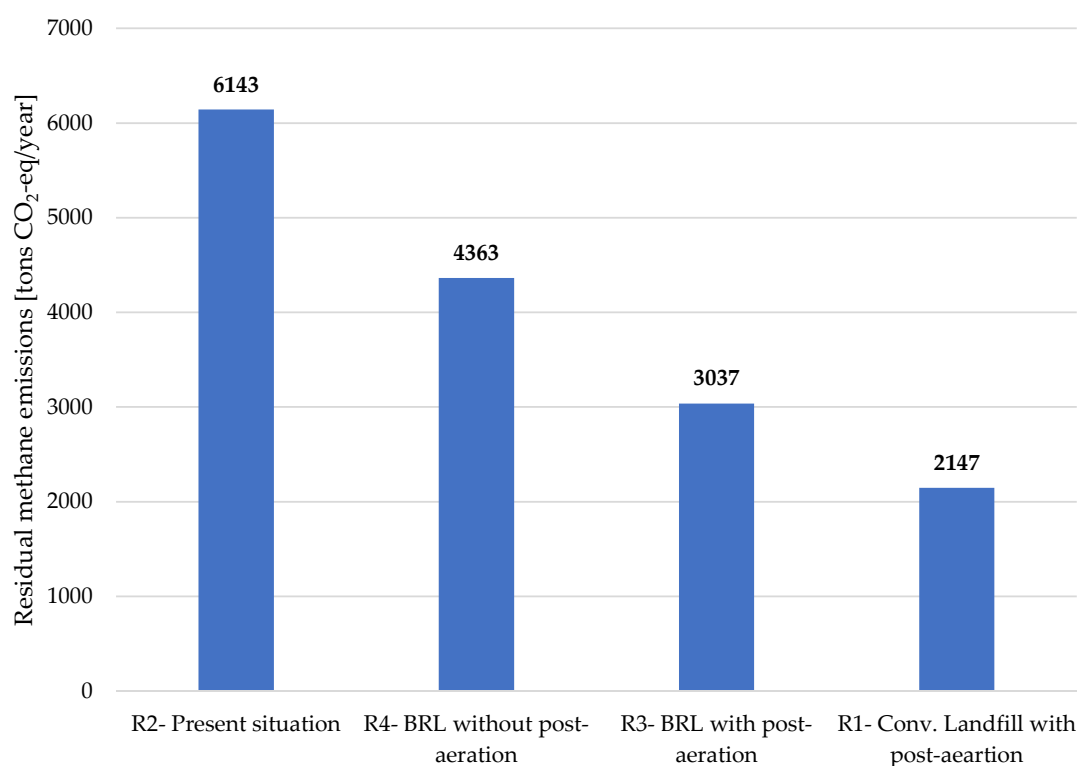
In consequence of low methane formation in anaerobic operation in reactor R2, higher residual methane emission was noticed from the waste sample extracted from the reactor during the BMP₂₁ test. These results indicate that waste disposal sites in Karachi have prolonged methane emission potential due to unfavorable conditions for waste biodegradation at dumpsites, e.g., limited moisture availability and formation of acidic conditions due to the high organic fraction in the MSW [43,44].

The waste sampled from reactor R1 produced a lower quantity of residual methane than reactor R3, showing a higher impact of aeration operation on waste stabilization in the presence of limited water than in the presence of high moisture content. However, waste sampled from reactor R3 (bioreactor (BRL) with post-aeration) shows a higher residual methane reduction than R4 (BRL without post-care). The lower residual methane emissions from R3 were the result of increased decomposition of organic matter due to the post-aeration phase observed in the reactor. Table 11 gives the detailed calculation of the residual methane emission potential from different landfill approaches assessed in this study.

In control of residual gas emissions, low methane emissions were noticed from reactors R1 and R3 during the BMP₂₁ test due to the post-aeration operation. However, reactor R4 (BRL approach) shows less residual gas emissions than reactor R2 during the BMP₂₁ assessment test due to enhanced in-situ biodegradation of waste in the result of leachate recirculation [55,56]. Figure 4 shows the comparison of cumulative methane emissions from different landfill conditions during the LSR experiment and the BMP₂₁ assessment test.

Table 11. Calculation of residual methane potential of waste from landfill approaches estimated from the BMP₂₁ test.

BMP ₂₁ Test Result Analysis	Landfill Approach	Conventional with Post-Aeration	Existing Situation	Bioreactor with Post-Aeration	Bioreactor without Post-Aeration
	Scenario	Case 1	Case 2	Case 3	Case 4
	Unit	R1	R2	R3	R4
Cumulative methane production	(L/kg DM)	3.45	9.87	4.88	7.01
BMP ₂₁ test duration	(days)	21	21	21	21
Methane production rate	(L/kg DM/d)	0.16	0.47	0.23	0.33
Volume of methane produced	(m ³ /year)	141,444.8	404,655.0	200,072.6	287,399.3
Quantity of methane produced	(tons/year)	93.4	267.1	132.0	189.7
Residual methane emissions	(tons of CO ₂ -eq/year)	2147.1	6142.7	3037.1	4362.7

**Figure 4.** Estimation of residual methane emissions from different landfill scenarios.

Through analysis of results from the LSR experiment (given in Table 10), the BMP₂₁ test (given in Table 11), and the data on waste management in Karachi (given in Table 9), it is estimated that about 11,500 MgCO₂-eq/year of methane enters the atmosphere from waste dumpsites in Karachi. The amount of methane emissions from waste disposal sites in Karachi is about 0.1% of the total quantity of methane emissions accounted for by the waste sector in Pakistan. The extent of methane emission reduction through applied approaches is summarized in Table 12.

Table 12. Summary of the methane emission reduction in different scenarios.

Scenario	Approach	LSR#	CH ₄ Emission Reduction Compared to Case-2 (%)
Case 1	Conventional landfill with post-care	R1	65
Case 3	Bioreactor landfill (BRL) with post-care	R3	51
Case 4	Bioreactor landfill (BRL) without post-care	R4	29
Case 2	Existing situation (open dumping)	R2	0.00

For the comparison of power generation potential, two cases (1 and 3) are considered. In the first case, power generation is evaluated from a conventional sanitary landfill approach, and in the second, it is evaluated from a bioreactor landfill approach. In both cases, anaerobic conditions in landfill simulation reactors were switched to aerobic in order to simulate a post-aeration phase at the time when the weekly methane production rate decreased to <0.5% of the cumulative methane produced till that period. The power generation is estimated till reaching <0.5% of the methane production rate by assuming that after that period, utilization of produced methane for power generation will not be profitable and/or technically viable as described by [57]. In reactor R3 (which used the bioreactor landfill approach) the limit of <0.5% of cumulative methane production was reached in only 140 days from starting with anaerobic operation. In contrast, in reactor R3 (which used the conventional landfill approach) this limit was reached in 231 days. At first, the thermal power (P_t) production from methane is determined by considering the energy content of methane to be 890.8 kJ/mol, the density to be 660 g/m³, and the calorific value of methane to be 55,526 MJ/ton as reported by [39,50]. The electric power generation is calculated by Equation (1) as reported by [39,52].

$$P_e = P_t \times r \times \eta_e \quad (1)$$

where P_e is electric power produced, P_t is thermal power, r is the methane recovery rate, and η_e is the electric efficiency of the generator. The methane recovery rate is assumed to be 70% and the electric efficiency of generator is assumed to be 35%, as given in Table 9. The estimated electrical energy generation potential of methane produced from conventional anaerobic and bioreactor landfill sites in Karachi is given in Table 13.

Table 13. Calculation for electrical energy generation potential estimations in the present situation in Karachi by considering $\leq 0.5\%$ CH₄.

LSR Experiment Results Analysis	Landfill Approach	Conventional with Post-Aeration	Bioreactor with Post-Aeration
	Scenario	Case-1	Case-3
	Unit	R1	R3
Cumulative CH ₄ generation from LSRs	(L/kg DM)	94.0	90.0
Weekly CH ₄ production reached <0.5% of cumulative CH ₄ produced	(days)	231	140
CH ₄ production rate	(L/kg DM/d)	0.41	0.64
Volume of CH ₄ produced	(m ³ /d)	1650.7	2607.7
Quantity of CH ₄ quantity produced	(tons/d)	1.1	1.7
Energy potential of CH ₄ recovered	(Mj/d)	60,492.4	95,565.1
Thermal power of CH ₄ recovered	(MWh)	16.8	26.55
Estimated electric power	(MWh)	4.4	7.0

Furthermore, the power generation potential from conventional landfill (case 1) and bioreactor landfill (case 3) conditions in different waste disposal rates in Karachi was also estimated and is given in Table 14. It was estimated that the power generation can be enhanced by improving the MSW collection and disposal rate in the city.

Table 14. Estimation of power generation from conventional and bioreactor landfill approaches.

Daily MSW Disposal Rate	(%)	60 *	70	80	90	100
Daily electric power generation in case 1	(MWh)	4.4	5.1	5.9	6.6	7.4
Daily electric power generation in case 3	(MWh)	7.0	8.1	9.3	10.5	11.6

* Present waste disposal rate in Karachi.

The results show that the post-aeration approach can be efficiently used in the present dumpsite to control methane emission. If waste dumpsites were to be transformed into conventional sanitary landfills and equipped with methane capturing and power generation facilities, 4.4 MWh of electric power could be generated on a daily basis. Afterwards, landfill in-situ aeration can be used as a post-care method to control residual methane

emissions when energy generation from methane is no longer possible or economical. Furthermore, it was estimated that through the BRL approach, 7.0 MW of power can be generated, which is 30% more than through conventional landfill.

4. Conclusions and Implications

According to the methane emissions estimated in this study by simulating different landfill situations, it is concluded that in existing operating conditions of open waste disposal, landfills in Karachi are emitting a significant amount methane into the environment. Through the results obtained from simulation of other landfill scenarios, it was also observed that the environmental sustainability of existing MSW dumpsites in Pakistan and other developing countries can be successfully enhanced by transforming open waste disposal sites into sanitary landfills. This study shows that in-situ aeration would be a promising approach for reclamation of old dumpsites to control prolonged methane emissions. Energy can be generated through capturing and utilization of methane produced from sanitary (conventional anaerobic) landfills. Furthermore, it was estimated that through reclamation of existing waste disposal sites in Karachi, 65% of present methane emissions can be controlled.

For the development of new landfill sites, bioreactor landfill with the post-care (in-situ aeration) approach is recommended. The bioreactor landfill approach, when combined with a landfill gas recovery system, offers rapid waste stabilization, enhanced landfill gas production, and more power generation. Through opting for the bioreactor approach with landfill gas recovery facilities, 30% more power can be generated as compared with the conventional anaerobic landfilling approach. Furthermore, power generation from conventional sanitary and bioreactor landfills can be increased through improving waste collection rates.

Further research into the selection of a more suitable water regime for the bioreactor landfilling approach, with awareness of the composition and physicochemical characteristics of MSW generated in Karachi and other cities of developing countries, should be done in order to generate more power and optimize the effect of post-care operations on waste stabilization.

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