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Greenhouse Gas Emissions Potential from Municipal Solid Waste Disposal Sites

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Abstract:
Municipal solid waste landfills emit greenhouse gases (GHGs), which negatively impact human health and the environment. These gases include primarily methane and carbon dioxide. The present study focuses on estimating the landfill emissions across all Iraqi governorates for landfilling all municipal solid waste (MSW) using the LandGEM model, which has high accuracy and is issued by the EPA. This model was applied, with parameters modified for Iraqi conditions, to estimate GHG emissions. These parameters include methane generation potential (l_o) and the Methane Generation Constant (k), which depend on Iraqi solid waste generation. Then, statistical analysis using SPSS was applied to verify the model used in this study. The results showed that in 2047, all governorates will achieve the maximum emissions due to the slow degradation of MSW organic fraction, which were 4.7×10^8, 2.1×10^8, 1.1×10^8, 1.4×10^8, 5.9×10^7, 3.7×10^7, 4.7×10^7, 3.2×10^7, 8.2×10^7, 8.9×10^7, 2.7×10^7 m^3/year for Baghdad, Ninavah, Babel, Duhok, Sulaimaniah, Erbil, Diyala, Karbala, Wasit, Salahalden, Najaf, Nassriah, Basra, Ammara, respectively. This huge difference is due to population and solid waste composition. Furthermore, the total accumulated GHG emissions for all Iraqi governorates from 2022 through 2061, i.e., after 15 years of landfill closure, which represent the degradation of the almost entirely rapidly and slowly decomposing MSW organic fraction, are about 55×10^9 m^3. To confirm LandGEM model results, a statistical model (ANOVA) was performed to estimate the generated greenhouse gas emissions in all Iraqi governorates as a function of time. The results showed that the coefficient of determination (R^2) was high across all governorates, ranging from 0.963 to 0.974. Based on the results and the significant GHG emissions, sustainable management of MSW across all Iraqi governorates is necessary to reduce climate change and negative health impacts.

Keywords:
Carbon dioxide; Emission; Landfill; Methane; Municipal solid waste.

Highlights:
- Greenhouse gases were calculated using LandGEM.
- SPSS software was used for the analysis.
- Methane generation potential and constant were the main parameters for modeling.

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1.INTRODUCTION

Municipal solid waste is considered a major environmental problem in developing countries such as Iraq. Many factors, such as rapid population growth and developing the lifestyle of the individual, have led to a dramatic increase in municipal solid waste (MSW) generation rates across all Iraqi cities [1, 2]. Waste generation rates in Iraqi governorates vary from 0.42 in Najaf to 0.8 (kg/c.d) in Baghdad, and the current waste management in Iraq is burying the solid waste [1, 3, 4]. Economically and practically, it is not feasible to completely recycle the produced MSW; therefore, an alternative solution is to address the requirement for this problem [5]. Landfilling is the most prevalent practical solution for MSW disposal worldwide [6] due to its simplicity and lower cost compared to other methods [7]. However, sanitary landfills pose a critical environmental issue by generating greenhouse gases (GHGs) from the decomposition of the MSW organic fraction [6]. These gases, particularly carbon dioxide (CO_2) (usually 40% to 60%), methane (CH_4) (usually 45% to 60%), and other compounds and oxides [8], contribute dramatically to climate change by acting as heat-trapping gases in the atmosphere. Moreover, anaerobic digestion in landfills is considered the fundamental source of GHG emissions, accounting for 95% of all emissions from other waste sectors. In addition, estimates indicate that the solid waste sector accounts for about 20% of global anthropogenic methane emissions [9]. Asian countries, due to their high population, are among the largest generators of MSW [10]. In Iraq, Waste generation will increase dramatically in the coming decades, increasing GHG emissions. Therefore, an appropriate solution should be prepared and implemented by the government based on studies and experience, and landfilling is the predicted future solution, which is evolving. It is being recognized as the recommended strategy for disposing of MSW worldwide. Various methods are available to predict and evaluate landfill methane emissions, such as field tests and mathematical models [11]. Modeling methods are used to predict emissions from future landfills, including the Intergovernmental Panel on Climate Change (IPCC) method, the First-Order Decay (FOD) process, the Triangular method (TM), and the Landfill Gas Emission Model (LandGEM) version 3.02 [12, 13]. The LandGEM model was initiated and developed by USEPA to estimate the landfill gas emissions, including methane, carbon dioxide, non-methane volatile organic carbon compounds, and other minor gases. This model is considered one of the most widely cited for predicting greenhouse gas emissions from landfills worldwide [14, 15, 16]. The LandGEM model depends on two important parameters, including methane generation potential (L_o) and generation rate (k). The model evolves the first-order dissociation rate equation to predict landfill emissions [17]. Researchers in different countries used the LandGEM model to predict GHG emissions from landfilled MSW in their countries. For instance, Thompson et al. applied the LandGEM model to estimate the emissions from 35 Canadian landfills. They found that this model achieved the best results compared with other models studied, i.e., German EPER and Scholl Canyon models [18]. Recently, Ramprasad et al. used the LandGEM model to predict methane emission rates and estimate the hydrogen generation potential from the Kanuru, Vijayawada landfill in India. It was estimated that methane emissions peaked in 2042 at 2.51×10^{8} Metric tons (CO_2) equivalents. Also, the predicted methane emissions range from 1.33×10^{6} to 9.22×10^{6} m^3 per year from 2010 to 2042 [19]. Furthermore, Şentürk and Yıldırım estimated gas emissions from the Sivas province landfill in Turkey. The results showed that the highest total gas and methane generation from the Sivas sanitary landfill were 7.976×10^{6} m^3/year and 4.068×10^{6} m^3/year, respectively [20]. Quantifying methane emissions is very important and urgent to raise awareness of landfills and the use of GHG reporting data to inform appropriate plans and decisions in Iraq, such as using the resulting gases as a source of energy. Therefore, the aim of the present study is to calculate the recent and future (CH_4) emissions from landfilling MSW in Iraqi governorates using the LandGEM model, based on data from reliable sources, including population growth projections and MSW composition.

2.MATERIALS AND METHODS

2.1.Sites Description

Iraq is located in Asia and has the following geographic coordinates: latitude 33° 22' N and longitude 440 24' E. It borders five countries: Turkey, Iran, Syria, the Kingdom of Saudi Arabia, and Kuwait [43]. Iraq has four major physiographic regions, each with distinct geological, hydrological, and climatic conditions. These zones include mountains, plains, and deserts. Iraq has eighteen governorates, as shown in Fig. 1 [21].

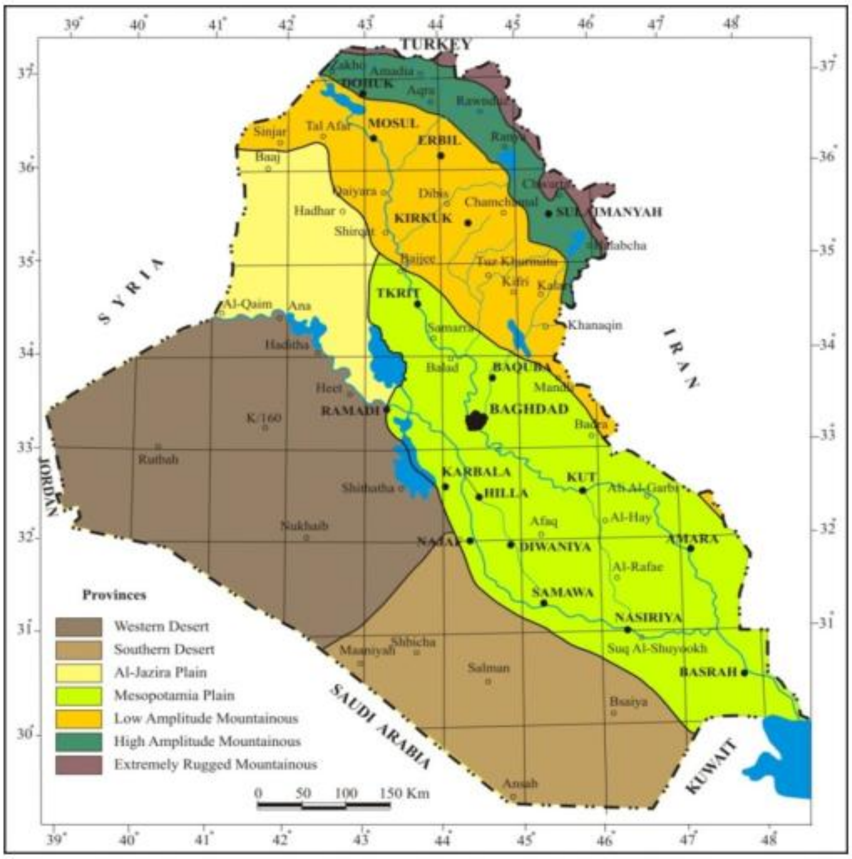


Fig. 1 Iraqi Physiographic Regions.

2.2.Prediction of Population and Waste Production in Iraq

Iraq is classified as a country with one of the fastest population growth rates in the region. This fact was emphasized by analyzing population data from the last two decades of the twentieth century, which showed that the annual population growth rate ranged from 2,68 to 3% [22, 44]. There are different models for predicting population growth. In this study, the Exponential growth method was used to predict the population of all Iraqi governorates using the following equation [23]:

$$P = P_0 e^{CT} \tag{1}$$

where P is the predicted population (capita), P_o is the initial population (capita), C is the growth rate (1/year), and T is time (year). To predict the population, the initial year for all governorates is 2022, and the final year is 2046, which also marks the last year of the landfill-accepted waste in the model.

2.3.LandGEM Model

The LandGEM model estimates the annual gas emission rate from municipal landfill sites decomposition using a first-order decay equation. All emissions results were calculated by applying this model. Mathematically, the model can be described as [24].

$$Q_t = \Sigma_{i=1}^{n}\, 2\, k\, L_0\, M_{ie} e^{-kt_i} \tag{2}$$

where Q_t is the total gas emissions rate from a landfill, volume/time increment, n is the total time period of waste placement, k is a landfill *methane generation Constant (k)*, time^{-1}, L_o is methane generation potential, volume/mass of waste, t_i is the age of the i^{th} section of waste, time, and Mi is the mass of wet waste, placed at time i. Methane (CH_4) emissions range from 45% to 60% of total landfill gas emissions. In the present study, it was assumed to be 50% [8].

2.4.LandGEM Parameters

The LandGEM model depends on several parameters, including the following:

2.4.1.Methane Generation Constant (k)

The Methane Generation Constant (k) is used to estimate the rate of methane production from the organic fraction of landfill solid waste. A high k value indicates that the reaction rate of organic waste decomposition is faster. This value depends on the moisture, nutrient, pH, and temperature of the organic fraction of solid waste. The methane generation constant (k) can be calculated depending on the annual mean rainfall using the following equation [25]:

$$k\,(yr^{-1}) = 3.2x10^{-5}\, x\, (Annual\ Mean\ Rainfall(mm)) + 0.01 \tag{3}$$

The annual mean rainfall was determined using the meteorological data collected for each Iraqi governorate, as shown in Table 1 [26]. k values were estimated for all governorates except Al-Muthana, Al-Qadisiah, Anbar, and Kirkuk due to insufficient information on annual mean rainfall. The values for these four regions were estimated based on data from their neighboring governorates, yielding an estimate of 0.02 Yr^{-1}.

2.4.2. Methane Generation Potential (L_o)

Methane Generation Potential (Lo) is defined as the volume of methane gas potentially generated by a ton (Mg) of waste as it decomposes. The first step in calculating the methane generation potential (L_o) is to estimate the chemical composition of the organic fraction of MSW. To calculate the chemical composition, an ultimate analysis should be performed to estimate the total weight of carbon (C), hydrogen (H), oxygen (O), nitrogen (N), and sulfate (S). Then, the total weight should be converted to moles by dividing by the atomic weights of the elements, and related ratios between the elements are used to determine the chemical composition. Methane generation potential (L_o) can be determined by calculating the chemical composition for the rapid and slow decomposition of organic waste components. Rapid decomposition occurs within 3 months to 5 years, while slow decomposition occurs up to 50 years or more. The rapidly biodegradable organic components in MSW include food waste, paper, cardboard, and 60% of yard waste. The slowly biodegradable organic fraction in MSW includes textiles, rubber, leather, and wood, as well as 40% of yard waste [6]. In the present study, the methane generation volume was estimated using Eq. (4), which assumes that all organic components will be completely converted to methane and carbon dioxide [7].

$$C_aH_bO_cN_d + \left(\frac{4a-b-2c+3d}{4}\right) H_2O \rightarrow \left(\frac{4a+b-2c-3d}{8}\right) CH_4 + \left(\frac{4a-b+2c+3d}{8}\right) CO_2 + dNH_3 \qquad (4)$$

where C is Carbon, H is Hydrogen, O is Oxygen, N is Nitrogen, NH_3 is Ammonia compounds, CO_2 is Carbon dioxide gas, CH_4 is Methane gas, and H_2O is water. Where a, b, c, and d are factors of the chemical elements of C, H, O, and N, respectively. To determine the methane generation potential (L_o) for the MSW organic fraction, the methane volume should be divided by the organic fraction for rapid and slow decomposition. The value of L_o depends on the type and composition of landfilled organic waste. Table 1 shows the L_o values. The values for the four mentioned regions were calculated based on data from their neighboring governorates, i.e., 193 m^3/ton.

Table 1 Annual Precipitation, Methane Generation Constant, and Potential Methane Generation for Each Governorate of Iraq.

Governorate	Annual Precipitation (mm)	k value (1/year)	L_o (m^3/ton)
Baghdad	300	0.020	175
Ninevah	500	0.026	220
Babylon	250	0.018	225
Wasit	250	0.018	218
Maisan	150	0.015	140
Thi Qar	150	0.015	222
Duhok	800	0.036	195
Erbil	750	0.034	123
Sulaimania	900	0.039	234
Salahudden	400	0.023	191
Diala	350	0.021	167
Najaf	95	0.013	221
Kerbala	95	0.013	188
Basra	200	0.016	176

2.5. Statistical Model

The statistical software (SPSS) was applied in this study to develop the optimal model that correlates each independent variable with the dependent variable. In this model, the dependent variable is methane generation, and solid waste generation and time are assumed to be independent variables. Multiple linear regression was chosen to generate the required statistical model. The coefficient of determination (R^2) and the level of relationship significance between the independent variables and the dependent variable, as determined by the analysis of variance (ANOVA) technique, were used to evaluate the statistical model.

2.6. Modeling Schematic

To apply the LandGEM model properly to Iraqi governorates, various parameters, such as waste composition, population, the methane generation rate, and the Methane Generation Constant, should be calculated for each governorate's conditions. Figure 2 illustrates the model flowchart.

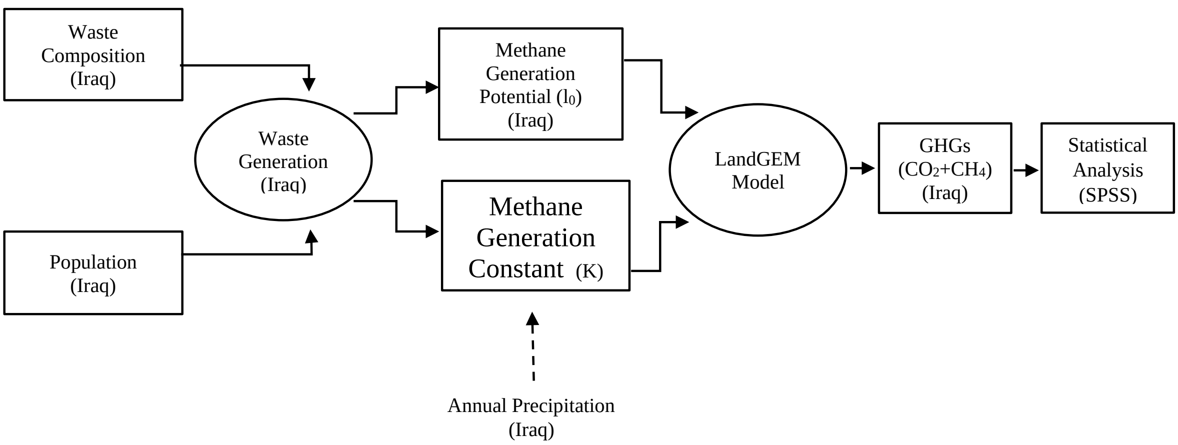


Fig. 2 Schematic of the Applied LandGEM Model for Iraqi Governorates with Modifications.

3.RESULTS AND DISCUSSION

3.1.LandGEM Model Results

Municipal solid waste composition plays a significant role in generating and emitting GHGs from landfills. Emissions increase with the biodegradable fraction of waste [6]. Table 2 describes the components of MSW (% by weight) and the generation rates for the Iraqi governorates, obtained from different sources. Table 2 indicates that food waste is the major component of MSW across all Iraqi governorates, accounting for an average of 58.3% of the total MSW. This average is close to the food waste component of MSW of other Middle Eastern cities and countries, such as Beirut, Egypt, Jordan, Abu Dhabi, and Tehran, i.e., averaging 52.5%, 55%, 63%, 49%, and 71.2%, respectively [27, 28, 29]. The United States of America's (USA) food waste component of MSW is only 15.2% [30]. The high percentage of food waste component of the Iraqi MSW is due to elevated food consumption by individuals and developing community lifestyles, resulting in considerable amounts of vegetable and fruit peel waste generated by Iraqis. Furthermore, environmental legislation related to MSW significantly changes the MSW composition. Moreover, food waste quantities are influenced by the time of year, with increasing trends during the fruit and vegetable growing season [6]. The second major biodegradable material, i.e., components of MSW, is paper and cardboard, accounting for an average of 9.7% of MSW in Iraq. This percentage is also similar to those in Beirut, Egypt, Jordan, Abu Dhabi, and Tehran, which are 16%, 10%, 11%, 6%, and 9.6%, respectively [27, 28, 29]. These organic components significantly generate gas emissions in landfills, especially methane and carbon dioxide. Other components of the MSW are insignificant contributors to GHG production, most likely because they are non-biodegradable [6]. A significant difference in MSW composition and generation rate between Iraq and the other countries, including the surrounding countries, is evident. These differences resulted from economic factors, war conditions, culture, and tourism. In general, the organic fraction of MSW in Iraqi and other developing countries is dominated by food and paper components. In the USA, the organic fraction of MSW depends mostly on food, paper, and yard waste. Thus, it is clear that the organic fraction of MSW is unaffected by a country's level of development, making the application of the LandGEM model, which was successfully used in the USA, suitable for MSW modeling in Iraq.

Table 2 Municipal Solid Waste Composition and Generation Rate for Iraqi Governorates. All components are (% by weight).

Governorate	Food waste	Paper and Cardboard	Plastic	Glass	Textile	Yard waste	Wood	Leather	Metals	Dirt, ash, etc.	Combustible	Non-combustible	Rubber	Other	Diapers	[b]Generation Rate (Kg/C.d)	Reference
Baghdad	49.0	18.9	19.2	6.5					6.4							0.8	[3, 43][a,b]
Babylon	60-70	7-10	7-10	2-3	3-4	3-4			2-3	8-14						0.802	[31, 41][a,b]
Basra	54.8	7.0	25.2	2.9	3.5		2.6	0.5	3.0	0.4						0.62	[3, 40][a,b]
Kerbala	56.6	12.3	14.9	3.7					3.7					8.8		0.685	[32][a,b]
Erbil	34.0	14.0	34.0	1.0			6.0		2.0	2.0					5.0	0.607	[33][a]
Wasit	70.4	3.4	4.2	2.3	6.8				2.4	10.6						0.53	[34][a,b]
Misan	44.0	4.9		4.2	4.0				4.0		0.6	32.3	1.1			0.66	[35][a,b]
Najaf	68.2	9.6	6.7	2.3	5.1	0.9	0.9	0.5	2.4	0.6			1.0		1.9	0.42	[1][a] [4][b]
Thi Qar	70.2	3.4	6.8	4.0	0.9	3.9			3.6	2.5			0.2			0.68	[45][a,b]
Diala	50.0	10.5	7.5		8.5		4.0		5.0					9.0	5.5	0.615	[36][a,b]
Sulaimania	75.0	3.0	7.0		6.0		5.0	2.0	1.0					1.0		0.613	[37][a]
Duhok	55.0	20.0	10.0	2.0					5.0					8.0		1	[38][a,b]
Ninevah	68.2	9.6	5.3	2.6	5.5				3.2							0.68	[2][a,b]
Salahuddin	56.9	11.3	13.3	4.3	1.9	2.0	0.5	0.9	4.4	4.5						0.46	[39, 42][a]

a: Components
b: Generation rate

Iraq is classified as one of the countries with the highest population growth compared to its neighboring countries. This fact is emphasized by its annual population growth rate during the last two decades of the twentieth century, which ranged from 2.68% to 3% [22]. Figures 3 (a) and (b) show the predicted population growth over time for the studied Iraqi governorates, starting from the landfills' open day in 2022 and ending on the landfills' closing day in 2046. For instance, the population of Baghdad is predicted to increase from 8.980.249 in 2022 to 15.411.347 in 2046.

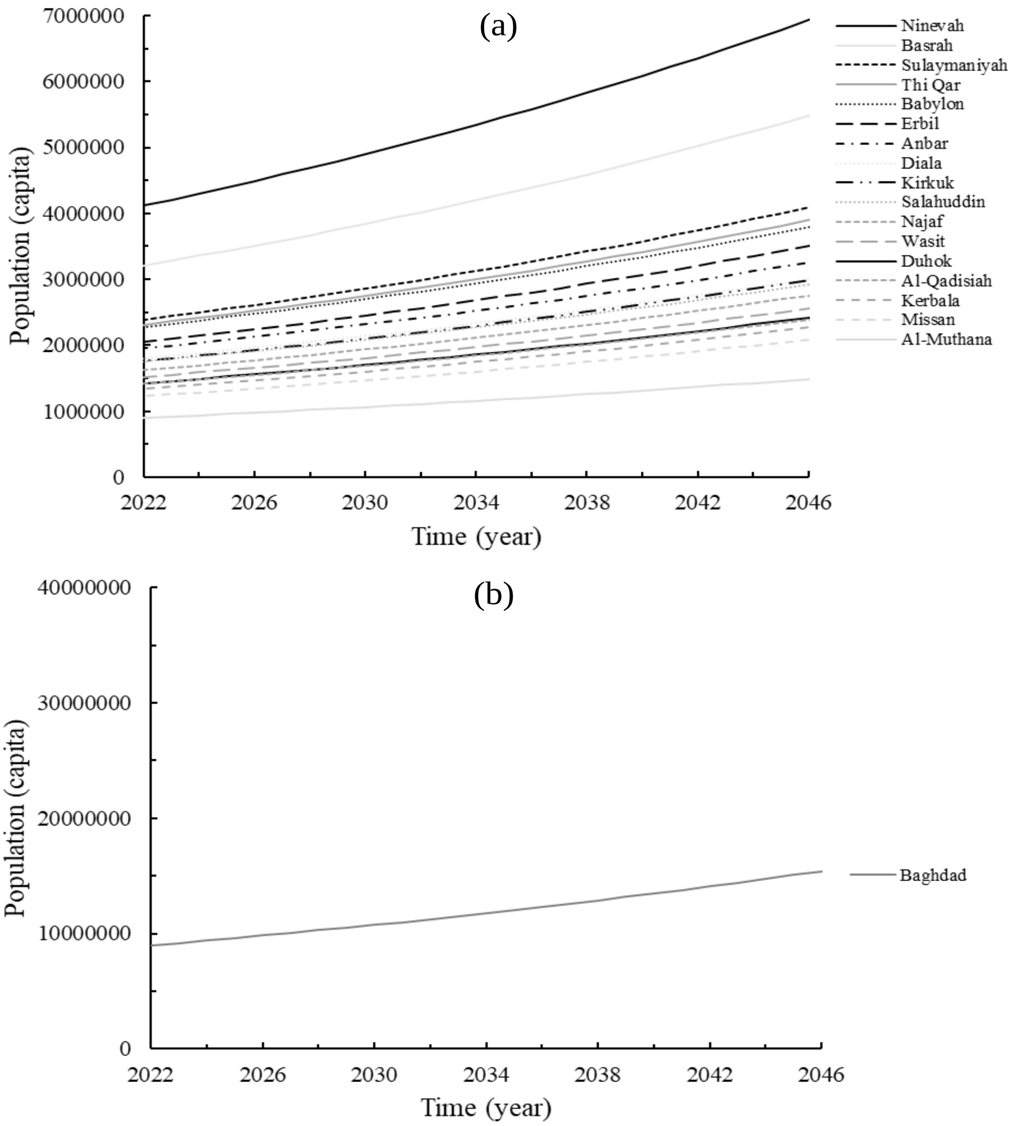
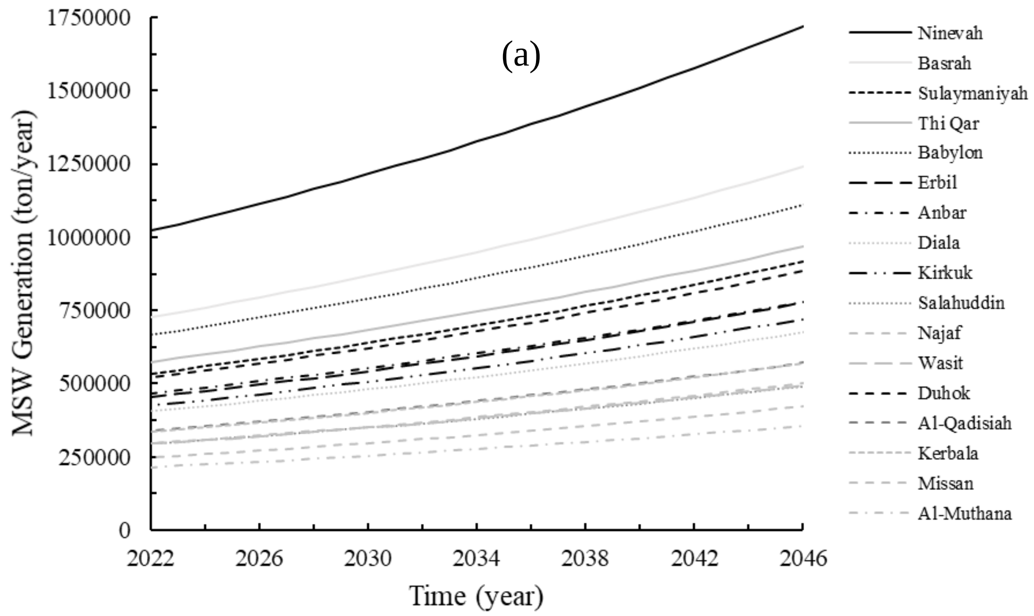


Fig. 3 Predicted Population for (a) Iraqi Governorates Except Baghdad, (b) Baghdad.

Several factors are increasing the volume of solid waste in Iraq, thereby increasing the volume of methane generation. These factors include inadequate solid waste management and low individual income. The recent and future amounts of generated MSW for the studied governorates were predicted based on various factors, including population, population growth rate, and waste generation per capita. Quantification of generated MSW is an essential step in calculating GHG emissions using LandGEM modeling. Figures 4 (a) and (b) show the annual MSW generation for all Iraqi governorates calculated from 2022 to 2046, i.e., opening and closing dates of the landfills. For example, Figure 3 (b) shows that MSW of Baghdad will increase by nearly 72%, from 2.622.233 tons/year in 2022 to 4.500.113 tons/year in 2046. The increase in solid waste indicates that this problem requires serious attention and an urgent, efficient management strategy. Landfill gas generation depends mainly on the equation of the biochemical reaction that decomposes the organic fraction of solid waste. From the equation, several parameters play a significant role in methane and carbon dioxide generation, including the number of moles and moisture content, which depend on the chemical formula of the organic MSW. Methane Generation Potential (Lo) was estimated using the equation mentioned. The LandGEM model was used to calculate total gas emissions, methane, and carbon dioxide for all Iraqi governorates using the calculated/predicted information, including population, MSW generation, MSW components, the methane generation constant (k), and potential methane generation (L_o). Figures 5 (a), (b), and (c) illustrate the total gas, methane, and carbon dioxide emissions. The data shows that gas emissions will peak in 2047. From 2047 to 2100, i.e., the modeling limit, gas emissions will gradually decrease until reaching a plateau, indicating that most organic material has been biodegraded.



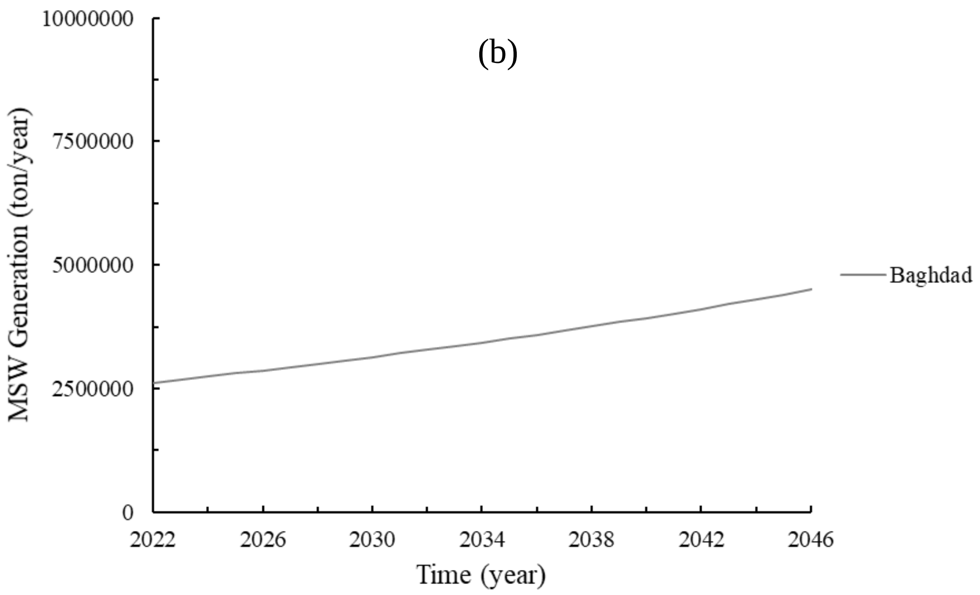


Fig. 4 Predicted MSW Generation for (a) Iraqi Governorates Except Baghdad, (b) Baghdad.

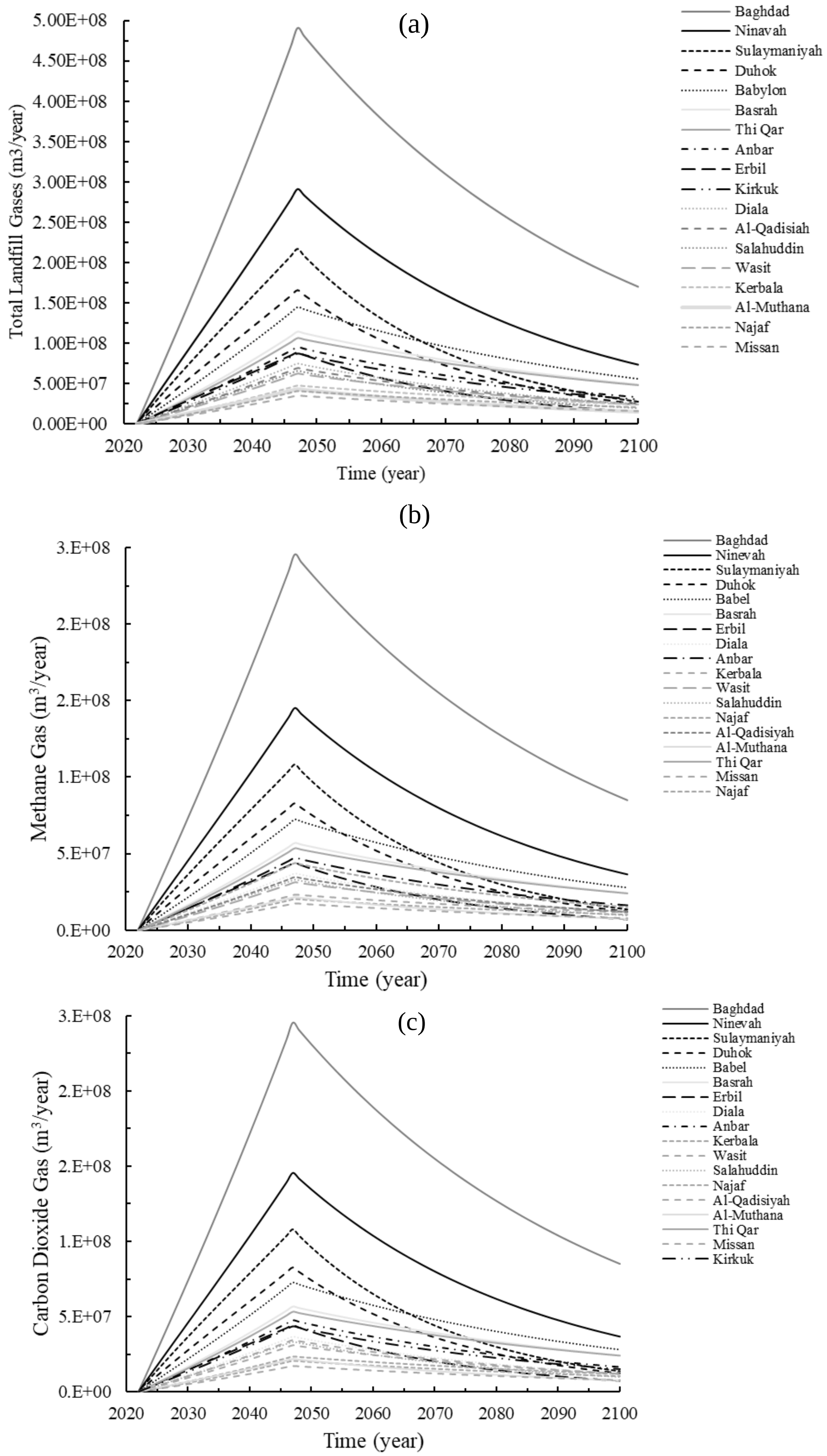


Fig. 5 Gas Emissions in (m^3/year) for (a) Total Gases, (b) Methane, and (c) Carbon Dioxide.

Figure 6 shows the total accumulated gas emissions generated from landfilling the MSW for all Iraqi governorates for the period from 2022 through 2100. The model results show that the highest emissions occurred in 2047, i.e., one year after the landfill closure date. It appears that Baghdad has the highest accumulated gas emissions (170,102,556 m3), nearly 10 times higher than the lowest calculated emissions for Misan (15,717,751 m3) and almost double the emissions calculated for Ninevah (73,316,601 m3). Figures 7 and 8 show the cumulative methane and carbon dioxide emissions from the start of landfilling in 2022 through 2100. Baghdad has the highest emissions of both gases, while Misan has the lowest emissions, most likely due to its lower population density. Duhok has high accumulated methane emissions (3020293611 m3) due to its MSW generation rate. Other governorates, such as Babylon, Thi Qar, Kirkuk, and Duhok, have similar accumulated methane and carbon dioxide emissions due to their similar population density and/or similar MSW generation rate.

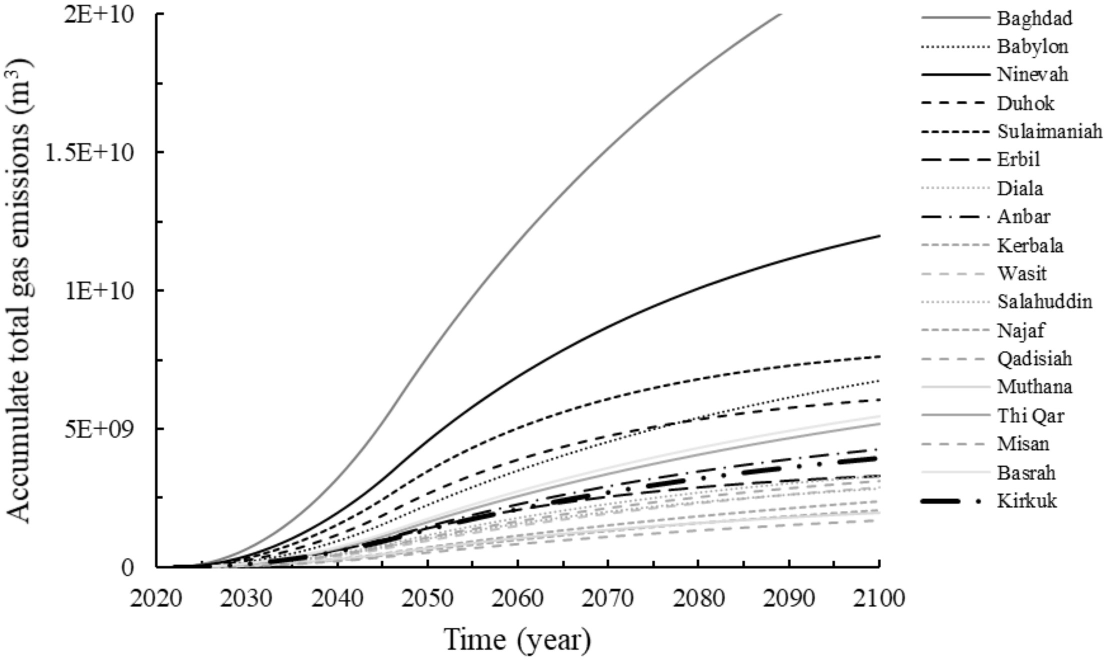


Fig. 6 Total Accumulated Gas Emissions for Each Iraqi Governorate.

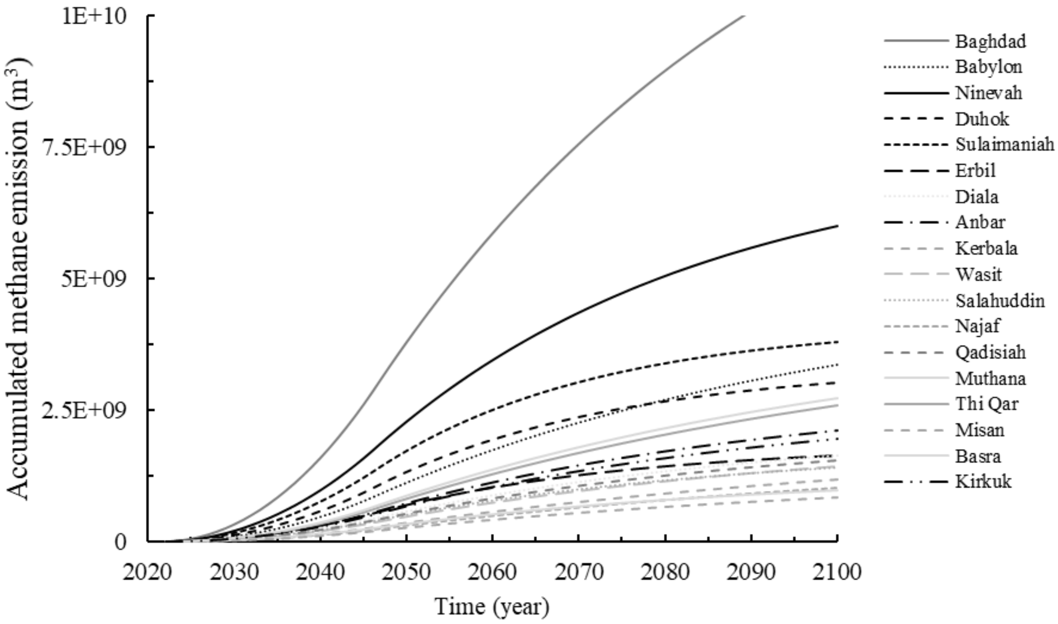


Fig. 7 Accumulated Methane Emissions for Each Iraqi Governorate.

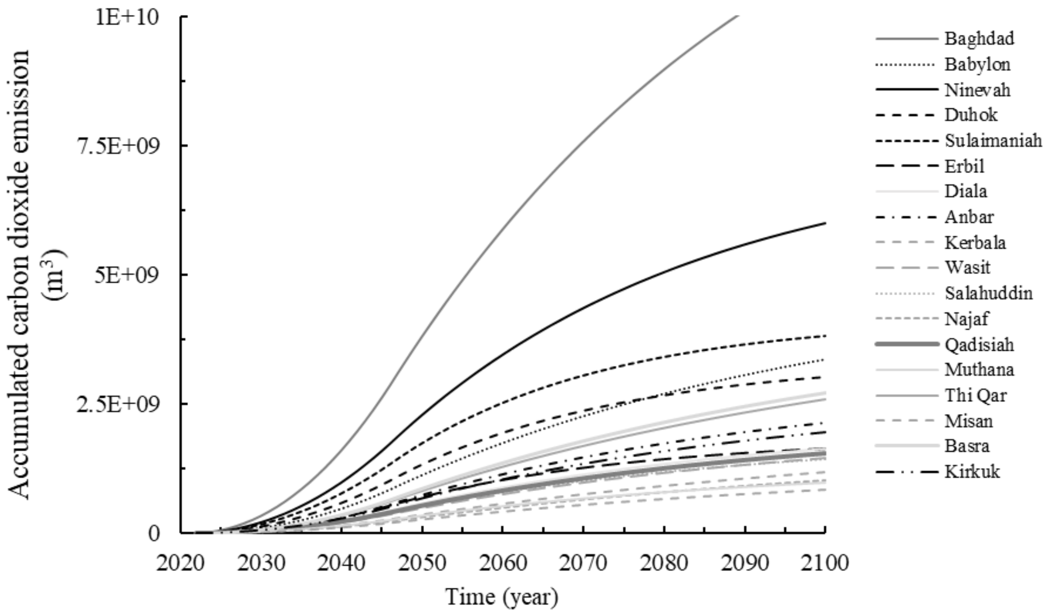


Fig. 8 Accumulated Carbon Dioxide Emissions for each Iraqi Governorate.

Figure 9 illustrates the total accumulated gas emissions for each governorate in 2061, i.e., 15 years after the landfill's closure date, which represent the total gases from the decomposition of the organic fraction in the landfill. The production of landfill gases depends on three main factors: population, MSW generation rate, and organic fraction of MSW [6]. Baghdad's emissions are almost 12.5 billion m^3, by far the highest total accumulated gas emissions among all investigated governorates. Such high emissions are due to its high population and MSW generation rate (0.8 kg/capita.d), as well as its status as Iraq's political capital, which receives many visitors each day. However, Duhok also has a high gas emission rate of approximately 4 billion m^3, likely due to its high MSW generation rate of 1 kg/capita, as shown in Table 2. This data indicates that, even though population density is likely the most important factor, MSW generation rate is almost as important for total gas emissions accumulation.

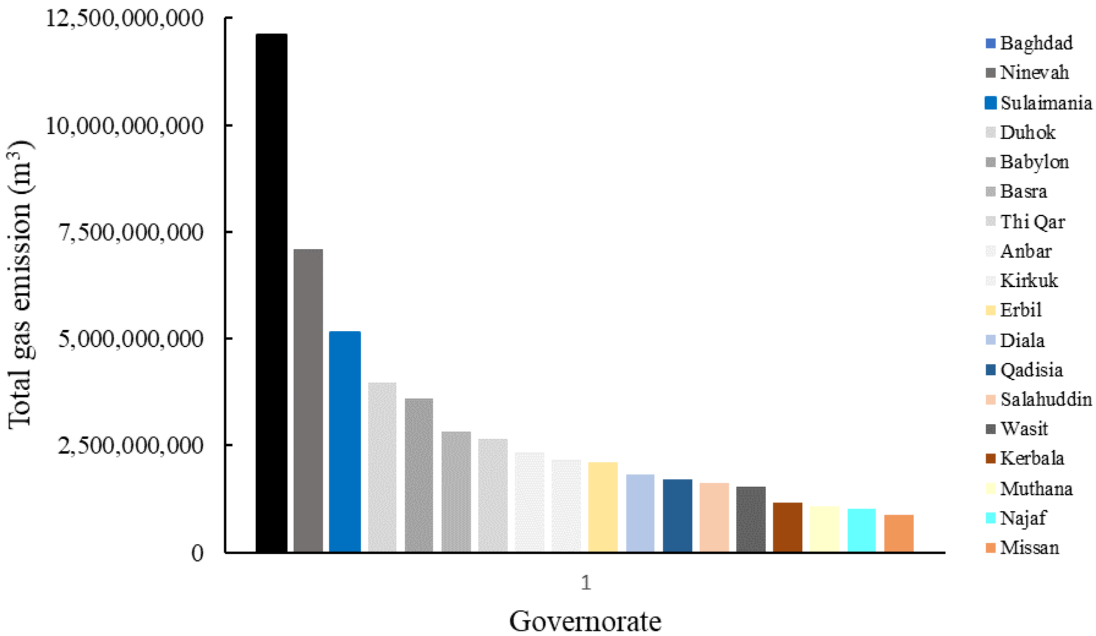


Fig. 9 Total Accumulated Gas Emissions for each Governorate from 2022 to 2061.

Based on the results of the present study, the following policies are recommended: improving solid waste management in Iraq; encouraging recycling and reducing solid waste; implementing taxes on activities that generate solid waste; and investing in the methane generated from landfilling solid waste.

3.2.Statistical Analysis

A statistical analysis was performed to ensure that the model used was appropriate and satisfied the requirements. It can be noticed from Table 3 that all models are highly significant, indicating that the relationships between the dependent variable (volume of methane generated) and the two independent variables (mass of solid waste generated and number of years) are very strong. Also, based on the high R^2 values ranging from 0.963 to 0.974, the majority of changes in methane volume are attributed to the two variables: the mass of generated waste and the number of years. Moreover, according to the standardized beta coefficients, the year variable has a greater influence on methane volume (range: 1.14-1.28) than the mass of generated solid waste. The statistical results confirmed that the LandGEM model is applicable and can be used to estimate greenhouse gas emissions, and that these results can be applied to MSW integrated management in Iraqi governorates.

Table 3 The SPSS Analysis of all Iraqi Governorates' Results.

Governorate	Statistical Model (CH_4)	R^2	Significance	Standardized Coefficients/Beta (M/y)
Babylon	215029457 – 346 M + 9258228 y	0.972	0.000	(-3.756/4.637)
Baghdad	644188152 – 266 M + 30524286 y	0.971	0.000	(-3.685/4.556)
Nineveh	466815907 - 489 M + 19957004 y	0.969	0.000	(-4.377/ 5.214)
Duhok	292451493 -599 M + 12300809 y	0.964	0.000	(-5.137/ 5.910)
Sulaymaniyah	375383100 -750 M + 16147901 y	0.963	0.000	(-5.262/ 6.014)
Erbil	145243127 -342 M + 6338344 y	0.965	0.000	(-4.884/ 5.671)
Diyala	115671517 -305 M + 4895942 y	0.971	0.000	(-4.027/ 4.893)
Anbar	145074186 -333 M + 6184690 y	0.971	0.000	(-3.933/ 4.804)
Karbala	58050343 -187 M + 2736661 y	0.974	0.000	(-3.187/ 4.092)
Wasit	88483340 -323 M + 3923145 y	0.972	0.000	(-3.688/ 4.569)
Salahaldin	108461368 -392 M + 4493644 y	0.970	0.000	(-4.237/ 5.091)
Najaf	49667416 -216 M + 2373083 y	0.974	0.000	(-3.161/ 4.067)
Qadisiyah	102742693 -324 M + 4476840 y	0.971	0.000	(-3.880/ 4.751)
Muthanna	67857335 -338 M + 2854634 y	0.972	0.000	(-3.966/ 4.837)
Thiqar	139817054 -263 M + 6420366 y	0.974	0.000	(-3.387/ 4.283)
Maysan	43894957 -161 M + 2071167 y	0.973	0.000	(-3.332/ 4.228)
Basrah	142230388 -212 M + 6798415 y	0.973	0.000	(-3.379/ 4.270)
Kirkuk	121680920 -309 M + 5527395 y	0.971	0.000	(-3.781/ 4.652)

CH_4: Volume of methane generated (m^3/year).
M: Mass of solid waste generated (kg/year).
y: year.

4.CONCLUSIONS

Based on the present study results, the following conclusions can be addressed:

- Iraqi governorates emit a large amount of greenhouse gases due to several reasons, including rapid population growth, which ranged from more than 42 M in 2022 (year of landfill opening) to more than 71 Mton in 2046 (year of landfill closure). A high biodegradable organic fraction of MSW composition was observed in Iraqi governorates. Furthermore, Lifestyle and seasons. These reasons generate considerable MSW in Iraq, ranging from more than 10 Mton/year in 2022 to 17 Mton/year in 2046, thereby increasing GHG emissions.
- The maximum GHG emissions will occur in 2047 (one year after landfill closure) due to degrading of most of the MSW organic fraction.
- The total accumulated GHG emissions for all Iraqi governorates from 2022 through 2061 (after 15 years of landfill closure, which represents the degradation of the almost entirely rapidly and slowly decomposing MSW organic fraction) are about 55 billion m^3.
- The statistical model results showed that LandGEM can be applied, given the high confidence in the model parameters.
- From the results, MSW in Iraq needs sustainable management to reduce its impact on climate change, and the optimal solution is to use solid waste as a source of renewable, clean energy.
- There is likely variability between the actual data and the LanGEM model's projected outcomes.
- Several external factors will affect MSW trends and GHG emissions in the future, including inadequate solid waste management and individual income.

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