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Municipal Solid Waste Characterization and Landfill Gas Generation in Kakia Landfill, Makkah

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Abstract: In many countries, open dumping is considered the simplest, cheapest, and most cost-effective way of managing solid wastes. Thus, in underdeveloped economies, Municipal Solid Wastes (MSW) are openly dumped. Improper waste disposal causes air, water, and soil pollution, impairing soil permeability and blockage of the drainage system. Solid Waste Management (SWM) can be enhanced by operating a well-engineered site with the capacity to reduce, reuse, and recover MSW. Makkah city is one of the holiest cities in the world. It harbors a dozen of holy places. Millions of people across the globe visit the place every year to perform Hajj, Umrah, and tourism. In the present study, MSW characterization and energy recovery from MSW of Makkah was determined. The average composition of solid waste in Makkah city is organic matter (48%), plastics (25%), paper and cardboard (20%), metals (4%), glass (2%), textiles (1%), and wood (1%). In order to evaluate energy recovery potential from solid waste in Kakia open dumpsite landfill, the Gas Generation Model (LandGEM) was used. According to LandGEM results, landfill gas (methane and carbon dioxide) generation potential and capacity were determined. Kakia open dump has a methane potential of 83.52 m^3 per ton of waste.

Keywords: landfilling; landfill gas; energy recovery; solid waste; characterization

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1. Introduction

Municipal Solid Wastes (MSW) cause major negative impacts on the environment. The waste management process encompasses practices like collection, disposal, landfilling, treatment, and recycling of the waste [1–6]. To avoid undesirable effects on the environment, solid waste management chain (waste generation, waste handling, and storage at site, collection, transfer and transport, and disposal) must be followed [7,8]. Thus, it is vital to choose a refuse disposal site that will have a minimal hazardous effect on human health and the environment. Solid waste management (SWM) has five main pillars: Reduction, recycling, recovery, reuse, and disposal [9–17]. Different approaches have been developed to manage MSW, but landfilling has remained the most common approach to manage MSW, mainly in developing countries. Due to changes in consumption patterns of commercial and households, the amount of solid waste generated per year has increased globally [9]. Improper management of this waste has led to many environmental problems like contamination of surface and groundwater bodies [18], air pollution [6], lack of land [19], and potential financial obligations [13,18,19].

Landfilling refers to the construction of a well-engineered site that can accommodate SW that cannot be reused in any way. The landfill can be built on ground or underground (depression) [5]. However, for economic purposes, some landfill is constructed on previously existing excavation like in the mines. The major aim of the engineered landfill is to protect the environment from any possible air, water, soil pollution, and human health [20]. Landfill can be categorized as: Uncontrolled dumps [1], total containment, modified containment, and controlled release. The latter has been applied in almost all developed economies, while uncontrolled dumping is common in low economies. Apart from the uncontrolled approach, the other categories are engineered sanitary landfills. The application of storage as MSW disposal includes as wastes is suitable for storage, while other disposal methods are economical, but they end up using tube technologies, while route elimination involves leftovers incineration [21]. In addition, landfill gas can be collected and used as a low pollutant fuel to produce heat and energy [22–28].

Landfill Gas (LFG) is a product of organic waste decomposition. LFG is a result of degradation processes that depend on a number of factors [29]. The presence of oxygen promotes aerobic respiration, which increases CO_2 production, while the presence of oxygen at high temperatures favors the formation of volatile compounds [30–32]. However, the main biological process that occurs in landfills is the anaerobic process [33]. LFG typically contains 45–60% methane (CH_4) and 40–55% carbon dioxide (CO_2). Landfill gas often includes small amounts of ammonia, sulfides, carbon monoxide, hydrogen, and Volatile Organic Compounds (VOCs) [34]. LFG potential generation can be calculated from the composition of the substrate. The amount of LFG varies from site to site, however, using empirical data or anaerobic degradation tests, the rate of LFG production can be determined. In one year, 200–300 m^3/ton of fresh MSW produce 1–40 m^3/ton of CH_4 [35].

Nowadays, there is much interest in energy production from MSW [36–39]. MSW generally comprises a mixture of organic matter (food wastes), plastics, paper, glass, metal, and other inert parts. It can also include some commercial and industrial waste that is similar in nature to household waste. MSW, if managed improperly, can cause severe human health problems and may seriously harm the environment [40]. Waste-to-Energy (WTE) is a process through which waste is managed to generate energy. The main aim of WTE is to foster the 3Rs (reduce, reuse, recover). The energy can be obtained by either direct thermal treatments of waste or using the generated gases [41,42].

The present work deals with the characterization of MSW and the estimation of landfill gas generation at Kakia Landfill, Makkah. This study consists of two parts: MSW characterization was carried out at Makkah city in the first part. This section provides reliable data on the main components of Makkah's MSW. The second part is investigation of LGF potential from solid waste in the Kakia open dumpsite.

The local body has approved a new Waste Management Regulation that aims to categorize the processing of integrated waste management, decrease waste formation, and handle activities, including the categorization, accumulation, collecting, transfer, and reprocessing of eco-friendly substances to attain the environmental sustainability model and to protect the community health [43]. The rapid increase in population of Makkah has led to the production of a vast amount of MSW, causing environmental and social challenges that have triggered questions on how to best manage this waste economically. Nizami et al. (2015) discussed the increase of the annual rate of pilgrims, which reported that the number of visitors was increasing with an annual rate of 1.19% from 1993 to 2014 due to a vast expansion in the Holy Mosque, increased facilities, such as advancement in accommodations, health services, transportation, food, and security services. Apart from increasing visitors, the local Makkah population is also increasing at a significant rate of 3.15% annually due to rapid urbanization [44]. Today, MSW received in Makkah's landfill has increased by 2000 tons daily, while in Ramadan, approximately 3000 tons are generated per day. In addition, 4500 tons of MSW are generated per day during the pilgrimage season. This MSW is composed mainly of organics and plastics [40,45].

2. Materials and Methods

2.1. MSW Sampling and Characterization

To understand the type of MSW in Makkah, samples were collected from residential districts of Awaly Khaldia, Shawkia, Reea Bakhsh, Mahbas Al-Genn, Masfallah, Shara'a, Hamra, and Buhairat districts, and the commercial zone of Aziziya. During sampling, 50 kg were taken (representing about 60–100% of the total ratio from the container) from the collection centers, a total of 14 collection points was sampled during the study period. The samples were mainly collected from residential districts (Awaly, Khaldia, and Shawkia), central area (Reea Bakhsh, Mahbas Al-Genn, and Masfallah), highly crowded district of Shara'a, new urbanized areas of Hamra, and Buhairat districts, and commercial district of Aziziya. The samples were collected during six days (first half of March 2017), then spread on a plastic sheet of size 5 × 5 m, sorted out, and classified as shown in Table 1 [46].

Table 1. MSW classification.

Waste Fractions	Waste Components
Organic matter	Food, animal excrements, vegetables
Wood	Wood, garden trimmings
Paper	Newspapers, office paper, bills, magazines, sales notes and receipts
Cardboard	Corrugated cardboard, boxboard
Plastic	HDPE, PVC, Film PE, polyethylene bag, hair, food containers, PS
Metal	Ferrous and non-ferrous material, aluminum cans and foils
Glass	Soda, beer, wine container, window glass, car glass
Textile	Clothes, ropes, sacks, sanitary products, cotton

The ASTM D5231-92 method (Standard Test Method for the Determination of the Composition of Unprocessed Municipal Solid Waste) was used to test the composition of wastes [47]. The samples were sorted out manually into waste components. The weight fraction of each component in the sorting sample was calculated by the weights of the components. The mean waste composition was calculated using the results of the composition of each of the sorting samples [48]. Description of sampling zones was given in Table 2. The locations of the collected solid waste samples of the city were also given in Figure 1.

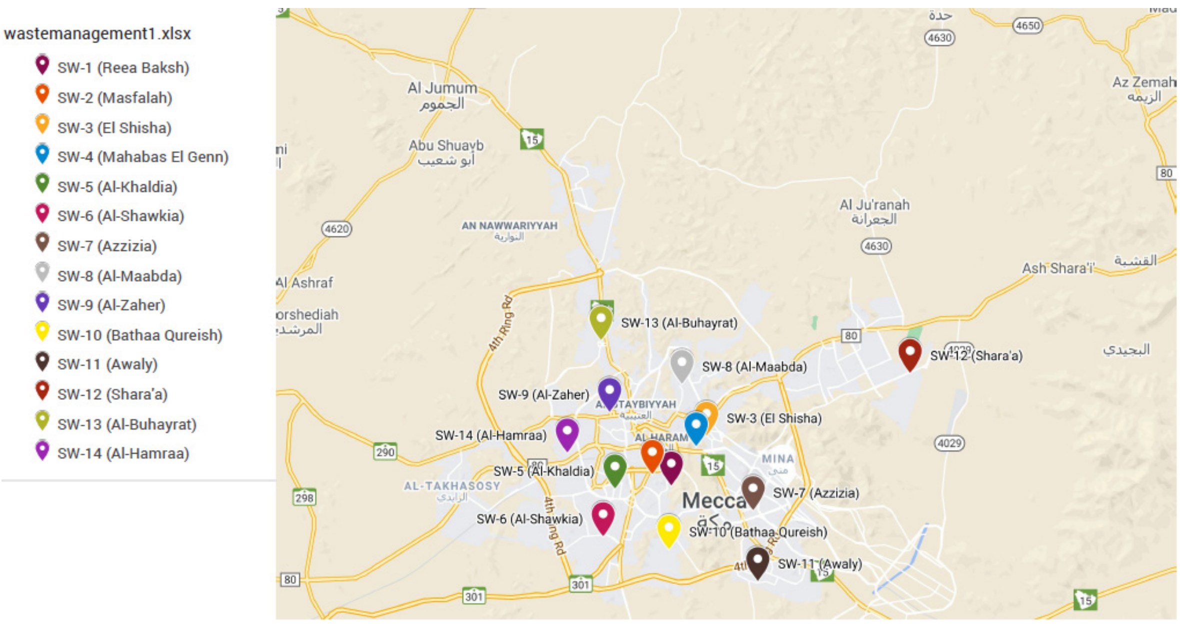


Figure 1. Locations of the collected solid waste sample in Makkah City.

Table 2. Description of the samples of MSW in Makkah City.

Sample Name	Geographical Coordinates	Ratio of MSW with Respect to the Container (%)	District	Spatial Description
SW-1	N 21° 24′ 7.74″ E 39° 49′ 57.9″	60	Reea Baksh	Central Zone
SW-2	N 21° 24′ 29.70″ E 39° 49′ 18.30″	70	Masfallah	Central Zone
SW-3	N 21° 25′ 44.34″ E 39° 51′ 11.94″	60	El-Shisha	Residential
SW-4	N 21° 25′ 23.58″ E 39° 50′ 50.10″	80	Mahbas Al-Genn	Central Zone
SW-5	N 21° 24′ 01.98″ E 39° 48′ 00.48″	90	Al-Khaldia	Residential
SW-6	N 21° 22′ 29.10″ E 39° 47′ 36.12″	90	Al-Shawkia	Residential
SW-7	N 21° 23′ 19.74″ E 39° 52′ 48.66″	80	Azzizia	Commercial
SW-8	N 21° 27′ 24.12″ E 39° 50′ 20.70″	70	Al-Maabda	Residential
SW-9	N 21° 26′ 30.18″ E 39° 47′ 49.44″	60	Al-Zaher	Residential
SW-10	N 21° 22 04.02″ E 39° 49 52.92″	95	Bathaa Qureish	Residential
SW-11	N 21° 21′ 02.22″ E 39° 52′ 58.74″	100	Awaly	Villas
SW-12	N 21° 27′ 45.54″ E 39° 58′ 16.08″	100	Shara'a	Residential
SW-13	N 21° 28′ 49.50″ E 39° 47′ 31.92″	90	Al-Buhayrat	New Urbanized
SW-14	N 21° 25′ 11.16″ E 39° 46′ 21.42″	90	Al-Hamraa	New Urbanized

2.2. Study Area and Modelling

Currently, in Makkah, SWM involves just collecting and dumping in an open site, Kakia, which is located south of Makkah. Kakia site is categorized as an open site and occupies 452,000 m^2. It is situated on the outskirts of Uranah and Malkan valley. It was opened in 2003 and is expected to be filled by 2020. Currently, it is receiving an average of about 3100 tons of MSW daily. To avoid advanced malignant effects on the environment, the Kingdom of Saudi Arabia (KSA) is planning to construct a geo-membrane clay lining that will impede the leaching of water while collecting the landfill gas. To estimate the amount of CH_4 emission in a landfill, the Landfill Gas Emission Model (LandGEM) is implemented [40].

The Landfill Gas Emission Model (LandGEM) with Microsoft Excel interface is considered a powerful tool to estimate the actual production of total landfill gases, CH_4, CO_2, and NMOCs (non-methane organic compounds) in a given landfill [18]. Equation (1) was developed by USEPA to estimate the amount of landfill gases. It is found to be quite reliable because it accounts for the deviations in the annual MSW flows. The model calculates the annual methane flow in 1/10th year increments.

$$Q_{CH_4} = \sum_{i=1}^{n} \sum_{j=0.1}^{n} kL_0 \frac{M_i}{10} e^{-kt_{ij}} \quad (1)$$

where Q_{CH_4} is the annual methane emission (m^3/yr), i is one year time increment, n is the difference between the year of calculation and the initial year of MSW acceptance, j is the 0.1 per year time increase, k is the methane generation rate per year, L_0 is the potential of methane production (m^3/ton), M_i is the mass of MSW accepted in the ith year (ton),

t_{ij} is the age of the ith section of MSW M_i accepted in the ith year. Note: 1 ton (metric ton) = 1 Mg (mega gram).

To determine the site-specific value of (L_o) the following equation is applied:

$$L_0\left(m^3\ of\ \frac{methane}{tone}\ of\ waste\right)^3 = MCF \times DOC \times DOC_F \times \frac{16}{12} \times F \quad (2)$$

where:

MCF = methane correction factor (1 = well managed landfill, assumed in this case 0.7),
DOC = degradable organic carbon (fraction),
DOC_F = fraction DOC dissimilated, and
F = fraction of methane in landfill gas (measurement at landfill has indicated a value of 56% CH_4 in biogas).

The site-specific degradable organic carbon (DOC) is calculated based on IPCC (1996) formula:

$$\%\ DOC\ (by\ weight) = 0.4(A) + 0.17(B) + 0.15(C) + 0.3(D) \quad (3)$$

where municipal solid waste consists of:

A = % paper and textiles,
B = % garden waste, park waste, or other non-food organic putrescibles,
C = % food waste, and
D = % wood or straw

DOC_F can be determined through the lignin content of the volatile solid (VS) [49].

$$DOC_F = 0.83 - 0.028\ LC \quad (4)$$

0.83 = empirical constant;
0.028 = empirical constant; and
LC = lignin content of the VS expressed as a percent of dry weight from leachate sample.

Methane generation potential (L_0) and constant (k) were 83.52 m^3/Mg and 0.050 per year, respectively.

3. Results

3.1. Characterization of Solid Waste

Characterization of solid waste is done throughout most of the districts of Makkah City. This is done to provide a preliminary indication of most of the streams of solid waste and a general figure of the organic matter. In addition, it is intended to specify the ratios of the recyclable materials. After manual sorting out of the collected materials, classification of solid waste was done, the data were statistically analyzed to get a graphical representation, as shown in Figure 2. From this figure, it is noticed that organic matter represents the largest component of solid waste, ranging from 30.60% to 88.12%. Whereas plastics represent between 5.35% and 35.88%, paper and cardboard represent between 4.66% and 29.48%, metals between 0.26% and 12.98%, glass ranging between 0% and 4.12%, textiles ranging from 0% to 3.60%, and wood represents 0–6.09%.

By comparing the data of classification of the collected solid waste samples, the researchers attain the maximum rate of 88.12% for the component of organic matter. This is found in the district of Awaly, and this can be attributed to the raising of the socioeconomic level of residents in this district. This is followed consecutively by Aziziya district with a rate of 70.70%, Shisha by a rate of 54.69%, Shara'a by a rate of 53.97, Khaldia by a rate of 53.36%, Al-Maabda by a rate of 48.10%, Al-Hamraa by a rate of 46.78%, Al-Zaher by a rate of 44.88%, Masfallah by a rate of 44.68%, Al-Shawkia by a rate of 43.16%, Al-Buhayrat by a rate of 40.89%, Bathaa Qureish by a rate of 31.53%, Mahbas Al-Genn by a rate of 30.60%, and Reea Bakhsh by a rate of 13.67%, as shown in Figure 2. The average classification of the fourteen collected SW samples can be arranged, as shown in Figure 3.

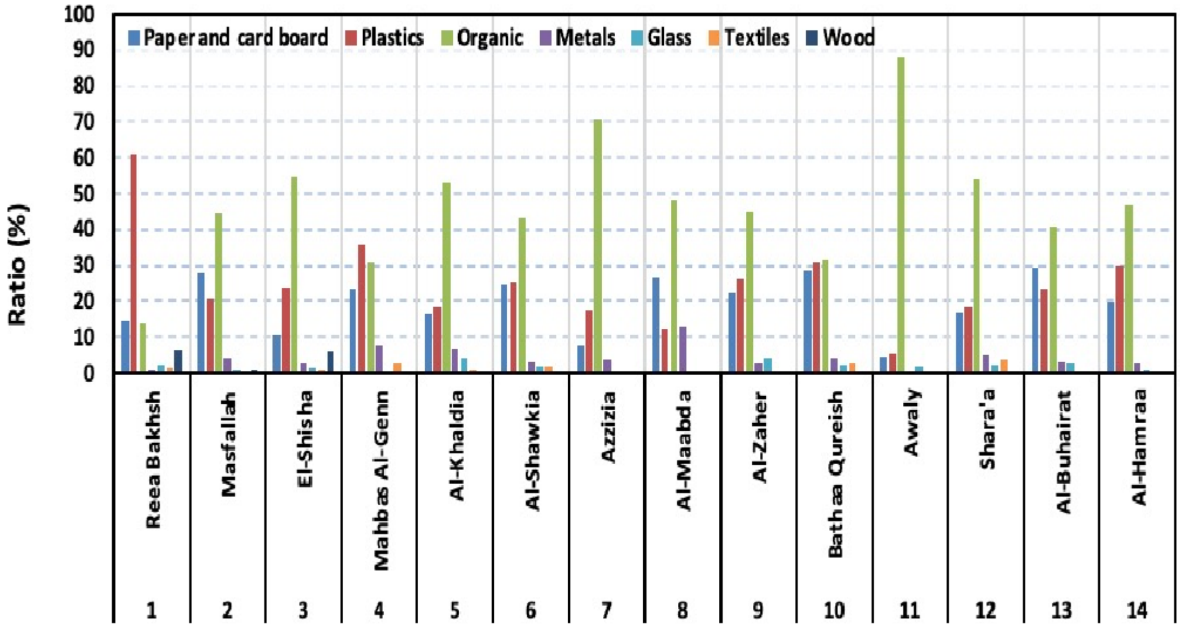


Figure 2. Comparison of classification of collected solid waste samples in Makkah City.

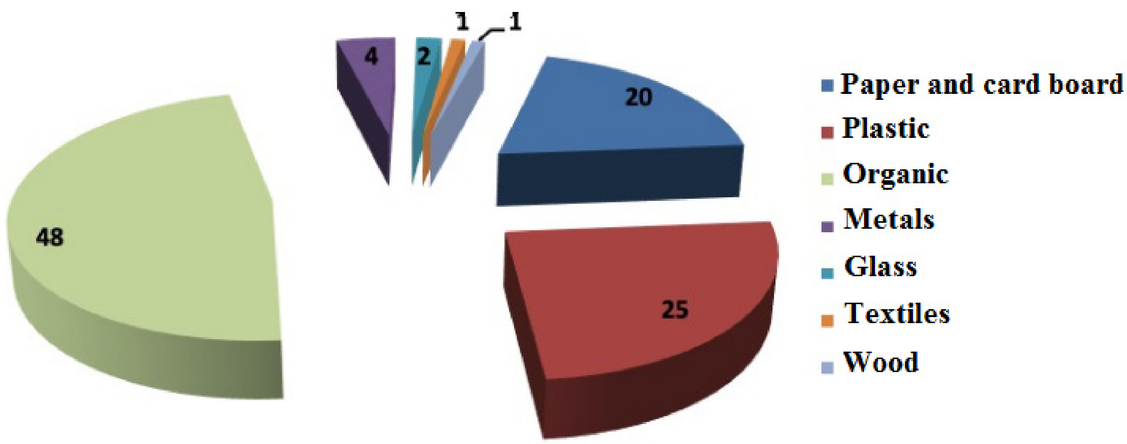


Figure 3. Average classification of solid waste samples in Makkah City.

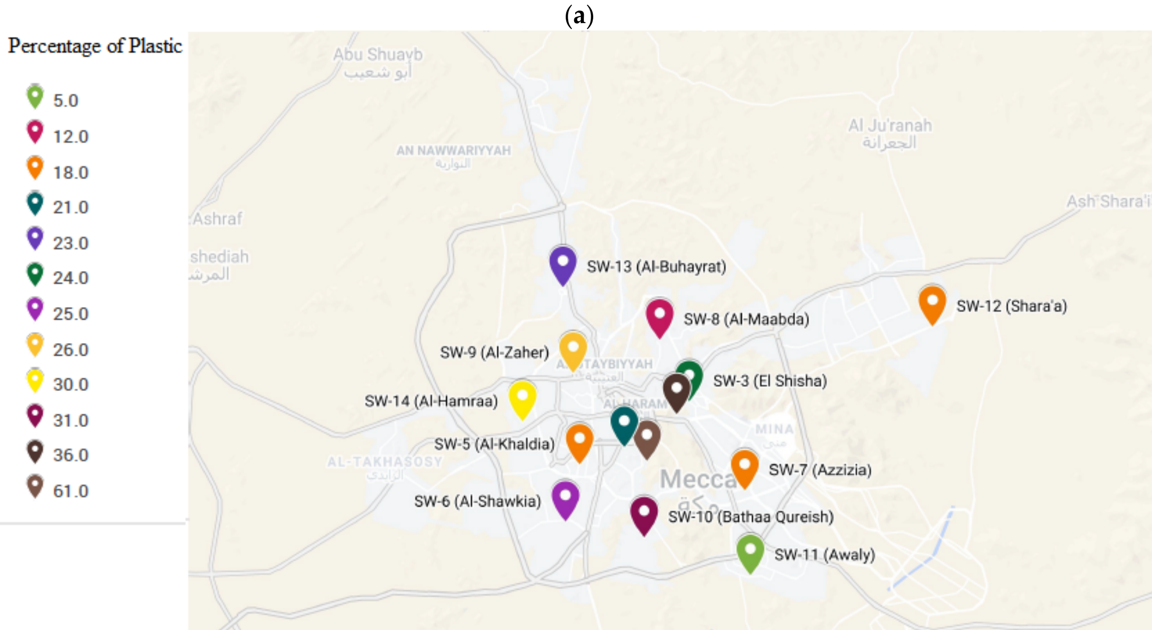
On average, plastics contribute a substantial value of the MSW generated in Makkah. However, easily biodegradable materials (organic matter and paper) contribute almost 70% of the entire MSW (Figure 3). Similar values have been reported in developing countries, where 60–75% of the MSW is biodegradable [50]. Figure 4a is a constructed contour map showing the aerial distribution of organic matter in the collected SW. Analysis reveals that there is a remarkable increase in organic matter content in the districts of Awaly (88.12%), Azizia (70.70%), and Shisha (54.69%), whereas the lowest rate of the organic matter is found in Mahbas Al-Genn (30.60%) and Reea Bakhsh (13.67%). In addition, Figure 4b shows the aerial distribution of plastic in Makkah city.

There is a remarkable increase in plastics content in the central district area (Reea Bakhsh by a ratio of 60.31% and Mahbas Al-Genn by a ratio of 35.88%). In addition, the contour map of the cardboard and paper (Figure 4c), shows a remarkable increase in the central zone (Masfallah: 28.14% and Mahbas Al-Genn: 23.27%). This increase is attributable to the fact that the central zone of Makkah city harbors dozens of hotels and houses for pilgrims. These residents depend mainly on fast food that requires excess plastic and paper bags.

3.2. *Estimation of Landfill Gas Production Potential in Makkah*

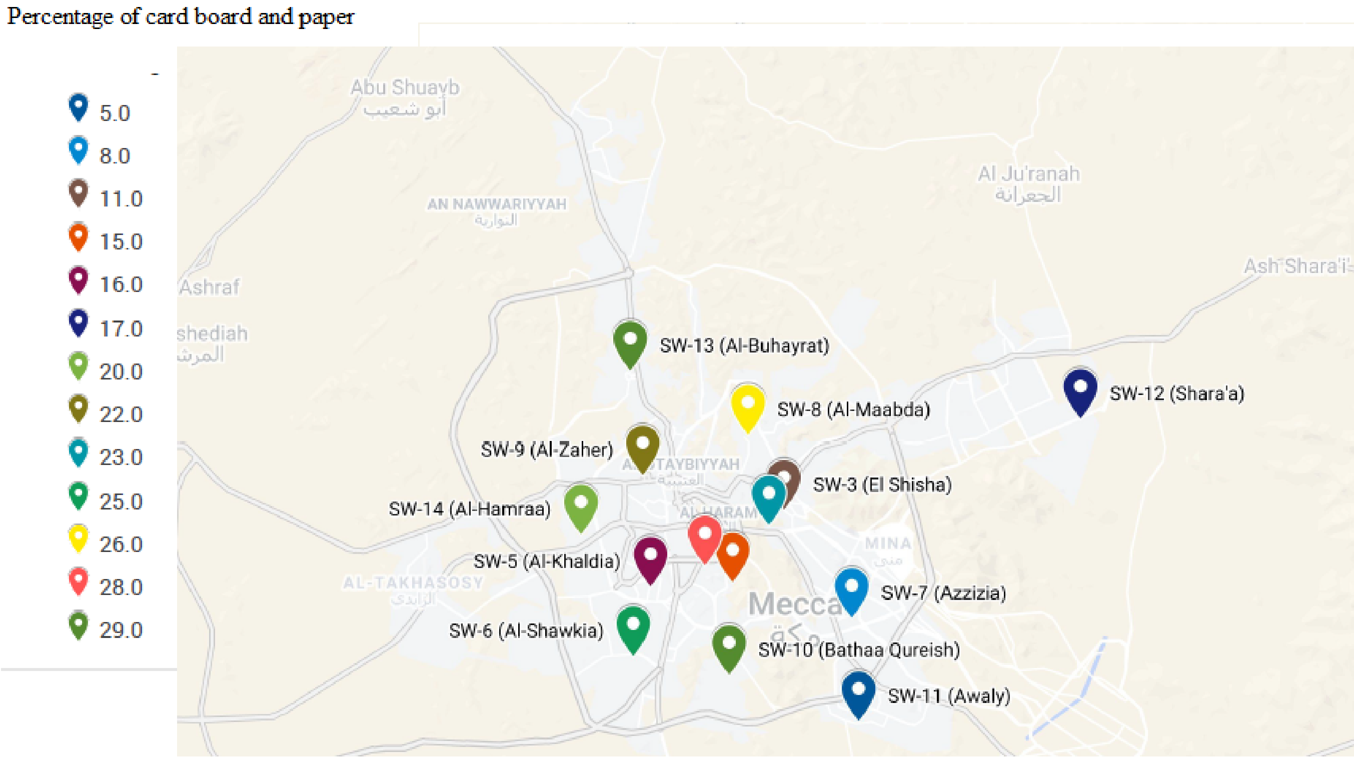
The Landfill Gas Emissions Model (LandGEM) with Microsoft Excel interface was expended to determine the total LFG quantity from SW landfill. Using LandGEM first-order decomposition rate equation was used to quantify emissions of MSW in the landfills. To calculate landfill gas production, different parameters were input into the model, including greenhouse gas production constants of upper and lower limits for both wet and dry climates as set by US EPA, 2012 [51], and Kakia Landfill site-specific parameters were applied. According to Equation (3), a content value of 19.49% was obtained based on the composition of waste, calculated from a weighted average of the carbon content of various components of the waste stream (Table 2). The biodegradable fraction was calculated by using Equation (3). The average volatile lignin content of 44.1% was employed in Equation (4). This yielded 0.82 DOC_F and was determined through the lignin content of the volatile solid (VS) as designed by Kreith and Tchobanoglous [52]. Using Equation (2) and the data profiled in Table 3, the methane potential was calculated as 83.52 m^3 of methane per ton of waste. This is the first time to calculate this value for Kakia landfill of Makkah City. The default recommended value is 170 kg of methane per ton of waste.

(**a**)



(**b**)

Figure 4. *Cont.*



(c)

Figure 4. Contour map of the distribution of the component of (**a**) organic matter, (**b**) plastics, (**c**) cardboard and paper for the collected solid waste samples in Makkah City.

Table 3. Determination of methane gas potential (L_o).

	Input Parameters				L_o (m^3 of CH_4/tonne of MSW)
	MCF	**DOC (%)**	**DOC_F**	**F(%)**	
Result	0.7	0.19488	0.82	0.56	83.52

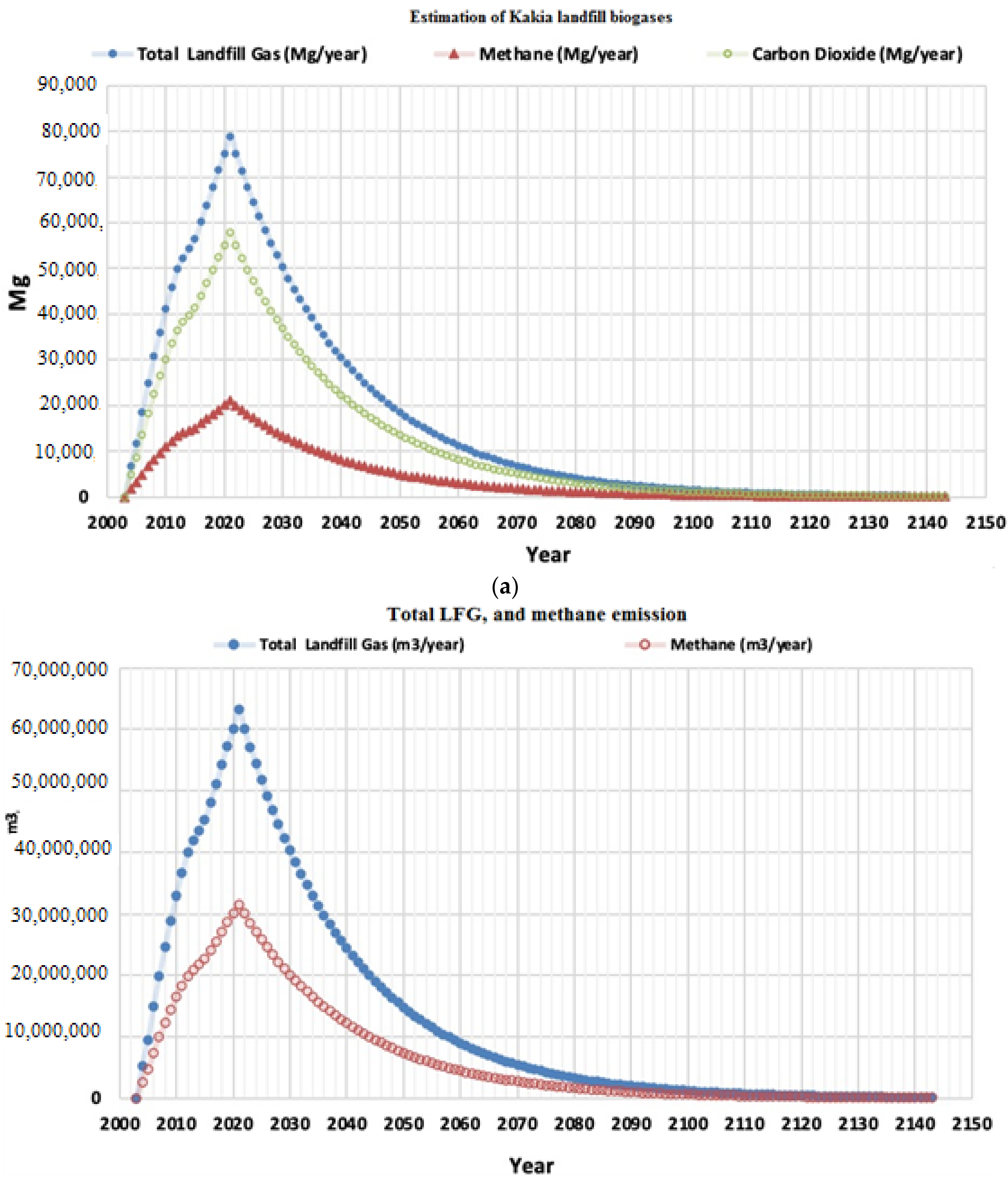
For the estimation of methane from the landfill sites, user-specified inputs were used in the LandGEM model. The methane generation potential (L_0) was specified as a default value of 83.52 m^3/Mg, while the methane generation constant (k) was 0.050 per year. The methane and carbon dioxide in the LFG were considered to be 50% [51] for the purpose of this study since Kakia landfill started operation in 2003 and the waste will be accommodated until 2020.

As shown in Figure 5a, it can be concluded that the estimation of Kakia landfill biogases in Mg/year for the period of 2003 to 2143 is as follows:

- Sum of landfill total gases = 2,380,203.3 Mg/year and 1,905,957,300 m^3/year,
- Sum of methane = 635,791.4 Mg/year,
- Sum of carbon dioxide gas = 1,744,388.6 Mg/year, an

Moreover, as shown in Figure 5b, it is concluded that the estimation of Kakia landfill biogases in m^3/year for the period of 2003 to 2143 is as follows:

- Sum of landfill total gases = 1,905,957,300 m^3/year,
- Sum of methane = 952,996,960 m^3/year,
- Sum of carbon dioxide gas = 952,996,960 m^3/year, and



(**a**)

(**b**)

Figure 5. (**a**) Landfill gas emission estimation in Mg/year, (**b**) total LFG, and methane emission estimation in m^3/year for Kakia landfill utilizing the LandGEM model for the years 2003–2143.

4. Comparison

MSW composition varies from area to area and is dependent on the source and community. It has been reported that most MSW consists of organic waste, which generally accounts for 40%, and in our study, also organic waste was found to be the highest, amounting to an overall 70%. Similarly, the second-highest ratio for MSW was found to be plastics. In our study also, the second-highest fraction of the waste was found to be plastics, as shown in Table 3. Moreover, it has been reported that 65.5% of organic waste is generated in the KSA, and our study shows that the highest number of organic waste might be in the Makkah region of KSA. The values show the dominance of organic waste in MSW for the Makkah region [53]. It has been reported that 21% of the renewable energy contribution is attributed to the residential sector globally [36], and for about 100,000 populations, the level of biogas production may increase significantly. In a Chechen republic initially, the biogas amount from the municipal solid waste landfill at Grozny was reported to be five million m^3/year through which 1000 kW of electricity could be produced [54]. In another study at Johar, a state of Malaysia, 832,800,484 m^3/y of methane was found to be emitted, while 4996,802,903 kWh/y of energy from raw biogas was produced [55]. Various software and modeling assumptions were used to assess the biogas production and composition and published biogas yields from anaerobic digester after treating different MSW fraction. According to the institute for global environmental strategies Japan, from dry and wet organic MSW, 592 m^3/mg and 118 m^3/mg of biogas can be generated, respectively. Moreover, California integrated waste management board has shown 100–150 m^3 biogas/mg wet MSW and 112 m^3/mg organic MSW can be generated [56]. Similarly, from a matured compost of 50,000 tons of undifferentiated waste in northeast Portugal, 2,700,000 KW energy was produced using a mechanical and biological treatment [57].

5. Discussion

In assessing energy recovery potential from MSW, more emphasis was put on organic matter since these matters play an important role during the generation of LFG. Characterization of MSW provides baseline data for the municipality to assess their progress towards specific sustainable waste management goals and opportunities of recycling refuse in Makkah. MSW samples were collected from 14 different locations in Makkah city (Table 2). The analysis of the fourteen samples revealed that, on average, Makkah's waste contains 48% organic matter, 25% plastics, 20% paper and cardboard, 4% metals, 2% glass, 1% textile, and 1% wood. By investigating the areal distribution of MSW classification, the researchers observed a remarkable increase in the content of organic matter in the districts of Awaly, Azizia, and Shisha, where the lowest rates of the organic matter were found in Mahbas Al-Genn and Reea Bakhsh. These findings can be attributed to the high economic levels of inhabitants of these districts.

Estimation of LFG production potential in Makkah was studied utilizing the LandGEM Model on the current Kakia dumpsite. Input classification parameters of solid waste were: Landfill opening year was: 2003, landfill closure year was: 2020, waste design capacity: was 12,538,000 tons, methane generation rate, K: 0.050 $year^{-1}$, potential methane generation capacity, L_0: 83.52 m^3/Mg (based on classification of solid waste in Makkah). Gases/pollutants selected: Total landfill gas, methane and carbon dioxide. The computations estimated Kakia landfill's LFG (m^3/year) potential for the period of 2003 to 2143 as: Total landfill gases = 1,905,957,300 m^3/year, methane = 952,996,960 m^3/year, carbon dioxide = 952,996,960 m^3/year, and NMOC = 7,623,709 m^3/year.

Makkah's solid waste is dominated by organic matter, the residue (humus) after recovery of biogas should be investigated for full-scale application in the agricultural sector. The area is located in a semi-arid region, therefore, the application of these residues will provide more fertile lands for agriculture, thus boosting food production. There is an incomplete institutional structure and limited participation of non-governmental organizations in managing solid waste, a low-level of environmental awareness, inadequate manpower to enhance environmental legislation. It is important to note that some private and commercial sectors are responsible for the transport of solid waste to the dumpsite, which leads to inaccurate data of solid waste quantities. All this needs improvement.

6. Conclusions

In this study, MSW characterization and the energy recovery of Makkah were determined. The Gas Generation Model (LandGEM) was used to evaluate energy recovery potential from solid waste from open dump site landfill and landfill gas generation potential and capacity were determined. The results estimate the methane potential of 83.52 m^3 per ton of waste from Kakia, collecting and dumping open site for Makkah. From the data, it was observed that most of the MSW collected in Makkah city are high in organic matter averaging accounting to 48%. In most of the districts, high content of organic waste was observed, which may be due to their high economic levels. On the basis of the result, it can be concluded that Makkah MSW has strong potential for recovery of biogas and afterward can be utilized further in the agricultural sector for boosting food production.

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