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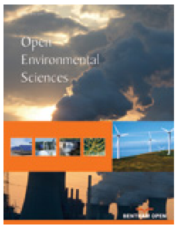

REVIEW ARTICLE

A Review of Landfill Gas Generation and Utilisation in Africa

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Abstract: This review evaluates the current Landfill Gas (LFG) utilisation technology across Africa and gives general overview on the global context. With the increase in global Municipal Solid Waste (MSW), the world has embraced landfilling to be its major way of MSW management. About 85% of the world's MSW is deposited in landfills. This has brought increased concerns of gases emitted from landfill sites. These gases have contributed enormously to the global anthropogenic Greenhouse Gas (GHG) emission which are detrimental to the world's environmental media. Although significant progress has been made on the utilization of landfill gases but this is limited to some developed countries, while in Africa, there has been limited strategies and control of LFG emissions. This review spotted several reasons that could have influenced the low development of LFG utilisation in Africa as ranging from lack of skilled expertise, inadequate knowledge of the technology involved, lack of political will, inadequate funding for LFG utilization projects and monopoly of the power sector among others. It is recommended that urgent attention should be given to LFG utilisation as it can aid in acquiring carbon credits, reduction in obnoxious smell and odours, and provide the much-needed energy which is crippling the economy in Africa as well as reducing the consequences associated with the release of greenhouse gases to the environment.

Keywords: Africa, Energy, Greenhouse gases, Landfill, Solid waste, Globalization, Anthropogenic.

1. INTRODUCTION

With the recent move towards globalization by the modern world, Municipal Solid Waste (MSW) generation is rapidly increasing. The world's urban residences generate approximately 1.3 billion tonnes/year of MSW, which is about 1.2 Kg/person/day and it is expected to increase to about 2.2 billion tonnes/year by 2025 [1]. Africa generates approximately 62 million tonnes/year of MSW, but there are differences among cities in Africa. Larger cities tend to generate more MSW than smaller ones. MSW generated in Africa ranges from 0.09-3.00 Kg/person/day with an average of 0.65 Kg/person/day [2]. Waste management is focused on managing all processes and resources for appropriate handling of waste materials, from maintenance to waste transport trucks and dumping facilities in compliance with health codes and environmental regulations [3]. Landfill has been a common acceptor for waste in the past decades. However, countries in Africa including South Africa, Algeria, Cameroon, Madagascar, Mauritius, Morocco, Niger and Tunisia deposit approximately 95%, 97%, 95%, 96%, 91%, 96%, 64%, and 95%, respectively, of their MSW in landfills and dumpsites [4]. According to the waste management hierarchy chart Fig. (**1**), waste disposal is considered to be the last favoured option of solid waste management, but most countries still prefer to use landfill because it is cheap in terms of capital and easy to use compared to other MSW management techniques [5, 6].

Landfill Gas (LFG) is a complex mixture of different gases formed by the action of microorganisms within a landfill [7]. Mismanagement of landfill can lead to uncontrolled emissions of LFGs such as CH_4 and CO_2 which contribute enormously to climate change; pungent odours, litters and dust in the vicinity; seepage of leachate formed in the landfill into ground water and surface water [8]. In 2011, the United States recorded 1908 landfills which generate approximately 1.03×10^8 metric tonnes of carbon equivalent of CH_4, which accounts for 17.7% of the total CH_4 emitted

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from the United States' into the atmosphere [9]. In 2013, China recorded 580 landfills and the CH_4 emitted from these landfills accounted for 13% of the total CH_4 emitted from China [9]. In Europe, landfill recorded the second largest source of CH_4 emitted from anthropogenic activity, which was 22% of estimated CH_4 from waste disposal sites [10]. Africa is the most vulnerable part of the world in relation to the consequences associated with uncontrolled emission of LFG [11]. The total potential methane generated from Africa in 2012 was $10{,}496\times10^6$ m^3 (assuming all the waste generated are landfilled), therefore management of LFG generated is of great importance [4].

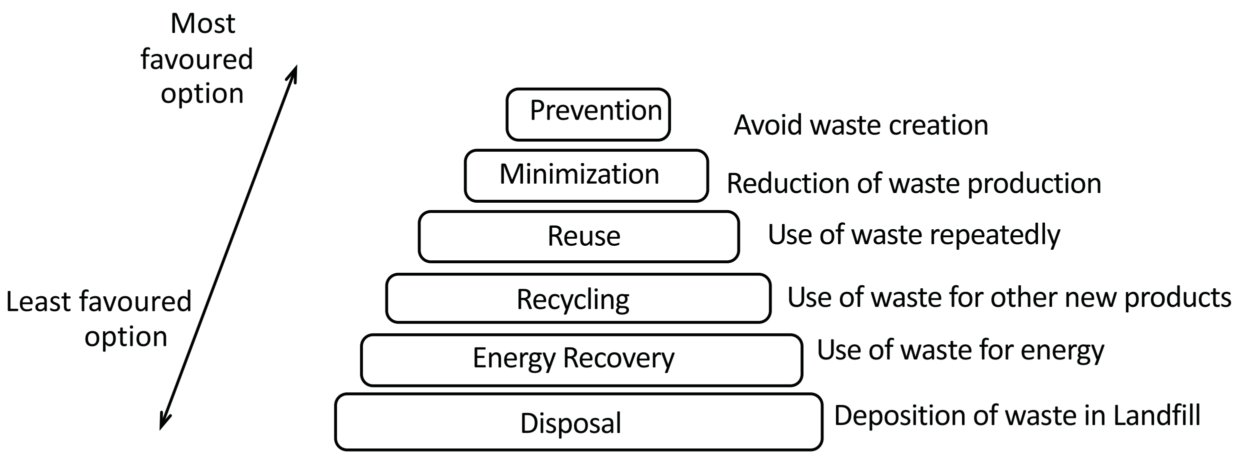

Fig. (1). Solid waste hierarchy.

LFG utilisation involves the process of collecting and processing LFG derived from the decomposition of solid waste from a landfill, in order to use it to produce electricity, fuel, heat and various useful chemical compounds. There are increasing numbers of LFG utilisation technologies which are functioning around the world. Africa has approximately 1% of the total LFG utilisation technology in the world and the rate of increase in the technology as the years go by is very low [12].

Africa has a population of approximately 1.2 billion people which is about 15% of the world's population [13]. However, Africa majorly depends on landfilling for its MSW management. Therefore, as the population of Africa increases in coming years, MSW generation is expected to increase, hence the increase in landfill sites. Africa has not been able to utilise this LFG generated from landfills and African leaders and scholars have not given much attention to the beneficiation of emitted LFG from African landfills. Gases generated from landfill sites could be useful alternatives for the provision of energy in most African countries. For example, In Kampala (Uganda), the estimated utilisation of LFG to electricity was 31000 megawatt (MWh) in 2009 and 26600 (MWh) in 2011 [14]. South Africa and Nigeria together with other African countries are considering LFG utilisation as a major source of electricity [15].

This paper therefore, seeks to give an overview of the LFG generation and utilisation technology in Africa and assess the global view of LFG utilisation. It focuses on the potential generation of energy from LFG generated in Africa. It also looks into the potential social-economic aspects of LFG utilisation in Africa. In addition, the study poses possible recommendations to LFG utilisation in Africa.

2. LFG GENERATION PROCESS

LFG is generated largely by bacterial decomposition of organic waste present in a solid waste landfill. LFG production in landfills involves three stages viz-a-viz bacterial decomposition, chemical reactions and volatilisation [7].

2.1. Bacterial Decomposition

this is the major process in the production of LFG and entails the decomposition of organic waste by bacteria into various gaseous products and by-products [7]. This first stage of LFG generation occurs in five phases shown in Fig.

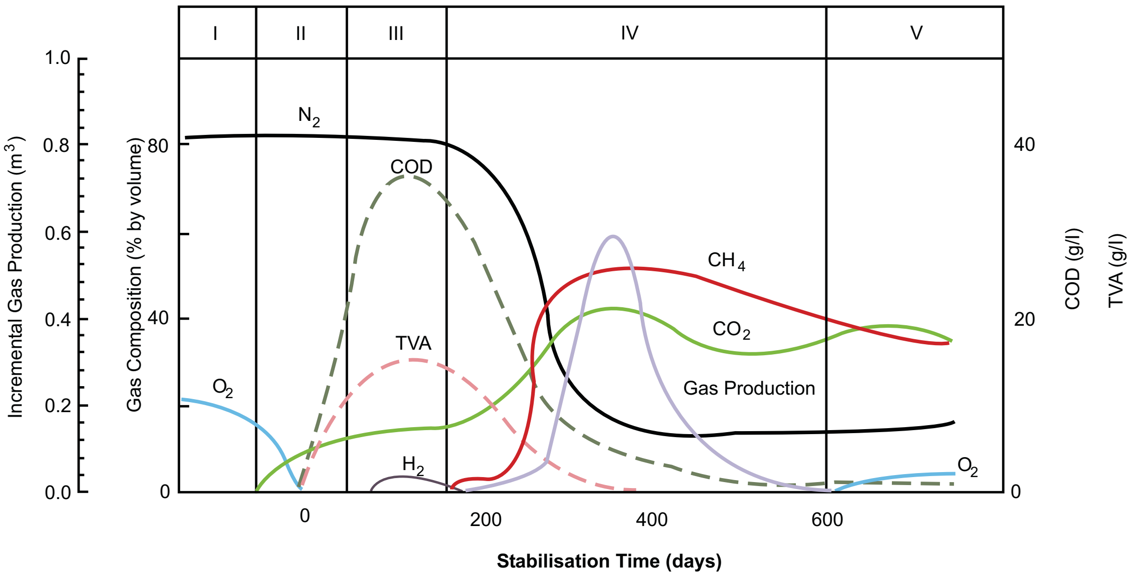

Fig. (2). Composition of Landfill Gas with Time [16].

In Phase I aerobic bacteria decompose the long molecular chains of carbohydrates, protein and lipids found in the organic waste in the landfills in the presence of available oxygen, this phase can go on for days - months until the total oxygen is used up. The oxygen present result from the loose compaction of solid waste when buried. The end –products of this phase are CO_2, heat and water. Nitrogen content is high but will continue to undergo decay as the phase continues [16]. The decomposition process then continues to phase II which begins after the oxygen in the landfill is exhausted. In this anaerobic process, bacteria change the compounds from phase I process into acetic, lactic, formic acids and alcohols such as methanol and ethanol. This is a very acidic process; the acid present in the waste combines with moisture and makes certain nutrients to dissolve producing chemical compounds like nitrogen and phosphorus in the landfill. Carbon dioxide and hydrogen are then generated as end products, if the landfill is disturbed and air enters then phase II goes back to the phase I process [17].

Phase III is mainly where the methanogenesis process starts. The anaerobic bacteria use the acid generated in phase II to form acetate. Furthermore, the methane producing bacteria begins to emerge. Acid manufacturing bacteria produce compounds for the methanogenic producing bacteria for use. At this phase hydrogen peaks, Chemical Oxygen Demand (COD), Total Volatile Acid (TVA) concentration peaks as well in the concentration of the leachate [16]. Phase IV is when the time for equilibrium has reached, making the production rate and composition constant. Approximately 45% - 60% methane, 40% - 60% CO_2, and 2% - 9% of other gases are produced. This can go on for a period of 20 years after closure of landfill [18]. Finally, the decomposition process reaches phase V in which most LFG emissions occur, the pressure in the landfill waste compartment is higher than pressure of the ambient atmosphere. In this long-term phase, the volume of CO_2 decreases with respect to the methane emissions, the ratio can range up to 4:1 CH_4 to CO_2 emissions [19].

2.2. Chemical reaction

different chemical substances present in the landfill waste can react chemically together in the presence and/or absence of moisture, oxygen (O_2) and carbon dioxide (CO_2) to produce different forms of LFG [17]. For example, anhydrous oxidation of aluminium from raw trash or metals reacts with oxygen with or without the presence of water.

$2Al + (3/2)\ O_2 \rightarrow Al_2O_3 + \Delta H°_T$; $\Delta H°_{298}$ (molecular enthalpy of the oxidation of aluminium = -1675.7KJ/mole) [20]. Amphoteric reaction – aluminium reacts with alkaline water at pH $\geq$ 8;

$Al + OH^{-1} + 3H_2O \rightarrow [Al\ (OH^{-1})_4]^{-1} + (3/2)\ H_2$.

Also, aluminium nitrite can react with water to form ammonium gas;

$AlN + 3H_2O \rightarrow Al\ (OH)_3 + NH_3$, the odour of ammonia gas indicates the landfill is alkaline in nature.

Aluminium sulphide can react with water to produce hydrogen sulphide with its characteristic pungent odour

$6H_2O + Al_2S_3 \rightarrow 2Al(OH)_3 + 3H_2S$, these end products are characterized by pungent odour [21].

2.3. Volatilisation

chemical substances vaporise or sublime into the atmosphere from a solid or liquid state. These chemical substances are usually characterised with low boiling point. A Study identified that volatile compounds like hydrocarbons, aromatic substances, oxygenated, chlorinated and sulphur compounds as present in landfill sites [22]. A study identified similar volatile compounds such as benzene and trim ethyl benzene as present in a landfill [12]. The study also concluded that polystyrene plastic waste was known as the major source of the volatile chemical compound in the landfill [12].

Fig. (**3**) shows the LFG generation and possible collection capacity in m^3/hour.

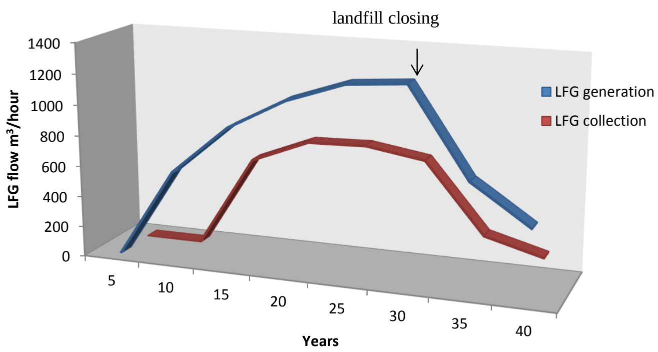

Fig. (3). A diagram for LFG generation and collection capacity in m^3/hour against time [4].

Table **1** shows the composition, characteristics and health and environmental effects of landfill gas

Table 1. Typical Landfill Gas Components [16].

Component	Percentage by Volume	Characteristics	Effects
Methane	45–60	Methane is a naturally occurring gas. It is colourless and odourless. Largest LFG emitted from landfill, it is a Greenhouse Gas (GHG), highly flammable.	Global warming, major cause of landfill fire
Carbon dioxide	40–60	Carbon dioxide is colourless, odourless, and slightly acidic. It exists in the earth's atmosphere at a concentration of 0.04 (400 ppm) percent by volume. It is a GHG.	Global warming, major source of ocean acidity
Nitrogen	2–5	Nitrogen comprises approximately 79% of the atmosphere. It is odourless, tasteless, and colourless.	Oxides of Nitrogen (NO_x) are toxic gases, source of smog and acid rain; respiratory problems, lung damage. Nitrites and nitrates can cause cancer, thyroid problems.
Oxygen	0.1–1	Oxygen comprises approximately 21% of the atmosphere. It is odourless, tasteless, and colourless.	Iron rusting, supports combustion in landfill fires, excess oxygen at partial pressure can lead to severe health problem like cells damage, brain damage.
Ammonia	0.1–1	Ammonia is a colourless gas with a pungent odour. Corrosive gas, highly irritating.	Burning of nose, throat and respiratory tract, coughing, skin and eye irritation. Pungent and suffocating odour. Eutrophication, soil acidification.
NMOCs (non-methane organic compounds)	0.01–0.6	NMOCs are organic compounds (*i.e.*, compounds that contain carbon). (Methane is an organic compound but is not considered a NMOC.) NMOCs may occur naturally or be formed by synthetic chemical processes. NMOCs most commonly found in landfills include acrylonitrile, benzene, 1,1-dichloroethane, 1,2-cis trichloroethylene, dichloromethane, carbonyl sulphide, ethyl-benzene, hexane, methyl ethyl ketone, tetrachloroethylene, toluene, trichloroethylene, vinyl chloride, and xylenes.	Carcinogenic, leukaemia, headaches, nausea. Some of the gases are highly flammable, pungent odour.

(Table 1) contd.....

Component	Percentage by Volume	Characteristics	Effects
Sulphides	0–1	Sulphides (*e.g.*, hydrogen sulphide, dimethyl sulphide, mercaptans) are naturally occurring gases that give the landfill gas mixture its rotten-egg smell. Sulphides can cause unpleasant odours even at very low concentrations.	Irritation to the eye, nose and throat, breathing difficulty, poor memory, tiredness. Pungent odour,
Hydrogen	0–0.2	Hydrogen is an odourless, colourless gas, tasteless, highly combustible, light gas.	Supports burning in landfill fires,
Carbon monoxide	0–0.2	Carbon monoxide is an odourless, colourless gas.	Reduces oxygen circulation in the body, vision problems, reduced manual dexterity and even death and formation of smog.

3. LFG UTILISATION TECHNOLOGIES

LFG management began in the USA in the years 1960s and 1970s, but the first LFG utilisation technology was commissioned in Germany around mid-1970 [23]. However, LFG utilisation technology considers various factors before the appropriate installation of the technology, some of these factors include;

- Assurance of continuous flow of municipal solid waste.
- The best LFG utilisation system for the proposed landfill.
- The availability of potential end users for the use of the technology.
- The quality and duration of the potential LFG generation.
- The capital cost, expenditure and operating costs for the utilisation technology.
- Availability of skilled operators for the operations of the technology.

The use of LFG can be in various forms which include, direct use; in the form of electricity; as a boiler system; use as vehicle fuels; use as natural gas network and use as leachate evaporation. The summary of the LFG utilisation, advantages and disadvantages are summarised in Table **2**.

Table 2. Summary of LFG utilisation [28].

LFG Utilisation	Discussion	Advantages	Disadvantages
As a source of natural gas	This involves the upgrading of LFG into natural gas quality [29]. A study investigated on the upgrading of LFG using a high-pressure water absorption process [30]. The study showed that using high pressure gas absorption technique, LFG can be improved to 87.9 ± 2.0% methane contents [31]. This refined LFG can be used in the natural gas network for domestic purposes. Developed nations such as the US and Europe nations commercially use LFG in place of the conventional fuel which has been used for domestic purposes [28].	Can be used domestically for cooking and in industries as a source of heat. Can be used in generation of revenue for the government, when sold. Used in natural gas pipelines.	Relatively expensive and requires LFG expensive processing techniques.
Boiler System	This technique is the second most common use of LFG. Boilers use LFG as a source of fuel for production of steam and hot water. In addition, the steams formed from the process can be used for heating buildings, schools, hospitals and even providing steam for large manufacturing industries (pulp and paper industries). Examples of landfill that uses LFG for boiler system are the Gaoantun landfill (Beijing, China), and three rivers regional landfill (South Carolina, USA) [28].	Relatively not expensive. Does not require large amount of LFG when processing. Can be used in landfill sites, schools, hospitals as a source of heating. Can make use of maximum amount of LFG collected.	Accessibility of end-users must be close by. The cost is tied to length of pipe lines.
Furnace, dryers and kilns	This involves the direct use of raw LFG from landfills as a source of fuel directly from the kilns [29]. Manufacturing companies that produce cements, ceramics, iron, wood and steel uses LFG directly from the landfill site as a source of fuel for infra-red heating mechanism. The infra-red heating can reach up to 800°C - 1000°C with efficiency up to 93% [28].	The raw LFG can be used directly from the kilns in some manufacturing companies. Inexpensive and easy to install.	Constraint of LFG utilisation, if used seasonally.

(Table 2) contd.....

LFG Utilisation	Discussion	Advantages	Disadvantages
Use as vehicle fuel	LFG are compressed and used as a source of fuel for powering vehicles. A study shows that the collection, purification drying and compression to acceptable pressure gauge of raw LFG can be used as fuel for vehicles [32]. This process is being utilized in some Africa nations but the process is not favourable in all nations. For example, Global Infrastructure Basel company carried out a project to convert LFG into vehicle fuel for fleet vehicles in the Ekurhuleni metro Municipality of South Africa. The project extended for one year and costed USD 5 million [33]. Before the production as vehicle fuel, it is advisable the project owners verify the tax system for vehicle fuel and other variables, to calculate if the project will be profitable or not [29].	Use as a source of fuel to landfill vehicles and trucks. Can also be used as a source of revenue to the government when sold.	Can be expensive due to the processing of the raw LFG collected into vehicle fuels
Use as a source of electricity	LFG can be used as fuel for power generation which can generate electricity up to 45 megawatts from a steam engine; this is the most common use of LFG utilisation technology [29]. A study analysed different methods to generate electricity and recent innovative technologies from LFG; some of these technologies included, reciprocating internal combustion engine, use of gas or steam turbine, power plant with organic rankine cycle, Stirling cycle engine, molten carbonate fuel cells and solid oxide fuel cells, the selection of method is owed to several conditions [34]. This form of utilisation has shown to be reliable, environmentally and economically friendly to its users [28]. A typical example is the Durban LFG plant in eThekwini Municipality South Africa.	Can be a source of electricity. Can be used as a source of revenue to the government due to the sale of the electricity generated. Maximum use of LFG, when the LFG is collected from the landfill site.	Relatively high cost of operations. Requires high level of expertise and technology. Cost may be negligible with countries with low electricity costs.

4. GLOBAL CONTEXT OF LFG GENERATION AND UTILISATION

Since the mid-1970, LFG has been used as a renewable source of energy in the form of electricity and fuel to communities, individuals and industries. The world population increased from about 3.1 billion in 1960 to approximately 7 billion in 2015 and by 2025 the population is expected to rise to approximately 8 billion people. As population, urbanization and world economy increases, the generation of MSW is expected to increase [24]. Therefore, as MSW increases the need for more landfill sites will also increase globally. LFG globally contributes approximately 8% of the world's total greenhouse gas (GHG) emitted into the atmosphere [4]. Globally, there are more than 1000 LFG plants where most of these plants are situated in Europe and US; with South Africa having 4 LFG plants and the technology has been growing in other parts of Africa [12].

The European Union (EU) approximately deposits an average of 45% of its MSW into landfills with greater percentage of MSW deposited from her new member states. The EU has been experiencing an increase in waste generation and adverse effects from landfill operations. The EU formulated a policy on landfill called the Directive 1999/31/EC which is geared towards possible reduction of the negative effects of landfilling in the environment [25]. The EU has the highest amount of LFG utilisation plants in the world, currently operational [12]. Croatia had 136 operational landfills and already 4 LFG plants were commissioned by the Croatian government in 2015 and a potential of 90 LFG plants existed [26]. Germany is the highest producer of energy from LFG; produced electricity from biogas that powered about 3.5 million homes in 2009. Since 2005, Sweden has been using LFG to power a biogas powered train which moves about 75 miles [27].

China has the world's largest population of approximately 1.3 billion in 2017 and the urban areas generate about 190 million tonnes of MSW with a projected increase to 480 million tonnes/year in 2030, if migration to urban cities averages more than 300 people. China with its rapid growth in economy and urbanization has increased drastically in its MSW generation, although the management of its MSW is on the development stage [35]. Landfilling is the most used technique for the disposal of MSW in China with 89% of total MSW deposited in landfills. China had its first LFG energy plant in June 1999 (Guangzhou Guang Jia), and as years went by, other LFG plants were constructed. Approximately 18 LFG utilisation plants were finalised at the end of 2007, with 15 generating electricity [36]. The Shanghai Laogang (one of Asia's largest LFG plants) produced about 24,400 MWh of electricity in 2012. Also, the Nanjing Shui-Ge LFG project which was mainly sponsored by United Nations Development Programme (UNDP) has generated more than 4050 KW since 2002 [37]. China is challenged with availability of land for landfill and proximity to residential areas, in 2014 according to Zhou- the general manager of Veolia He said, "The Chinese have not been focusing on landfill- if they can avoid it, they will" [37]. Furthermore, a research conducted at the biotechnological laboratory at the Institute of Clean Energy and Environment (ICEE) Aerospace University showed the comparison between Chinese MSW degradation potential and Western MSW. The study showed that the Chinese MSW has a higher degradation potential than the Western MSW, because of the high level of organic waste present in the MSW [36].

Some of the success stories accounting for the use of LFG as a source of energy in the US includes; Coca-Cola's Atlanta syrup branch - 48 million kw/h of electricity generated from a nearby landfill. This LFG project provides almost all the needed company energy in the form of steam, electricity and chilled water. Furthermore, about $1.3 million is being saved annually by the U.S. Navy in utility cost at the Marine Corps logistics base in Albany Georgia, because of the cogeneration plant that started operations in 2011. Gudersen health systems on Alaska campus use LFG from La Crosse county, Wisconsin for electricity to supply the campus with heat energy, resulting to saving about $100.000 annually [27]. Fig. (**5**) shows the approximate number of world-wide LFG utilisation technology as of 2001 [29]. However, as of November 2017, the LFG utilisation technology in the USA doubled to 637 operational LFG utilisation plants and some additional potential 400 landfills are good candidates for future LFG utilisation technology [27] Fig. (**4**). In England, 2015 the LFG utilisation plants rose up to 361 LFG utilisation plants, this is about triple the LFG utilisation plants since 2001 and generated approximately 4106.4 GWh of electricity from LFG technology in 2015 [45]. However, with the continuous rise in LFG utilisation technology in mostly developed nations, the introduction of the Clean Development Mechanism (CDM) and JI projects gave rise to LFG utilisation technology in developing nations.

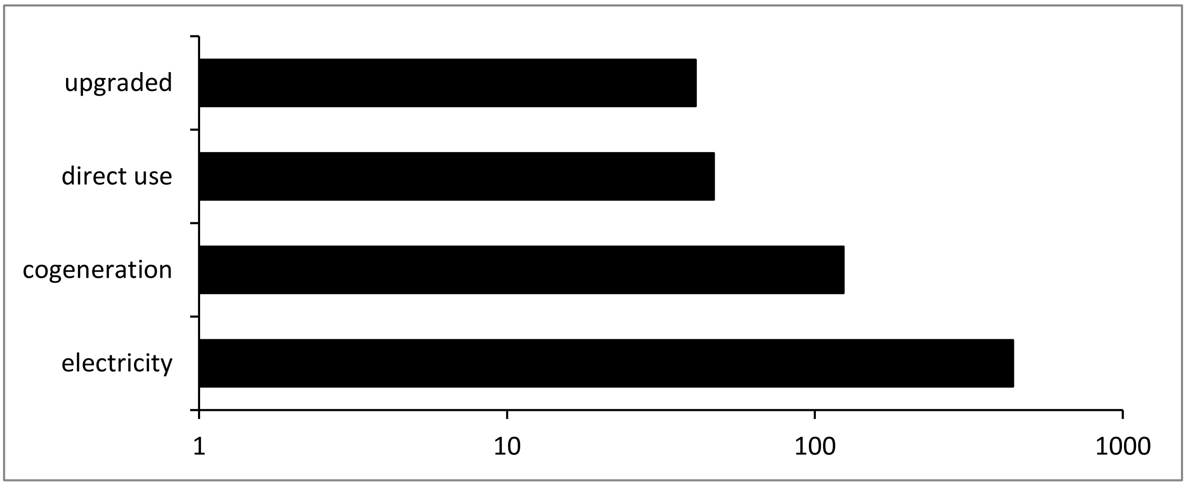

Fig. (4). LFG utilisation projects as of July, 2016 [38].

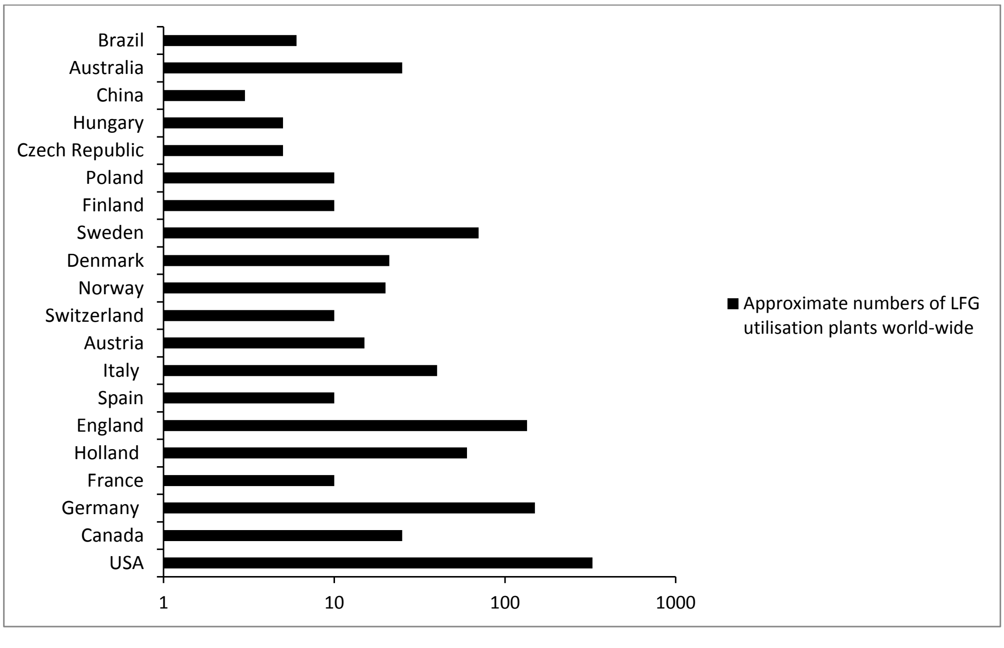

Fig. (5). As of 2001, LFG utilisation technology available world-wide [29].

Fig. (**6**) shows the number of registered LFG to energy CDM projects all around the world.

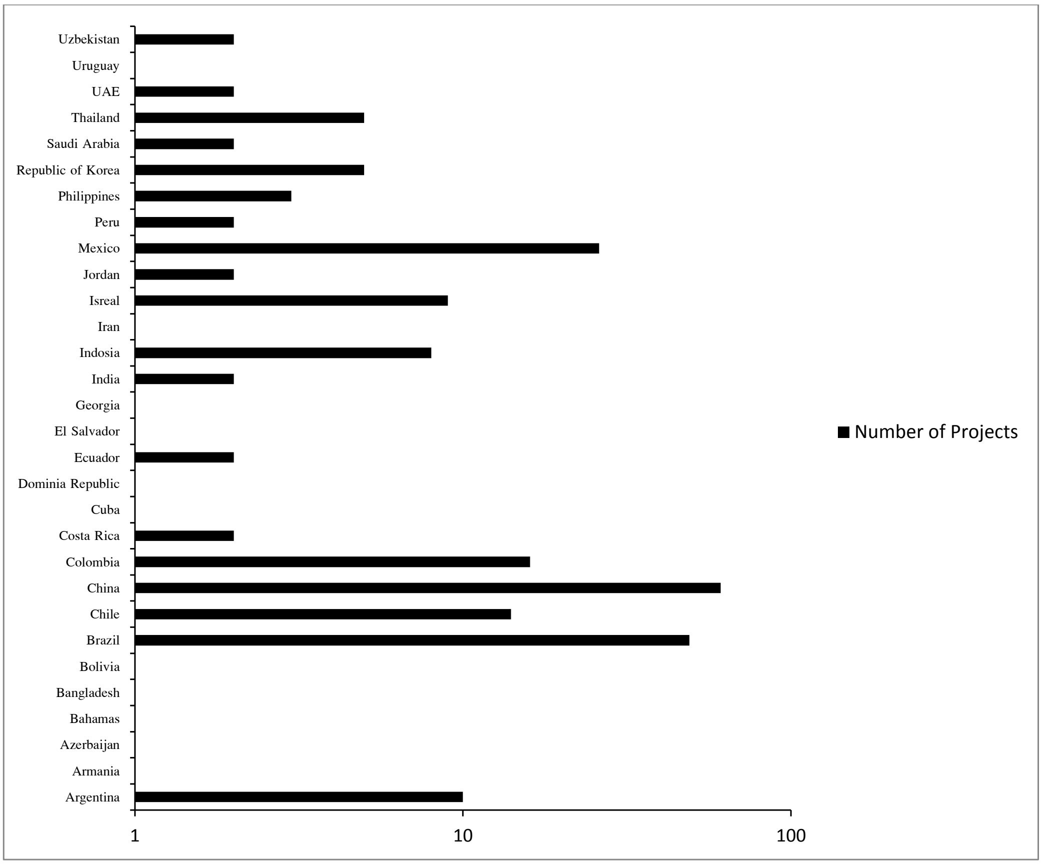

Fig. (6). Number of CDM LFG utilisation projects around the world [40].

5. LFG UTILISATION AND GENERATION: THE AFRICAN CONTEXT

Africa is comprised of both developing and underdeveloped nations, where most regulations, technologies and management practices are still emerging. MSW is one of the major problems faced by African countries, of which about 20-50% of their budget is allocated to solid waste management [41]. The open dumping system- which is the primitive stage of landfill is still the major way in which MSW has been disposed in Africa. Although, it is paramount to upgrade open dump system to sanitary landfills, many African countries do not see it as a priority or a necessity [42]. Nigeria and South Africa manage most of their MSW in open dump sites and unsanitary landfill, respectively [43]. Hence, these open dumping systems and unsanitary landfills increase the pollution from landfills into the environmental media. Therefore, stringent guidelines, regulations and implementation should be put in place to reduce the LFG generated from MSW [44]. LFG utilisation techniques are still new technologies in Africa due to limited expertise, poverty, and the government's laxity towards LFG utilisation in the continent, despite the increasing MSW generation coupled with population and industrial growth.

South Africa is embracing the LFG utilisation as a necessity and has regulations and guidelines that support landfill operations. South Africa had its first utilisation plant of LFG in 1980's - the Robinson Deep landfill gas scheme where a gold ore extraction process utilised the LFG. The now Department of cleansing and solid waste of the eThekwini municipality, formally called Durban solid waste city of Durban organised the second LFG utilisation in the early 1990's [23]. South Africa recorded a success in the first Clean Development Mechanism (CDM) waste-to-energy project in Africa, the project was tasked with the conversion of LFG to electricity from three landfills situated in the eThekwini Municipality (Bisasar, Mariannhill and La Mercy landfills). Some other similar registered CDM LFG projects in South Africa include the New England LFG energy project; Environserv Chloorkop LFG recovery project (registered 27th April, 2012); Alton LFG project (registered 24th August, 2009) and Ekurhuleni LFG project. Fig. (**7**) shows the registered CDM LFG projects in Africa.

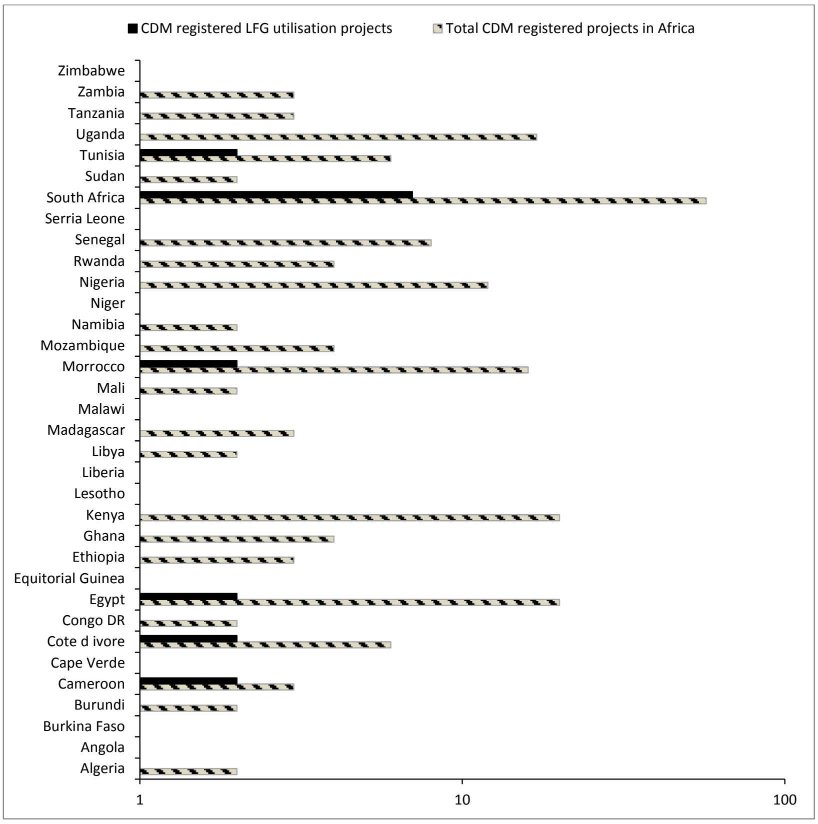

Fig. (7). Registered CDM LFG utilisation projects in Africa as of December 2017 [40].

The total LFG utilisation projects in Africa is about 15% of the total registered CDM projects. This, however shows a positive move about LFG utilisation in Africa, hence the usage of LFG is viable and a major means of methane reduction in the world. Furthermore, it implies that the governments of African countries have increased awareness of landfill emissions and their potential impacts on human health and the environment. Fig. (**7**), shows that South Africa is the leading country in Africa in the CDM LFG utilisation project, having a total of 50% of the total CDM LFG projects registered in Africa because of the policies and guidelines introduced by the South African government.

A study identified the potential CH_4 produced from landfills in Africa as approximately 10496 × 10^6 Nm^3 in 2012 [4]. Table **3** shows the potential quantities of CH_4 produced in Africa in 2012, if all LFG generated could be collected and used for energy recovery. Also, Table **3** shows the potential amount of methane generated, assuming all the waste generated is landfilled.

Table 3. waste generation and collection, potential CH_4 generation and possible capture, and potential electricity generation in Africa [4].

Countries	Waste Generation (10^3 t/year)	Waste Collection (10^3 t/year)	Potential CH_4 Emission (10^6 Nm^3)	Potential CH_4 Captured (10^6 Nm^3)	Potential Electricity Generation (TJ/year)	Potential Electricity Generated Using The Total CH_4 Captured (TJ/year)
Algeria	10,905	10,032	916	632	24,663	22,690
Angola	2126	914	179	58	4808	2067
Benin	792	182	63	11	1692	389
Botswana	483	208	43	14	1152	496
Burkina Faso	892	357	71	21	1905	762
Burundi	205	82	16	5	437	175
Cameroon	3448	1483	290	93	7799	3353
Cape Verde	58	55	5	3	130	124
Central African Rep.	329	132	26	8	704	281
Chad	620	124	49	7	1325	265
Comoros	210	42	17	2	449	90

(Table 3) contd.....

Countries	Waste Generation (10^3 t/year)	Waste Collection (10^3 t/year)	Potential CH_4 Emission (10^6 Nm^3)	Potential CH_4 Captured (10^6 Nm^3)	Potential Electricity Generation (TJ/year)	Potential Electricity Generated Using The Total CH_4 Captured (TJ/year)
Congo DR	4640	1856	368	110	9911	3965
Congo	515	222	43	14	1166	501
Cote d'Ivoire	1878	751	149	45	4013	1605
Djibouti	129	55	11	3	291	125
Egypt	18,350	11,560	1541	728	41502	26146
Equatorial Guinea	84	36	7	2	200	86
Eritrea	230	92	18	5	492	197
Ethiopia	1615	646	128	38	3450	1380
Gabon	223	96	20	6	532	229
Gambia	211	84	17	5	450	180
Ghana	444	377	35	22	949	806
Guinea	627	251	50	15	1340	536
Guinea-Bissau	79	31	6	2	168	67
Kenya	1071	429	85	25	2288	915
Lesotho	115	49	10	3	260	112
Liberia	339	135	27	8	723	289
Libya	2219	954	197	63	5297	2278
Madagascar	1984	357	157	21	4237	763
Malawi	604	253	48	15	1289	541
Mali	1449	580	115	34	3095	1238
Mauritania	278	83	22	5	594	178
Mauritius	462	452	41	30	1102	1080
Mayotte	60	57	5	4	144	137
Morocco	10,326	8880	867	559	23,354	20,085
Mozambique	500	210	40	13	1069	449
Namibia	169	73	14	5	383	165
Niger	518	218	41	13	1106	465
Nigeria	17,451	7329	1384	436	37275	15656
Rwanda	416	175	33	10	888	373
Réunion	687	652	61	43	1639	1557
Saint Helena	2	2	0	0	4	4
Sao Tome	20	19	2	1	42	40
Senegal	1070	225	85	13	2286	480
Seychelles	53	51	5	3	127	121
Sierra Leone	394	173	31	10	841	370
Somalia	412	173	33	10	881	370
South Africa	23,214	11,607	2058	772	55420	27710
Sudan	5481	2357	486	157	13084	5626
Swaziland	48	23	4	2	116	55
Tanzania	1237	519	110	35	2953	1240
Togo	535	508	42	30	1142	1085
Tunisia	2154	840	191	56	5143	2006
Uganda	605	182	54	12	1445	433
Western Sahara	85	17	8	1	203	41
Zambia	385	162	34	11	918	386
Zimbabwe	989	490	88	33	2361	1170
Total Africa	124,994	68,150	10,446	4304	282,602	154,520
Sub-Saharan Africa	80,955	35,865	6776	2264	182,439	81,275

6. ENERGY POTENTIAL FROM LFG IN AFRICA

Every nation needs energy for its development. African countries generate energy majorly from oil, solar and coal.

South Africa's energy (electricity) generation is 90% powered by coal. Oil-producing African countries like Nigeria (hold about 30% of oil reserves in Africa) mainly rely on oil and gas as a source of energy [45]. In 1995, South Africa consumed approximately 50% of the total electricity generated in Africa, followed by Northern African countries which consumed about 30% and the rest of the continent accounts for 20%. The consumption of electricity in Africa is very low with exceptions of South Africa and some North African countries. Fig. (**8**) shows a summary of some Africa countries and their electricity consumption rates [45].

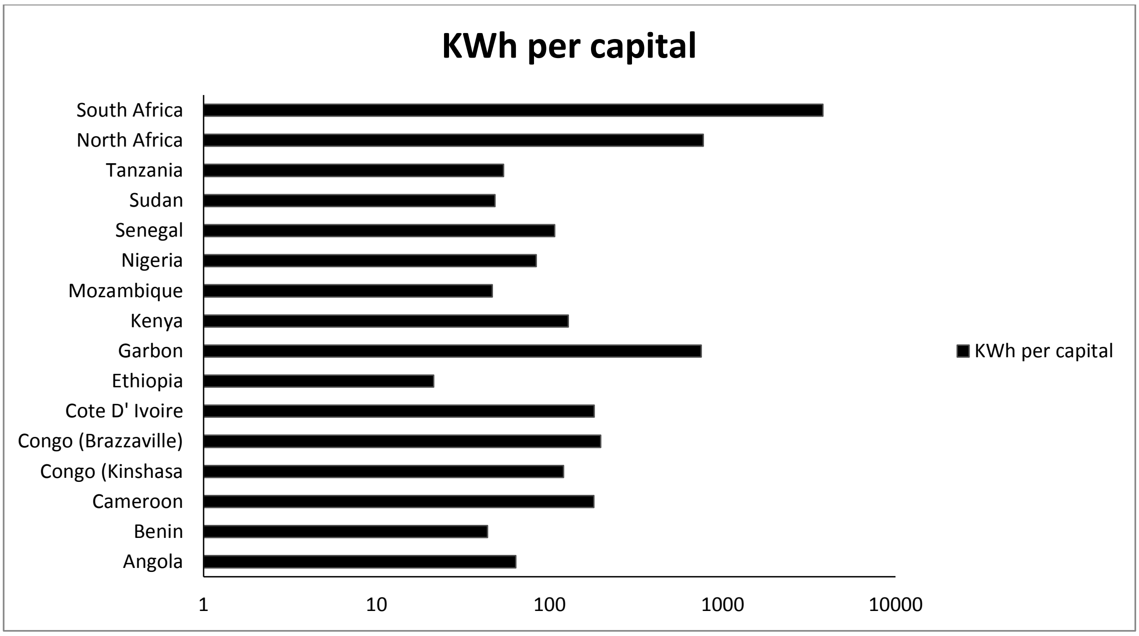

Fig. (8). Electricity consumption in some African countries [45].

African governments have failed to make LFG utilisation a priority in their agenda. A study conducted on the potential energy from utilisation of LFG and incineration of MSW in urban areas of Africa (with efficiency of 20% and 30% for incineration and LFG plants efficiency, respectively). The results show that the energy generated was approximately 1125 PJ in 2012 and estimated to be 2198 PJ in 2025 (assuming all waste generated is collected) [4].

Nigeria has the highest population in Africa and generates about 17.4 million tonnes/year of MSW at a range of 0.21-0.35 kg/person/day and deposits 74% of its MSW in dumpsites and landfills [43], [46]. A study was conducted by the Centre for People and Environment (CPE) on four different landfills in Nigeria in 2010, to estimate the potential electricity that can be generated from the collected LFG. The result shows that the utilisation of the LFG in the four different landfills was economically viable and at a minimum electricity cost of $0.2 KW/h. Therefore, if most of the LFG from landfills and dumpsites are utilised, then some economic challenges the country faces on electricity generation can be minimised. Morocco generates approximately 1.0×10^7 t/year of MSW, with about 0.75 kg/inhabitant/day of waste generation. Morocco mainly uses fossil energy resources as a source of electricity and the fossil energy serves as 97% of its energy source [4], [31] The results of a study conducted on accessing a prospective LFG energy in Agadir, Morocco, showed that the introduction of LFG utilisation technology into the energy sector in Morocco will help relieve the country from its monopolistic source of energy and provide a viable business for the government [31].

7. CHALLENGES/BENEFITS FOR AFRICAN COUNTRIES IN ADOPTING LFG UTILISATION TECHNOLOGY

Countries in the developed world are knowledgeable on the win-win situation from exhausting LFG emitted from landfill, and the projects on LFG utilisation are increasing on daily basis. However, Africa has significantly underutilised LFG technology, but what are the challenges impeding Africa from developing and using LFG technology? A research conducted on the challenges impeding South African municipalities from adopting waste-to-energy schemes; the conclusion showed the major problems were inappropriate landfill management from Municipalities for power generation and poor data on waste generation; monopolising the electricity sector, thereby making investors lose interest; poor policies on waste sector which do not give room for establishing waste to energy industries; limited knowledge on technologies by government and lack of political will; small tariffs on landfill; lack of expertise to implement project; and limited awareness of the benefits associated with the project [47].

Other challenges associated with LFG utilisation technology in Africa include;

- Lack of technical solution – LFG utilisation technologies need certain technical skills, which can only be acquired through training and experience. The LFG utilisation technology in Africa is relatively new, hence as more projects commence the skills and expertise will continue to increase [48].
- High initial cost for the project – the equipment and expertise used for LFG utilisation project are expensive. The first CDM project in Africa which was implemented in South Africa costed about \$6.5 million for the LFG utilisation project [49]. This is relatively expensive for private or government body to embark on.
- Lengthy CDM process – due to the fact that LFG utilisation projects are expensive for African government, the process to approve and register a LFG utilisation project is challenging and very long [48]. A proposed project with the CDM takes over 24 months for a LFG utilisation project to be registered [50].
- Harmful toxins – Compounds like mercury, cadmium, arsenic, benzene, dioxin and furan derivatives are in most cases found in landfill sites. These toxins are occasionally found in LFGs in trace quantities. The emissions and burning of these toxins can lead to harmful effects on humans including cancer, endocrine disruption and heavy metal poisoning. Africa still lacks in technology to reduce these toxins before collection of the LFG [51].

Most African countries suffer from inadequate electricity generation. Africa is immensely behind with the capacity of electricity generated from LFG. A lot of opportunities are achieved from LFG utilisation technology today. Although, some forms of renewable energy such as wind and solar are inadequate to produce energy consistently, LFG utilisation projects help combat climate change, improve waste management, reduce air borne diseases from landfill and generate energy. Some African countries have adopted great potential from LFG utilisation projects, like South Africa. Private companies have also initiated LFG utilisation projects, for example in September 2014, the summer and jack landfill site in Germiston Gauteng which generates approximately 1MW of electricity. A study showed that the adoption of LFG energy project in Morocco will lead to increase in renewable energy (and reduce non-clean energy in the country); encourage technology transfer from developed countries for enhancing LFG utilisation plants; reduce the countries CO_2 emissions and reduce environmental pollution; provide revenue for the Morocco government and energy for the people [10]. The study also emphasised that the introduction of LFG utilisation fully into Morocco's energy sector will be a win-win party for all and sundry [10].

Some other opportunities for LFG utilisation projects include;

- Reduction in greenhouse gas emission effect: LFG operation is a major source of methane gas in the atmosphere. It contributes about 17% of the total anthropogenic methane emission in the atmosphere. Therefore, when LFG utilisation project is installed CH_4 is burnt and converted to carbon dioxide and water. In addition, the conversion and burning of CH_4 reduces the emission of GHGs into the atmosphere.
- Acquire Carbon credits: in developing world CDM helps in financing projects of renewable energy so as to reduce GHG emissions of which LFG utilisation projects is one of. LFG projects are registered with the CDM thereby earning carbon credits for the reduction of the amount of methane emitted into the atmosphere.
- Reduction of odour in the vicinity: with the LFG utilisation projects, the collection of LFG helps in the reduction of odour. Gases like H_2S which are formed during the decomposition of waste in the landfill are collected along with the LFG during the utilisation process.
- Reduction in potential fire outbreak: CH_4 which is a highly flammable gas has the potential to cause fire outbreaks in landfill sites. The collection of the LFG helps reduce the uncontrolled emissions of the LFG thereby avoiding contacts with objects that can easily ignite a fire.
- Electricity generation: LFG utilisation project is known for its electricity generation capacity and has been a success over the years. Approximately, 70% of LFG projects are used for electricity generation. These LFG projects can serve as alternatives to power generation in Africa, which is one of the major problems facing the African continent.

CONCLUSION

Since 1970 LFG utilisation technology has been thriving over the years, developed nations have recorded positive progress in the utilisation of LFG into various forms of energy. However, European Union seeks to reduce MSW generation, which will result in reduction in the disposal of MSW in landfills. Africa comprises of developing nations, compared to the developed nations. Most of the MSW generated in Africa is deposited in dumpsites and very few in landfills; this alone reduces potential collection of LFG. Although, some plans and executions have been put in place for construction of landfills, factors like capital, human resources and expertise have led to poor execution. The utilisation of LFG in Africa is in its preliminary stage owing to poor technical knowhow and expertise on the collection, management and operation of LFG utilisation technologies.

With the rising demand for energy across Africa and rapid urbanization, energy supply has not increased at the same pace with urbanisation. There could be tremendous increase of potential energy generation in Africa if the potential LFG generated is collected and used for energy generation. Most African countries face energy problems; with proper use of LFG generated some of Africa's energy problems will be averted and this will also result in increase in economic development.

RECOMMENDATIONS

- The African governments should enforce and provide good policies and guidelines on MSW management and waste disposal.
- More extensive research should be conducted on the different ways in which LFG can be used for energy generation in Africa.
- More sensitisations and workshops by the government/waste authorities on proper waste disposal and management in homes, schools, market places, industries etc., are needed.
- Sponsorship and scholarship programs should be introduced to environmental scholars in Africa to learn the basics and techniques of LFG utilisation technologies and operations. This will increase the knowledge on the utilisation of LFG in Africa.
- Although landfilling is not the best technique for MSW management; the government should encourage and build more landfill sites to reduce many illegal dumpsites in Africa.

AUTHORS CONTRIBUTION

All authors had equal input to this paper

CONSENT FOR PUBLICATION

Not applicable.

CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

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