SPATIO-TEMPORAL VARIABILITY ANALYSIS OF METHANE EMISSIONS FROM MUNICIPAL SOLID WASTE DISPOSAL SITES IN KANO METROPOLIS, NIGERIA

BY

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A THESIS SUBMITTED TO THE SCHOOL OF POSTGRADUATE STUDIES, AHMADU BELLO UNIVERSITY, IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF A DOCTOR OF PHILOSOPHY IN GEOGRAPHY

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DECLARATION

I declare that the work in this Thesis entitled "SPATIO-TEMPORAL VARIABILITY ANALYSIS OF METHANE EMISSIONS FROM MUNICIPAL SOLID WASTE DISPOSAL SITES IN KANO METROPOLIS, NIGERIA" has been carried out by me in the Department of Geography and Environmental Management, under the supervision of Professor Edwin Osawe Iguisi, Professor Aliyu Baba Nabegu and Professor Ibrahim Jaro Musa. The information derived from the literature has been duly acknowledged in the text and a list of references provided. No part of this Thesis was previously presented for another degree or diploma at this or any institution.

_____ _____

Salisu GWADABE Signature Date

CERTIFICATION

This Thesis entitled "SPATIO-TEMPORAL VARIABILITY ANALYSIS OF METHANE EMISSIONS FROM MUNICIPAL SOLID WASTE DISPOSAL SITES IN KANO METROPOLIS, NIGERIA" by SALISU GWADABE meets the regulations governing the award of the degree of Doctor of Philosophy in Geography of the Ahmadu Bello University, and is approved for its contribution to knowledge and literary presentation.

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DEDICATION

This Thesis is dedicated to my parents Ahmad Gwadabe (Wakilin Gurduba) and Khadija M. Dauda, my wife Khadija Muhammad and my children Khadija (Ummi), Fatima, Ahmad, Abubakar, Abdullahi, Aisha, Mustapha, Muhammad and Maryam.

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TABLE OF CONTENTS

Title Page 2

Declaration 2

Certification 3

Dedication 4

Acknowledgments 5

Table of Contents 5i

List of Tables x

List of Figures xi

List of Appendices xii

Abstact xiii

CHAPTER ONE: INTRODUCTION

1.1 Background to the Study 16

1.2 Statement of the Research Problem 21

1.3 Study Aim and Objectives 23

1.4 Research Hypothesis 24

1.5 Scope of the Study 24

1.6 Justification of the Study 25

CHAPTER TWO: CONCEPTUAL, THEORETICAL FRAMEWORK AND LITERATURE REVIEW

2.1 Conceptual Framework 28

2.1.1 Definition of Waste 28

2.1.2 The Municipal Solid Waste: Definition, Composition and Management 29

2.1.3 The Methane gas 34

2.2 Theoretical Framework 36

2.2.1 Methane formation process 36

2.2.2 The migration of Methane gas 40

2.2.3 Subsurface migration of Methane emission 42

2.2.4 Modelling the potentials of Methane emission 45

2.2.5 Mathematical Modeling for Methane Emissions 49

2.2.6 The Climate Models 59

2.3 Literature Review 62

2.3.1 Meteorological Variables Affecting the Surface Methane emission 62

2.3.2 Factors Influencing Methane Production in Solid Waste Disposal Site 67

2.3.3 Effects of Methane Emissions 70

2.3.5 Quantification/Monitoring of Methane Emission from Municipal Solid Waste Disposal Sites/Landfills 75

2.3.6 Variations of Methane Emission at Different Points Away from the Municipal Solid Waste Disposal Sites 83

2.3.7 Diurnal and Seasonal Variability of the Levels of Methane Emissions at Solid Waste Disposal Sites 84

2.3.8 Model Emission Results Versus Direct Monitoring Values at Landfills 89

2.3.9 Influence of Temperature and Pressure on Methane Emission from Municipal Landfills 93

CHAPTER THREE: THE STUDY AREA AND METHODOLOGY

3.1 The Study Area 101

3.1.1 Location of Kano metropolis and history 101

3.1.2 The physical setting 102

3.1.3 The human setting 105

3.2 Methodology 109

3.2.1 Types of data used and their sources 109

3.2.2 Methods and procedures of data collection 109

3.2.3 Selection of solid waste disposal sites 111

3.2.4 Quantification and monitoring of Methane emissions and other meteorological variables 117

3.2.5 Method of data analysis 123

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Levels of Methane Emissions in Kano Metropolis 125

4.1.1 Levels of Methane Emissions Estimated Using IPCC Default Methodology 125

4.1.2 Levels of Methane Emission from Solid Waste Disposal Sites, Using Crowcon-Gasman 'FL' 128

4.2 Variation of Methane Emission at Different Points Away from Center of Solid Waste Disposal Sites 110

4.3 Diurnal and Seasonal Variability of the Levels of Methane Emissions 115

4.3.1 Diurnal variation of Methane emissions 115

4.3.2 Seasonal variation of Methane emissions 139

4.4 Comparison of Results Obtained from IPPC Model and Field Monitoring (Crowcon-Gasman 'FL') 143

4.5 The Influence of Meteorological Conditions (Temperature and Pressure) on Methane Emissions 123

4.5.1 Relationship Between Temperature and Methane Emissions 123

4.5.2 Relationship Between Atmospheric Pressure and Methane Emissions 149

CHAPTER FIVE: SUMMARY, CONCLUSION AND RECOMMENDATIONS

5.1 Summary 151

5.2 Conclusion 152

5.3 Recommendations 153

REFERENCES 130

APPENDICES 157

LIST OF TABLES

Table Title

Page

2.1 Usual Gases Contained in Solid Waste Disposal Site/Landfill, Their Percent by Volume, and Their Features 19

3.1 Data Used, Sources and Materials Used 90

3.2 The GPS Readings of the Center of the Respective Solid Waste Disposal Sites Selected for the Study 91

3.3 An Example of Parameters Used for Determining Methane Emissions at the Selected Solid Waste Disposal Sites of the Metropolis 100

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4.1 Level of Methane Emissions Estimated by Means of IPCC Default Method in Kano Metropolis During Wet and Dry Seasons 104

4.2 Level of Methane Emission from Solid Waste Disposal Sites by Means of Crowcon - Gasman 'FL' 107

4.3 Level of Methane Emissions at Different Points Away from the Center of Solid Waste Disposal Sites 110

4.4 Variations in Methane Emissions at Different Points Away from the Center of Solid Waste Disposal Sites 111

4.5 Level of Methane Emission at Different Points Away from the Center of Solid Waste Disposal Sites in the Morning and Afternoon Periods 111

4.6 Level of Methane Emissions in the Morning and Afternoon 115

4.7 Level of Methane Emissions with Seasons of the Year 116

4.8 Variation in Methane Emissions Amongst Seasons 117

4.9 Comparison of Monitoring Values with Modelled Results (wet season) 121

4.10 Comparison of Monitoring Values with. Modelled Results (dry season) 121

4.11 Influence of Temperature on Methane Emissions 123

4.12 Effect of Atmospheric Pressure on Methane Emissions 125

LIST OF FIGURES

Figure	Title	Page
2.1	The Four Sequential Stages of Methane Formation Through Decomposition of Organic Waste at a Particular Time	23
2.2	Approximation Error in First Order Model	32
3.1	The Kano Metropolis	82
3.2	The Kano Metropolis Showing the Locations of Sampling Sites	92
4.1	Methane Emissions Against Distance	114
4.2	Methane Emissions Against Season	120
4.3	Methane Emissions as a Function of Temperature	124

LIST OF APPENDICES

Appendix	Title	Page
I	Plate I and Digital Map of Study Area	162
II	Plates and Location on Kano Layout Map of Respective Solid Waste Disposal Site	163
III	Methane Emissions and Meteorological Conditions' Field Recording Sheet Using Crowcon-Crowcon – Gasman "FL" by Seasons	178
VI	Variation of Methane Emissions at Different Points Away from the Solid Waste Disposal Sites by Means of Crowcon–Gasman "FL" During The Two Periods	182

ABSTRACT

This study analzed the spatio-temporal variability in Methane emissions at ten (10) selected solid waste disposal sites in Kano metropolis. The study was conducted by applying IPCC default methodology for two seasons (wet and dry), and Crowcon – Gasman "FL" for a period of four seasons of the year (cool dry season - the harmattan (January, 2018); hot dry season (April, 2018); wet season (August, 2018); .and harvest season (November, 2018) respectively. The monitoring took place in the first seven consecutive days of those months. The Crowcon–Gasman "FL" monitoring was carried out during morning (0700 hours to 1000 hours' local time) and afternoon (1300 hours to 1600 hours' local time). Firstly, for each period, and over each site the monitoring was carried at about the center of each disposal site, and then one each at 100m away from the center at the four cardinal points (North, East, South, and West). This makes a total of five readings per site and per period for each observation day. The monitoring points over a disposal sites were labeled as D1, D2, D3, D4, and D5, in which D1 is the point at the center, D2 at the North, D3 at the South, D4 at the West and D5 is the point at the East. The mean of the five readings constitute the average for each site for a day and for each period of the month. The geographic coordinates of the center of the monitoring points (D1) were recorded using a portable Garmin Global Positioning System receiver. Secondly, the Methane emission level was read in a radial pattern, at 100m interval away from the center of disposal site. During the monitoring, the Crowcon – Gasman "FL" was held within 30 to 60 cm above the ground surface. This is because anything above 60cm methane emission to the atmosphere decreases. The concentration of Methane emission was recorded in percentage (lower explosive limit (LEL)). Two meteorological variables considered along with Methane emission are Temperature

and Pressure, and these were measured using Kestel 400 version 3.00 handheld weather tracker. The results shown that Kuntau (5,251.13 Gg/yr.), Court Road (5,107.90 Gg/yr.), Hajj Camp (4,626.15 Gg/yr.), Maimalari (3,603.37Gg/yr.) and Ubagama (3,537.99 Gg/yr.) disposal sites recorded the highest Methane emission by means of IPCC default methodology during the wet season period, while, by means of Gasman Fl, Court Road (29% LEL Methane), Kuntau (28.25% LEL Methane), Hajj Camp (26.00% LEL Methane), Ramin Hassan (25.25% LEL Methane), and Ubagama (24.00% LEL Methane), emitted the highest concentration of Methane emission during the afternoon monitoring. Similarly, Methane emission decreased considerably according to distance travelled away from the center of the solid waste disposal sites during the morning and afternoon monitoring. The significance (sig.) value (0.000) was less than the significance level (0.05). Therefore, the null hypothesis was rejected and concluded that Methane emissions vary considerably according to distance travel away from the center of the solid waste disposal sites during the morning and afternoon period. Nevertheless, the differences in Methane emission away from center of the disposal sites between morning and afternoon period was tested using t-test, the result obtained did not showed statistically significant differences at 0.05 probability level (0.065 > 0.05). Besides, the results obtained indicated that there is no significant diurnal variation of Methane emissions, this is because the sig. value (0.074) is greater than the level of significance 0.05, therefore, the null hypothesis was accepted. Furthermore, Methane emission monitoring by means of Crowcon-Gasman Fl, varied with the seasons of the year. The highest mean value occurred during the harvest season (26.29%), whreas the least emission occurred in the cool dry season of the harmattan (12.20%). The differences in values between the seasons are statistically significant at level greater than 0.05 probability level. Likewise, the mean of modelled results by IPCC default methodology during wet and dry seasons are higher

than that of direct monitoring values by means of Crowcon – Gasman “FL”. This is because the independent samples test shown that the significance values (0.000 and 0.001) are less than 0.05 probability level. Lastly, the correlation coefficient value of Temperature and Methane emission is positive and greatly significant ($r = 0.686$, $sig = 0.000 < 0.05$), confirming that Temperature has a significant and positive effect on Methane emissions. Conversely, the correlation coefficient value (-0.646) for Pressure and Methane is very significant, statistically ($0.000 < 0.05$). Unlike the trend for Temperature, the relationship is negative, thus, certifying that Pressure has a significant negative effect on Methane emissions at the sites. The study recommends for continuous monitoring of Methane emissions from the disposal sites during the harvest and hot dry seasons. Equally, the study suggested policies meant at sequestrating Methane emissions at the disposal sites, like the reuse, recycling and reduction of waste stream in the study areas.

CHAPTER ONE

INTRODUCTION

1.1 Background to the Study

Cities are recognized as engines of social modernization and economic growth but are also areas where globalization impacts are manifested (Nabegu, 2011). Impacts include the increased volume and variety of solid waste resulting from increased flow of goods and services, change in life styles, and consumption patterns (Nabegu, 2008). Available statistics show that more than half of the world 7 billion people live in urban areas and are crowded into 3% of the earth's land area (Angotti, 1993; United Nations Population Fund, 1993; United Nations Center for Human Settlement, 2007). The proportion of the world's population residing in urban areas, which was less than 4% in 1800 A.D. increased to about 47% in year 2000 and is expected to reach 66% in year 2050 (United Nations, 1990; World Bank, 2000). However, nearly 90% of the world's increase in population in the next three decades will occur in Africa and Asia and a large percentage of this population will be poor (Peters, 2000; United Nations Population Fund, 2007). Within the global context, Africa is the least urbanized continent. Mega-cities, defined as cities with 10 million inhabitants or more, are few. However, the continent is currently urbanizing faster than in the late 1990s and is expected to be the fastest urbanizing region from the year 2020 to 2050 (Tannerfeldt, 1995; United Nations Center for Human Settlement, 2007). Conservative estimates indicated that within the next two decades, 87% of the population growth in Africa will take place in urban areas (United Nations Center for Human Settlement, 2007).

Since the beginning of the oil boom of the 1970s, Nigeria has become an increasingly urbanized and urban oriented society. In the 1970s, Nigeria had possibly the fastest urbanization growth rate in the World (Ochuo, 1986; International Center for Migration Policy Development

(ICMPD), 2010). The great influx of people into urban areas causes the growth rate of urban population in Nigeria in 1986 and was estimated to be close to 6% per annum. This is more than twice that of rural population (Afolayan *et al.,* 2008). The documented progress of urbanization was estimated to be 20% in 1970 (World Bank, 1995), 23% in 1984 (United Nations, 1984), 38% in 1991 (Onibokun, 1992), 40% in 1996 (Alausa, 1997), with a projection of 60% in 2010 (World Bank, 1995).

Closely associated with rapid urban growth is rapid waste generation. The intensity of human activities has led to increased volume of waste globally, regardless of the current level of scientific advancement and development of waste management and controlling options (Qdais, 2007). The enormous expansion of urban, agricultural and industrial activities, stimulated by rapid population growth and change in consumer habits, have produced vast amounts of solid waste (Anonyei, 2012). The generation of industrial and municipal waste and its disposal or management has been a major concern and threat to the society at large. The developing countries in particular like Nigeria, Ghana, have had more critical environmental problems arising from poor or non- existent environmental management plans (Offiong, 2007).

In many developing countries like Nigeria, Uganda, Kenya, the dominant disposal method of solid wastes is dumping on land surface directly as opposed to the use of sanitary landfills in the developed World (Nasrabadi *et al.,* 2008). This is due to lack of finances of the government, rapid population growth, increasing urbanization, lack of facilities to collect the gas which is generated (Visvanathan, 2006; Abduli *et al.,* 2007; Barton *et al.,* 2008). Majority of the waste produced goes to the solid waste disposal sites. That is why the solid waste disposal site is likely to remain a substantial source of not just ground water contamination but also air contamination (Ugwu and Nwosu, 2009).

Besides, the nature of municipal solid waste differs with the country, city, suburb, and seasons. Biodegradable food materials and yard waste normally dominate in municipal solid waste of undeveloped countries while paper and cardboard dominate in technologically advanced nations (Joseph *et al.,* 2003). Similarly, Methane production mostly starts two months after burial of the wastes and continues up to 100 years (Tian *et al*., 2013).

Solid waste is any left-over arising from human, animal or plant activities that are normally discarded as useless and not having any consumer value to the person abandoning them (Oyedele, 2009). Municipal solid waste is the kind of waste produced in the cities and any area of human habitation. This is mostly consisting of degradable (paper, textiles, food waste, vegetable matter, straw and yard wastes); partially degradable (wood, disposable napkins and sludge); and non-degradable materials (leather, plastics, rubbers, metals, glass, ash from fuel burning like coal, dust, and electronic waste) (Tchobanoglous *et al.,* 1993; United States Environmental Protection Agency, 2003; Jha *et al.,* 2007; and Herat, 2009). The volume of waste produced in any given society is directly related to population growth, urbanization, industrialization, economic activities and household consumption levels (Itaru, 2007; Kumur *et al*., 2008; and Thaddeus, 2011). These wastes are collected from different sources, transported and finally disposed of in solid waste disposal site/landfill. Hence, solid waste disposal site refers to a whole disposal facility in an adjoining geographic space where municipal waste is placed. In the solid waste disposal site, physical, chemical and biological processes intermix with each other in the degradation of organic matter, resulting in the generation of gaseous refuse (landfill gas) and liquid refuse (leachate) (Alcantara, 2007).

Landfill gas emanating from the anaerobic biodegradation of the organic matter content of waste, mostly comprises of 45 to 75% Methane and 25 to 50% Carbon dioxide (Amini and

Reinhart, 2011; Mescia *et al.*, 2011). It also contains trace amounts of various chemical compounds and metals (Khalil, 1999). Moreover, about 2% to 9% other trace gases, such as Nitrogen, Oxygen, Ammonia, Carbon Monoxide, Hydrogen Sulfide are also found. Other by-products of the decomposition process include Organic Compounds such as Hydrocarbons, Acidic Hydrocarbons and Organic Alcohols, Aromatic Hydrocarbons, Halogenated Compounds, Sulfur Compounds and inorganic compounds. Others are Mercury and Non-Methane Organic Compounds such as TriChloroethylene, Benzene and Vinyl Chloride (Tchobanoglous *et al.*, 1993; Metz *et al*., 2007; Agency for Toxic Substances and Disease Registry, 2011).

Methane is a hydrocarbon that is a primary component of natural gas. It's a powerful Greenhouse gas, which is colorless, odorless and naturally present in the atmosphere at a concentration of about 0.0002% (Kjeldsen, 1996). The development in Pressure, concentration and Temperature gradients inside the solid waste disposal site result in Methane emissions or Methane release to the atmosphere and in horizontal migration through the adjacent soils (Nastev *et al.*, 2001). The lateral migration of Methane gas through soil beyond the boundaries of solid waste disposal site causes the displacement of Oxygen from soil faunal populations and burrowing animals and causes vegetation dieback. It is also a combustible gas which is explosive in air at concentrations between 5% lower explosive limit and 15% upper explosive limit by volume (Christophersen *et al*., 2001).

Methane plays a significant role in the radiation balance and chemistry of the atmosphere. According to the International Panel on Climate Change (IPCC) Fourth Assessment Report (IPCC, 2007) and other studies like Rohde, 1990; Hansen and Sato, 2001. Methane is the second largest driver of climate change after Carbon dioxide. It currently contributes 18% of the radiative forcing by long-lived Greenhouse gases (Dlugokency *et al*., 2011). In addition to

climate driving, the increase in atmospheric Methane has added about half of the expected increase in global Tropospheric Ozone which has a negative effect on human health (Ehhalt and Prather, 2001). Atmospheric Methane concentrations have increased by 30% in the last 25 years and multiplied by a factor of 2–3 since the 1700s all due to human activities (IPCC, 2006). The present global Methane emissions are estimated at about 550 Tera-grams per year and the net annual increase at 40 to 70 Tera-grams per annum (Dlugokencky *et al.,* 1998). In total, human activities presently account globally for some 70% of the emissions each year with landfills/solid waste disposal sites as the third most important anthropogenic source (Bogner *et al.,* 2007). However, these emissions are caused by inadequate Methane gas active recovery systems, uncontrolled emissions from solid waste disposal sites and in making landfills one of the most vital Worldwide sources of the Greenhouse Gas Methane. In spite of Methane concentrations level falling between the early 1980's and 1998 levels, due to better management of landfills, as well as drought in wetland areas, there is a 150% increase in atmospheric Methane since 1750 (Hartmann, 2011).

The links between urbanization, waste, Methane emissions and global climate change are complex (Sanchez-Rotriguez *et al*., 2005). The irregular dumping of waste will tend to increase Methane emissions and Temperatures in the city thus causing urban warming. Reducing Methane emissions is therefore a way of reducing global warming. It is also an important part of any strategy to avoid dangerous climate change as agreed by World leaders at the December, 2015, Paris conference. Also, Methane reductions can result in substantial and widespread decreases in premature human mortality. Recent modeling shows that Methane reductions of 65 metric tons per year, beginning in 2010, would prevent 370,000 premature mortalities globally between 2010 and 2030 (West, 2010).

1.2 Statement of the Research Problem

Rapid increase in human population and urbanization with enormous consumption of goods, have increased the amount of municipal solid waste generated in Kano metropolis. Hence, solid waste disposal sites are ubiquitous within the metropolis. These disposal sites are the main solid waste management method employed by waste disposal authority- Refuse Management and Sanitation Board (REMASAB) in Kano metropolis. The wastes contained in these disposal sites are not properly managed to reduce Methane emissions produced from the anaerobic (without Oxygen) decomposition of waste by microbial activities. Thus, while aerobic (with Oxygen) decomposition of organic wastes in these disposal sites produces Carbon dioxide emission, the anaerobic putrefaction produces Methane emissions (Levis and Barlaz, 2011). Even though, both are Greenhouse gases, the Carbon dioxide component is generally not counted as such because it is of biogenic origin; consequently, the emission of Methane is of greater concern (IPCC, 2006; Börjesson *et al.*, 2007).

Methane, being a powerful Greenhouse gas, which is more effective in trapping heat in the atmosphere than Carbon dioxide, has the potential of causing global warming 34 times more than Carbon dioxide (IPCC, 2013). Once in the atmosphere, it absorbs terrestrial infrared radiation that would otherwise escape to space. This property can contribute to the warming of the atmosphere (Houghton *et al*., 1992). Equally, inhaling of Methane emission from solid waste disposal sites poses serious health hazard (Health Protection Agency, 2011). It acts as an asphyxiant, by displacing air in the body and replacing Oxygen in the blood at a concentration of 2% lower explosive limit (Macklin, 2011). Likewise, breathing of Methane emission can cause nausea, vomiting, headache, and at very high concentrations it might cause unconsciousness and death due to respiratory arrest (Health Protection Agency, 2011). Methane can also contaminate

ground water and the presence of it in water used for drinking may indicate a risk of other contaminants for instance, Benzene, Toluene, Xylene, Ethylbenzene and so forth (Kjeldsen, 1996; Christophersen *et al*., 2001; Osborn *et al.,* 2011). It is, therefore, believed that significant amount of Methane emissions might be released regularly from these solid waste disposal sites on to the environment, with considerable adverse consequences.

Numerous studies have been undertaken to assess the levels of Methane emissions from municipal solid waste disposal sites/landfills in both developed and developing countries using different mathematical models (Landfill Gas Emission Model (LandGEM), Triangular Model, GasSim Model) and monitoring equipment/measuring techniques (Closed Chamber Technique, Mass Balance Method, Eddy Covariance Measurement, Portable Real-Time Monitoring Technique, Portable Multi-Gas Analyzer of Model VEP 200). Prominent among these studies include Oonk and Boom (1994), Qdais *et al.* (2010), Nava-Martinez *et al.* (2011), Li *et al.* (2013), Daura *et al. (*2014), Niloufer *et al.* (2014), Abdu, 2016, Abualqumboz *et al.* (2016), Rafiq *et al.* (2018). However, a review of literature indicated that only few studies have been conducted to assess Methane emissions from municipal solid waste disposal sites in Kano metropolis like that of Daura *et al.* (2014) and Abdu (2016). Nevertheless, a review of these studies revealed that LandGEM were used to examine Methane emissions from four solid waste disposal sites in Kano metropolis. Also, there are several barriers to applying LandGEM in developing countries like Nigeria with tropical climates. In particular, the basic design of the model does not fit the unmanaged, non-engineered solid waste disposal sites of developing countries with vastly different waste characteristics, high leachate levels, poor waste compaction, and other conditions that can significantly limit generation and collection of the gas (Tononon *et al.,* 2011). Therefore, this study attempted to analyze the spatio-temporal variations of Methane

that was emitted from 10 selected solid waste disposal sites of Kano metropolis using IPCC default methodology and field monitoring approach adopted by Crowcon Gasman Fl. Thus, an attempt was made to fill these identified gaps using Kano metropolis as a case study.

Based on the above-mentioned, the key research questions addressed in this study were:

i. What was the level of Methane emissions in the selected solid waste disposal sites in Kano metropolis?
ii. What was the variation of Methane emissions at different points away from the center of solid waste disposal sites in the Kano metropolis?
iii. What was the diurnal and seasonal variability of the levels of Methane emissions in the selected solid waste disposal sites of the study area?
iv. How did the modeled emissions results obtained by IPCC default methodology differ from direct monitoring values obtained by the Gasman Fl in the study area?
v. How did meteorological variables of Temperature and Pressure Influence Methane emissions in the selected solid waste disposal sites of the metropolis?

1.3 Study Aim and Objectives

The aim of this study was to analyze the spatio-temporal variations of the level of Methane emissions from 10 selected solid waste disposal sites in Kano metropolis. This aim was achieved through the following specific objectives, which were to:

i. determine the levels of Methane emissions from the selected solid waste disposal sites in Kano metropolis;
ii. determine the variation of Methane emissions at different points away from the center of solid waste disposal sites in the study area;

iii. determine the diurnal and seasonal variability of the levels of Methane emissions from the solid waste disposal sites in the study area;

iv. compare the modeled emission results obtained by IPCC default methodology with direct monitoring values using Gasman Fl in the metropolis;

v. assess the influence of Temperature and Pressure on Methane emissions in the study area.

1.4 Research Hypothesis

The study was guided by the following null hypotheses:

a. There was no significant difference in the levels of Methane emitted at the selected solid waste disposal sites.

b. There was no significant variation in the levels of Methane emissions at different points away from the center of solid waste disposal sites.

c. Diurnal and seasonal variability of the levels of Methane emissions did not significantly differ.

d. Methane emission results by IPCC default methodology did not differ significantly from direct monitoring values using Gasman Fl.

e. Temperature and Pressure did not have significant influence on Methane emissions.

1.5 Scope of the Study

The spatial extent of this study was Kano metropolis, which covered eight Local Government Areas of: Gwale, Dala, Tarauni, Kumbotso, Fagge, Nassarawa, Municipal and Ungogo. The focus was on analzing the spatio-temporal variability of the level of Methane emissions from 10 selected municipal solid waste disposal sites in Kano metropolis noted for heavy waste dumps.

These were identified from a survey of a number of several solid waste disposal sites in the metropolis. The selected sites for the study are: Court Road, Ubagama, Hajj Camp, Maimalari, Kuntau, Ramin Hussain, Yankaba, Ramin Birji, Kwarin Goshi, and Ramin Hassan solid waste disposal sites respectively. The temporal scope of the study covered four seasons, namely: the cool dry season of the harmattan (January, 2018); the hot dry season (April, 2018); the wet season (August, 2018); and the harvest season (November, 2018). This is because the climate of Kano was categorized into four distinct seasons (Udo, 1981; Essiet and Tudun Wada, 1999). The monitoring was conducted according to Atlanta Environmental Protection Division (2015), that monitoring of Methane emission from landfill facility was required to be performed at a minimum of once every calendar quarter. Equally, monitoring of Methane emissions performed during the different seasons produced a better estimation of the annual Methane emissions. In addition, the purpose of monitoring on a seasonal schedule was to identify the existence of any seasonal variations (Maurice and Lagerkvist, 2003).

Monitoring were performed in the morning (0700 hours to 1000 hours' local time) and afternoon (1300 hours to 1600 hours' local time) time of the day. This was to identify if there could be any diurnal variation in the level of Methane emissions in the study area. Lastly, the content scope of the study was confined to spatio-temporal variations of the level of Methane emissions from 10 selected solid waste disposal sites in Kano metropolis, Nigeria.

1.6 Justification of the Study

Kano metropolis is the administrative center of Kano State and the third largest city in Nigeria after Lagos and Ibadan (Okeagu *et al*; 2004). In terms of population, it is the second most populous city in the country after Lagos (Official Gazette, 2009). The reason why this study was crucial was that solid waste disposal sites in Kano metropolis required considerable attention

because of the present population growth, economic development and increased urbanization which has impacts on solid waste generation in the metropolis.

According to World Health Organization (2000), it is estimated that about a quarter of diseases facing mankind today occur due to continued exposure to environmental pollution (Pruss-Ustun and Corvalan, 2006; Kimani, 2007). Issues related to the disposal of waste pose an important challenge for many communities developed or otherwise. They affect not only the environment but also public health. While developed communities have established improved waste management strategies, solid waste disposal sites are a common eyesore in African cities (United Nations Development Programmed (UNDP), 2006). Solid waste disposal sites generate various environmental and health hazards because of unregulated and haphazard dumping of restricted materials such as car batteries, metals, pathological wastes and sharps from nearby health facilities. Households and market wastes also contribute to solid waste disposal sites (Agunwamba, 1998).

The decomposition of waste materials in the sites under anaerobic conditions produce Methane gas. Methane from solid waste disposal sites is highly flammable and if it is not collected, it will lead to potential fire and explosive hazards (Aydi, 2012). Similarly, in order to assess the risks and hazards related with Methane, it is essential to know the difference in Methane emissions both seasonally and annually and how changes in meteorological variables affect the production of the gas (Maurice and Lagerkvist, 2003). It is also of importance that Methane emissions be assessed at individual solid waste disposal site to help in appraising the possibility of Methane extraction and use. Additionally, when mixed with atmospheric air, Methane is explosive in concentrations between 5% lower explosive limit and 15% upper explosive limit by volume (Aydi, 2012). Consequently, if it is not collected properly and the concentration reaches to the

range (5% lower explosive limit to 15% upper explosive limit), it will explode (Kreith, 2002). Moreover, Methane emissions from municipal solid waste disposal sites released to the atmosphere contributes and will continue to contribute significantly to global warming. For these reasons, quantification/monitoring of Methane emissions from solid waste disposal sites is very important. This quantification/monitoring also can help to determine the national and global emissions of Methane at different countries (IPCC, 2001). Hence, these emissions need to be reported to national Greenhouse gas inventories under United Nations' Framework Convention on Climate Change (Jens *et al*., 2009).

It is hoped that the results obtained from this study would be used by engineers, national and international regulatory agencies as well as assist policy makers and planners in the state to design effective disposal and treatment alternatives. Also, can be used to illustrate how solid waste management may contribute to the alleviation of Methane emissions. All these can help in the decision making process by developing a preferred waste management strategy. Moreover, assessment and prediction of the emission rate are useful for planning, proper application of Methane as an energy source and determining the contribution of numerous Greenhouse gas emissions to global warming (Rezaee *et al*., 2013).

CHAPTER TWO

CONCEPTUAL, THEORETICAL FRAMEWORK AND LITERATURE REVIEW

2.1 Conceptual Framework

2.1.1 Definition of Waste

Recognized as the by-product of human activity, waste mostly refers to anthropogenic material or product that has lost its value to the owner (White *et al.*, 1995; Agamuthu, 2001). In other words, according to European Council Guidelines (2008), a waste is any substance or object the holder discards or intends to discard or is required to discard. Once a substance or object has become waste, it will remain waste until it has been fully recovered and no longer poses a potential threat to the environment or to human health (European Directive, 2008). Also, according to Bhailall (2015), waste is defined as an undesirable or excessive by-product, emission, or residue of any process or activity, which has been discarded, accumulated or stored for the purpose of discarding or processing. It may be gaseous, liquid or solid or any combination thereof, which may originate from residential, commercial, institutional or industrial sources.

Nabegu (2012) identified two categories of waste in Kano metropolis. The first group is the light and predominantly non-biodegradable waste. This comprises mainly tins, plastic materials and bottles. The second is the heavier predominantly biodegradable wastes which contain high proportion of food scrap, ash, dirt and vegetables. The non-biodegradable wastes are commonly found in commercial areas while the biodegradable wastes are mostly linked to residential quarters.

The term “solid waste” is commonly used to designate non-liquid waste material (normally solid) that is generated from the daily human activities and generally does not carry any value to the user, hence, in urban settings it includes municipal and industrial solid waste (United States

Environmental Protection Agency, 2006). Solid waste comprises both organic and inorganic fractions such as product packaging, grass clippings, furniture, clothing, bottles, kitchen refuse, paper, appliances, hospital and institutional garbage, street sweepings and construction waste in different sizes depending upon various factors (Zerbock, 2010). Equally, Schubeler (1996) points out that while certain contaminated medical wastes, human faces and hazardous industrial wastes are not involved by definition. In all Nigeria's urban centers, solid waste consisting of food scrap, plastics, vegetables, papers, textiles, dead animals and so forth are generated every year (Nabegu, 2008). When dumped in inappropriate solid waste disposal sites, they can decompose to produce Methane emissions under anaerobic conditions. The management of solid waste is a worldwide problem that is a growing source of concern in developed and developing nations due to increase urbanization; changes in consumer pattern and industrialization, which all directly influence solid waste generation (Kadafa *et al.*, 2013).

2.1.2 The Municipal Solid Waste: Definition, Composition and Management

Municipal solid waste has received considerable attention as it is produced in residential areas. It encompasses; all household, commercial and institutional wastes, as well as street sweepings, yard and garden waste, wastes from hotels and restaurants, sanitation residue, construction and demolition debris, and sludge, thrown away in urban areas and collected by a municipality (Coffey and Coad, 2010; Hoornweg and Bhada-Tata, 2012). There are considerable differences in the precise definition of municipal solid waste between countries, organizations and people. The United States Environmental Protection Agency (2012), for example defined municipal waste more commonly known as trash or garbage comprises of everyday items human beings use and then thrown out, such as product packaging, grass clippings, furniture, clothing, bottles, food scraps, newspapers, appliances, paint, and batteries, which comes from household, schools,

hospitals, as well as businesses. According to Organization for Economic Cooperation and Development (OECD) (2011), municipal solid waste refers to a waste that was collected and treated by or for metropolises. It covers waste from households, including bulky waste, similar waste from commerce and trade, office buildings, institutions and small businesses, yard and garden, street sweepings, contents of litter containers, and market cleansing. Waste from municipal sewage networks and treatment, as well as municipal construction and demolition is excluded. According to the United Nations, (2014) commercial, industrial and institutional waste that have similar nature as household waste and waste from public spaces are municipal solid waste. Waste water or sewage sludge is not included in municipal solid waste (United Nations-Habitat, 2010). According to Intergovernmental Panel on Climate Change (IPCC), (2007), municipal solid waste embraces: food waste; garden (yard) and park waste; paper and cardboard; wood; textiles; nappies (disposable diapers); rubber and leather; plastics; metal; glass (and pottery and china); and other (for example, ash, dirt, dust, soil, electronic waste). Municipal solid wastes typically include household waste and bulky consumer wastes, as well as similar wastes from small commercial and industrial firms, institutions and markets, which are collected and disposed of by, or for local authorities (Novella *et al.*, 1999).

Despite the variation in definition, however, municipal solid waste constitutes a substantial problem in both industrialized and unindustrialized nations. As a population continues to increase, it consumes more, and by extension increases its production of waste (IPCC, 2006). By placing of these compostable and organic waste materials in solid waste disposal sites, Methane emissions are increased, unless waste management practices are reconsidered and more sustainable methods are implemented.

Though, municipal solid waste disposal site is an enormous concern in developing countries across the world, as poverty, population growth, and high urbanization rates combine with ineffectual and underfunded governments to prevent effective management of wastes (Cointreau,

1982; UNEP, 2002). There are several factors that set municipal solid waste management in unindustrialized countries apart from management in industrialized countries. First, the types of materials that compose the majority of the waste are different. In unindustrialized countries, there is a much higher proportion of organics, and noticeably less plastics (Cointreau, 1982). The large amount of organic material makes the waste denser, with greater moisture and smaller particle size (Cointreau, 1982). A second difference is that technologies used in industrialized countries are often inappropriate for developing countries. Even garbage trucks are less effective because of the much heavier, wetter, and more corrosive quality of their burden (Cointreau, 1982). Other technologies, such as incinerators, are often far too expensive to be applied in less developed nations. Third, less developed countries' cities are characterized by unplanned, haphazardly constructed, sprawling slums with narrow roads that are inaccessible to collection vehicles (Daskalopoulos *et al.*, 1998).

The exact composition of the municipal solid waste is determined by various factors, which comprises geography, population, social and economic factors, climate and season etc. (Tchobanoglous *et al.*,1993). The Composition of municipal solid waste varies between countries and is the pre-determinant factor for sustainable waste disposal method. Developed countries generally produce more inorganic materials such as plastics and paper, while developing countries produced comparatively more of organic waste (Nabegu, 2007). However, in Nigeria, organic waste controls the waste stream by more than 40% and it mainly consists of kitchen waste and food waste (Nabegu, 2007). This is in contrast with many industrialized countries whose waste consist more of recyclable and bio-degradable organic waste (Zhang *et al.*, 2010). For example, in Western Europe and the United States of America, the waste composition features a high percentage of paper and plastic (Zhang *et al.*, 2010). From the report by World

Bank (2012), it is further gathered that the unindustrialized countries make up for 64% and 5% of organics and paper in their municipal solid waste whereas in the industrialized countries it is 28% and 31%, correspondingly. Developed countries have applied many procedures to modify its own unique waste management system. This is to manage various components of waste streams in a flexible manner. Knowledge of waste composition and characteristics is important for determining Methane emission from solid waste. Decomposition rate of waste and production Methane would vary depending on waste composition.

Municipal solid waste handling is a global issue that is a growing source of concern in developed and developing countries due to increase urbanization; changes in consumer pattern and industrialization, which all directly influence solid waste generation (Kadafa *et al.*, 2013). Adedibu (1993) is of the view that the nature and composition of municipal solid waste is a product of climatic and business activities in urban centers. He argues further that most of the agricultural produce such as maize, cassava, vegetables, millet are brought unprocessed during the rainy and harvesting seasons from the nearby farms. The composition of refuse generated in an area determines the type of disposal method suitable for a particular form of waste and the effectiveness of a collection system depends on the cooperation of households and individuals in various sectors of the city in providing containers for storing refuse in accordance with the regulation and regularly placing the materials for collection (Afon, 2003). Abumere (1983) links socio-cultural factors to land use pattern such as housing density and eating habits. He further states that municipal solid waste accumulation is a product of chaotic land use pattern, the number of households living and that the eating habit in a house greatly determines the composition of refuse generated. Adewole (2009) claims that continuous indiscriminate disposal

of municipal solid waste is hastening and is linked to poverty, poor governance, urbanization, population growth, poor standards of living and low level of environmental awareness.

Solid waste disposal site is the term used to designate the physical facility used for the disposal of solid waste and solid waste residuals in the surface soils of the earth (Tchobanoglous and Kreith, 2002). In other words, a solid waste disposal site, a waste management option, is the term used to designate the physical facility and area of land or excavation/burrow pit that is used for permanent disposal of solid waste, that is, waste is discarded with the objective of leaving it there indefinitely (Tchobanoglous and Kreith, 2002; Keramida, 2003). A solid waste disposal site is a disposal site without waste compaction during placement, neither compact nor cover with soil. The land is used without preparation of engineering planning. The uncontrollable wastes are placed as mountain of waste. It is typically a source of Methane emissions produced from anaerobic deprivation of waste (Cheremisinoff, 2003). Solid waste disposal site is the most preferred option, especially in the developing country like Nigeria, because of its easy operation, low cost, non-technological participation and ease of implementation (Hasan *et al*., 2009).

Solid waste disposal sites are the third largest anthropogenic emission source, accounting for about 13-20 percent of global Methane emissions (USEPA, 2005). According to a report by USEPA's Global Anthropogenic Emissions of Non-Carbon Dioxide Greenhouse gases, Nigeria's estimated anthropogenic Methane emissions ranked ninth in the world (USEPA, 2005). Approximately 2.23 carbon equivalent of world Methane emission are produced in the solid waste disposal sites of Nigeria, a Methane to Markets member country (USEPA, 2005). Therefore, Nigeria is a major contributor to the global Methane emission.

Waste management selections such as solid waste disposal sites, composting, incineration/mass burns and anaerobic digestion collectively emits substantial amount of Greenhouse gases most

especially Methane. Likewise, according to Nnaji (2011), the role of waste management is significant and Methane emissions can be reduced through a thorough articulated waste management approach.

2.1.3 The Methane gas

Table 2.1 indicates the list of usual gases contained in solid waste disposal site, including percent by volume, and their features.

Table 2.1: Usual Gases Contained in Solid Waste Disposal Site/Landfill, Their Percent by Volume, and Their Features

Constituent	Features	Percent by volume (%)
Methane	Methane is naturally occurring gas. It is colorless and odorless. Its concentration in the natural chemistry of the atmosphere is 0.0002% (Kjeldsen, 1996). The gas is highly explosive when mixed with air at a volume between its lower explosive limit of 5% and its upper explosive limit of 15%. At concentrations lower than 5% and beyond 15%, it is not explosive.	45 – 75
Carbon dioxide	This is naturally found at minor concentrations in the atmosphere (0.03%). It is colorless, odorless, and slightly acidic. Carbon dioxide is nonflammable gas.	25 – 50
Nitrogen	The normal chemistry of Nitrogen in the atmosphere is almost 79%. Nitrogen is colorless, odorless, tasteless and non-explosive gas	2 – 5
Oxygen	Oxygen contains roughly 21% of the atmosphere. It is odorless, tasteless, colorless and non-flammable gas.	0.1 – 1
Carbon Monoxide	Carbon Monoxide is an odorless, colorless gas. Its atmospheric concentrations are less than 0.00001%.	0 – 0.2
Ammonia	Ammonia is a colorless gas with a strong odor and combustible. Its lower explosive limit is 15% and its upper explosive limit is 28%. Nevertheless, Ammonia is not likely to collect at a	0.1 – 1

	concentration highly adequate to pose explosion hazard.	
Sulfides (for example Hydrogen Sulfide, dimethyl Sulfide, mercaptans)	Sulfides are naturally occurring gases that produces a rotten egg smell in the solid waste disposal site/landfill. They can cause unpleasant odors even at very low concentrations. Hydrogen Sulfide is combustible. Its lower explosive limit is 4% and its upper explosive limit is 44%. Nonetheless, in most landfills, Hydrogen Sulfide is not likely to collect at a concentration high sufficient to create an explosion hazard. The natural concentrations in the atmosphere are less than 0.001%.	0 – 1
Hydrogen	Hydrogen is an odorless, colorless gas. Its atmospheric concentrations are less than 0.00005%.	0 – 0.2
Non - Methane Organic Compounds	Non - Methane Organic Compounds are organic compounds that is compounds that contain carbon. Methane is an organic compound but is not considered an Non - Methane Organic Compound. Non - Methane Organic Compounds may occur naturally or artificially by chemical processes. Non-Methane Organic Compounds most usually found in landfills comprises of Acrylonitrile, Benzene, 1,1- Dichloroethane, 1,2-Cis DichloroEthylene, DichloroMethane, Carbonyl Sulfide, Ethyl-Benzene, Hexane, Methyl Ethyl Ketone, TetrachloroEthylene, Toluene, TrichloroEthylene, Vinyl Chloride, and Xylenes. Probable explosion hazards differ by chemical. For instance, the lower explosive limit of benzene is 1.2% and its upper explosive limit is 7.8%. Conversely, benzene and other Non - Methane Organic Compounds only are not likely to collect at concentrations high enough to form explosion hazards.	0.01 – 0.6

Source: **Tchobanoglous *et al.*, 1993; USEPA 1995; Amini and Reinhart, 2011.**

Of major significance in this study is Methane. Methane, a potent Greenhouse gas, is a colorless, odorless gas, which is naturally present in the atmosphere at a concentration of about 0.0002% (Kjeldsen, 1996). However, when breathe in, it can produce suffocation by reducing the concentration of Oxygen inhaled. It is lighter than air, at normal Temperatures and Pressures, it will condense to a liquid at –164 ºC and will become solid at -183ºC (1PCC, 2007). Methane is the second major contributor to Global warming after Carbon dioxide (IPCC, 2006). Its emitted from a variety of natural and human influenced sources such as landfills/solid waste disposal

sites, petroleum systems, coal mining, stationary and mobile combustion, waste water treatment, certain industrial processes, wetlands, rice paddy, and stomach of ruminant animals (IPCC, 2006). Methane is a natural gas and it is widely used around the world as a fuel. The largest uses of natural gas as a fuel are for space heating, water heating and the generation of electricity (Bengtson, 2010). It is produced and released to the atmosphere by biological process occurring in anaerobic environments. Even though a more powerful Greenhouse gas than Carbon dioxide, Methane remains in the atmosphere for a much shorter period: only 8 to 12 years compared to 50 to 200 years for Carbon dioxide (IPCC,1996; Mathews and Bogner, 2003). Nevertheless, once in the atmosphere, Methane absorbs terrestrial infra-red radiation that would otherwise escape to space. This property can contribute to the warming of the atmosphere which is the reason that Methane is a Greenhouse gas (Ayodele and Emmanuel, 2007).

The occurrence of Methane in the atmosphere was not known until the 1940s, when it was recognized in its ultraviolet line in the solar band (Migeotte, 1948). By means of Migeotte's fairly accurate column abundances, Bates and Witherspoon (1952) made the first study of the photochemistry and atmospheric cycle of Methane. Bates and Witherspoon (1952) recognized that the gas must have a considerable natural source, and they singled out anaerobic fermentation for special attention. However, a growth of up to 18 parts per million per volume per year within the periods 1980 to 1990 was observed (Rodhe, 1990).

2.2 Theoretical Framework

2.2.1 Methane formation process

The solid waste buried in solid waste disposal sites are exposed to physical, chemical and biological processes in which the decomposable portions decay under anaerobic condition through a complicated series of microbial and abiotic reactions (Wang Yao *et al*., 2010).

Consequently, the biodegradation of organic waste takes place in four stages (Figure 2.1) which are; (a) an initial aerobic stage; (b) anaerobic stage; (c) acid formation stage and (d) a final stable Methane fermentation stage (Farquar and Rovers,1973). Furthermore, as organic matter is decayed, it will lead to the generation of emissions to air, water and land. One of the gases emitted is Methane, which is produced through a chain of metabolic interactions by a number of different microorganisms. The production of Methane occurs in specific stages of the decomposition as mentioned earlier. Since neither the composition, nor the time of disposal tend to be very similar in a landfill/solid waste disposal site, all stages of Methane production will occur in different parts of the solid waste disposal site at the same time. The stages will, however, follow a sequential order since the products of one process is a precondition for the following one (RVF, 2000). The time after placement scale contrasts with solid waste disposal site conditions (Staley *et al.*, 2009), chemical reactions associated with microbial degradation (Scheutz *et al.*, 2009) and Methane gas realization. These stages are further described below:

i. Initial aerobic stage

The first stage is associated with initial placement of solid waste within solid waste disposal site. However, immediately after the solid waste has been disposed of, its internal environment will be aerobic; Oxygen gas will be present. Consequently, the stage is characterized by rapid breakdown of complex organics in the presence of water and Oxygen into simple sugars – often termed hydrolysis. During this stage of decomposition, aerobic bacteria -bacteria that live only in the presence of Oxygen-consume Oxygen and breakdown the long molecular chains of complex carbohydrates, proteins, and lipids of organic waste (Palmisano, 1993). The primary byproduct of this process is Carbon dioxide. Nitrogen content is high at the beginning of the stage (about 20 % Oxygen and 80 % Nitrogen) but declines as the solid waste disposal site moves through the

four stages. The stage will continue until available Oxygen is depleted. The decomposition in the stage is relatively short and will only last from a couple of hours to some weeks or months, depending on how much Oxygen is present when the waste is disposed of in the solid waste disposal site (RVF, 1995). Oxygen levels will vary depending on how loose or compacted the waste is in that specific area of the solid waste disposal site and will determine the length of stage I decomposition. If Oxygen is reintroduced during any other stage, then decomposition will revert back to stage I until all of the Oxygen is consumed.

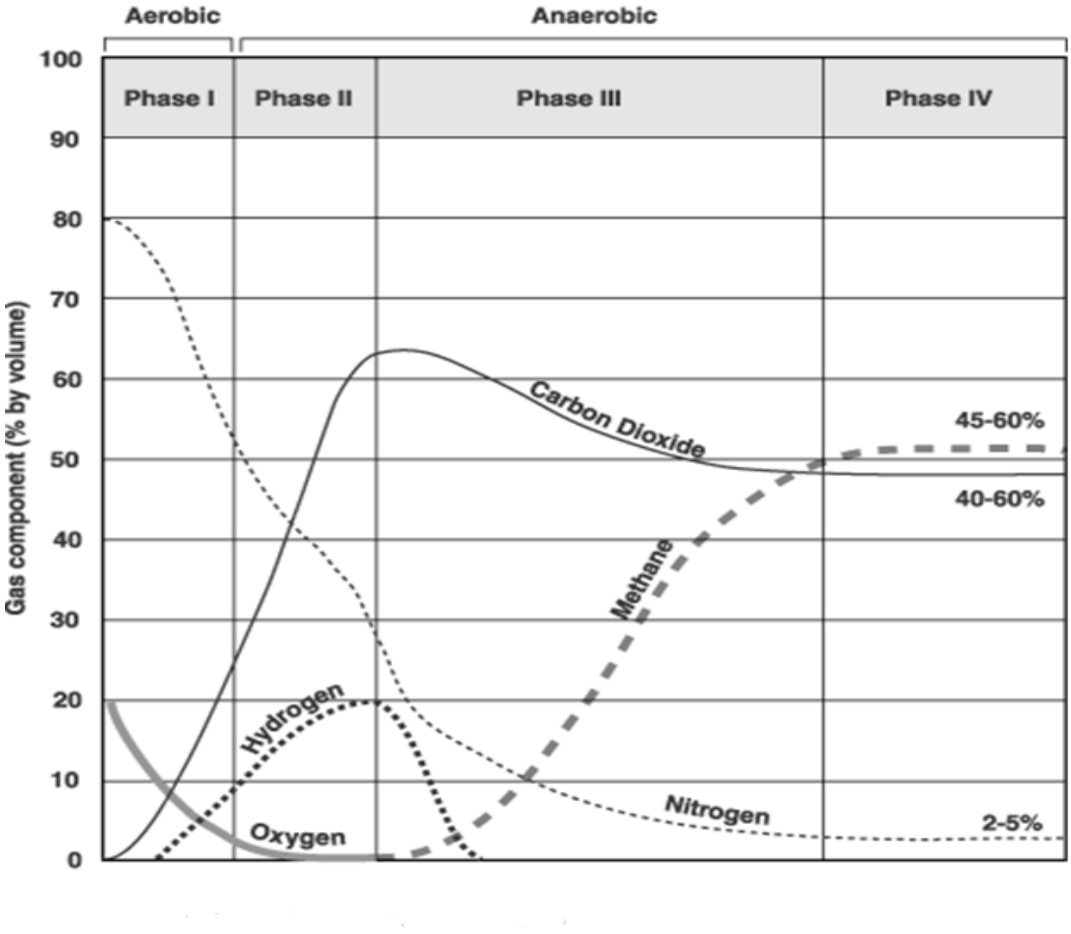


Figure 2.1: The Four Sequential Stages of Methane Formation Through Decomposition of Organic Waste at a Particular Time (Tchobanoglous *et al*., 1993).

Note: Time scale (total time and stage duration) of gas generation varies with the landfill conditions (USEPA, 1997).

ii. Anaerobic stage

This stage will start once all of the Oxygen in the waste area have been consumed by aerobic bacteria. Anaerobic bacteria begin converting the products of the aerobic bacteria in stage I into acetic, lactic, formic acids, and alcohols such as methanol and ethanol (Barlaz, 1989, Bogner *et al.,* 2009). During this stage, the pH environment of the solid waste disposal site area becomes acidic. As the acids mix with the moisture present in the solid waste disposal site, it dissolves other nutrients, creating increased levels of Nitrogen and phosphorus available for additional anaerobic bacterial proliferation (Barlaz, 1989; Hilger *et al.,* 2009). This stage produces mainly Carbon dioxide and Hydrogen gases; the odorous Sulfides are also produced during this stage and continue through stages III and IV (Kim, 2003). However, if the solid waste disposal site is disturbed or if Oxygen is somehow introduced into the solid waste disposal site, microbial processes will return to stage I.

iii. Acid formation stage

This is the stage where Methane production initiate. The decomposition begins when certain kinds of anaerobic bacteria (methanogenic bacteria) consume the organic acids produced in stage II and form acetate, an organic acid (Bogner *et al.,* 2009). This process causes that the solid waste disposal site become closer to pH 7 (neutral media) corresponding to the bacteria that produce Methane. The acetate that is produced begins neutralizing the acids produced in stage II, providing a more suitable environment for Methane-producing bacteria to grow (Figure 2.1). Furthermore, the Methane-producing bacteria form a symbiotic relationship with the acetate or acid producing bacteria (Kjeldsen *et al.,* 2003). Acetate – producing bacteria produce the compounds that Methane – producing bacteria use for feeding. The Methane-producing bacteria

(methanogenic bacteria) consume the Carbon dioxide and acetate, which are toxic in high concentrations to the acetate-producing bacteria (Zinder, 1993, Hilger *et al.*, 2009).

iv. Methane fermentation stage

In the fourth stage, decomposition starts when both the composition and production rates of solid waste disposal site gas remain relatively constant (Hilger *et al.*, 2009). Nonetheless, transition from the acid stage to the Methane fermentation stage occurs in the range of 1 to 5years after waste placement and may continue over a period of several years (Krug and Ham, 1995). During this stage, intermediate acids are consumed by methanogenic bacteria and converted into Methane (45% to 75%) and Carbon dioxide (25% to 50%) (Amini and Reinhart, 2011) and 2% to 9% other trace gases which includes small amount of Nitrogen, Oxygen, Ammonia, Carbon Monoxide, Hydrogen Sulfide (Gebert *et al.*, 2009). All of the gases are harmful to human health at high doses (Staley *et al.*, 2009). Methane production can continue at a constant rate in this stage, typically for about 20 years after a solid waste disposal site is closed yet can continue producing Methane for 50 or more years after the waste is placed in the solid waste disposal site depending on the amount of organic waste (USEPA, 1997). Due to the fact that refuse is placed in a solid waste disposal site at different times and consists of different types of solid waste at different moisture content, all four stages of degradation may be occurring simultaneously within the solid waste disposal site.

2.2.2 The migration of Methane gas

As soon as Methane gas is produced beneath the surface of solid waste disposal site/landfill, it normally moved away from the site (Agency for Toxic Substances and Disease Registry, 2001). Nonetheless, Methane gas tends to expand and fill the available space, so that it can migrate,

through the limited pore spaces and soil available within the refuse dumps. The usual tendency of Methane is to move upward, generally through the surface of the solid waste disposal site because it is lighter than air. Upward movement of Methane gas can be reserved by heavily compressed waste. When upward movement is inhibited, the gas tends to migrate horizontally to other areas within the solid waste disposal site or to areas outside the solid waste disposal site, where it can resume its upward path. Essentially, the gas followed the path of least resistance (IPCC, 2007). Three key features influence the migration of Methane gas, namely: diffusion (concentration), Pressure, and permeability (Agency for Toxic Substances and Disease Registry, 2001).

i. Diffusion (concentration)

According to Agency for Toxic Substances and Disease Registry, 2001, diffusion designates a natural trend of Methane gas to reach a uniform concentration in a given space, whether it is a room or the earth's atmosphere. Mostly, Methane existing in a solid waste disposal site move from areas of high concentrations to areas of low concentrations. Because Methane concentrations are usually higher in the solid waste disposal site than in the surrounding areas, it therefore diffused out of the solid waste disposal site to the surrounding areas with low concentrations (Czepiel, *et al*., 2003).

ii. Pressure

Methane collecting in a solid waste disposal site generate areas of high Pressure in which its movement is controlled by compressed refuse and areas of low Pressure in which movement of the gas is unobstructed (Scheutz, 2009). The disparity in Pressure through the solid waste disposal site results in Methane moving from areas of high Pressure to areas of low Pressure

(Agency for Toxic Substances and Disease Registry, 2001). Movement of Methane gas from areas of high Pressure to areas of lower Pressure is known as convection. As more Methane is produced, the Pressure in the solid waste disposal site rises, generally producing sub-surface Pressures in the solid waste disposal site to be greater than either the atmospheric Pressure or enclosed air Pressure. When Pressure in the solid waste disposal site is greater, Methane incline to transfer to ambient (Poulsen *et al.*, 2003).

iii. Permeability

Methane gas will likewise migrate according to where the corridors of minimum resistance occur (Agency for Toxic Substances and Disease Registry, 2001). Permeability is a measure of how well the gas flow through connected spaces or pores in refuse dumps and soils. Dry, sandy soils are very penetrable, whereas, saturated clay have a habit of abundant less pervious. Methane have a tendency to migrate through areas of high penetrability (for example areas of sand or gravel) rather than through areas of low perviousness (for instance areas of clay or silt) (Liukang *et al.*, 2013).

2.2.3 Subsurface migration of Methane emission

Methane does not only diffuse to the surface of the solid waste disposal site/landfill and scatter into the atmosphere, but it also migrates within the solid waste disposal site and is administered by different factors. There are several factors that forces Methane to migrate horizontally within the body of solid waste disposal site rather than vertically. Most notably, there must be a driving force that transfers the gas through an available pathway (Hooker and Bannon, 1993; Pitchel, 2005). Methane migrate as a function of the density of the gas mixture and other parameters for

instance, Temperature and limited Pressure. It will migrate through a path of least resistance (Tchobanoglous *et al*., 1993; Pitchel, 2005). The gas migration is also controlled by a number of processes in the solid waste disposal site operation including the placement of the waste (Pitchel, 2005).

In most of the solid waste disposal sites, waste is commonly dumped in a layered formation which supports in the production of horizontal channels within the solid waste disposal site. The horizontal migration of Methane is further aided by the compaction of the waste which results in lower permeability primarily at the surface of each waste layer (Kjeldsen, 1996). Drainage systems, troughs, and buried utility corridors (such as pipelines) can act as channels for gas movement. The natural geology frequently provides underground paths, such as fractured rock, and buried stream channels, where the gas can migrate (IPCC, 2006). Moreover, if the cover of the landfill comprises of somewhat pervious material, such as gravel or sand, then Methane will probably migrate up through the cover. If the cover involves silts and clays, it is not very penetrable; Methane will then tend to migrate laterally underground (Kjeldsen, 1996).

Some meteorological variables also affect the migration of Methane, the most important of which are changes in the barometric Pressure over time. At most active solid waste disposal site, there is often a high variability in the gas Pressure within the solid waste disposal site. Nonetheless, the internal Pressure is usually larger than atmospheric Pressure. This results in convective (Pressure-driven) and diffusive Methane flow (Tchobanoglous *et al.,* 1993; Kjeldsen, 1996).

Methane gas naturally emitted into the atmosphere at the surface of the solid waste disposal site is carried by the wind. The wind dilutes the gas with fresh air as it moves it to areas outside the

solid waste disposal site. Wind speed and direction determine the gas's concentration in the air, which can differ significantly from time to time or day to day, even hour by hour. In the early morning, for instance, winds tend to be gentle and provide the slightest dilution and scattering of the gas to other parts. Likewise, intensifications of Temperature encourage gas particle movement, tending also to increase gas diffusion, so that Methane gas might spread more quickly in warmer conditions (Christophersen and Kjeldsen 2001; Wang *et al.*, 2012). Similarly, wet surface soil conditions (moisture content/rainfall) could inhibit Methane gas from migrating through the top of the landfill/solid waste disposal site into the atmosphere. Rainfall and moisture may also percolate into the pore spaces in the landfill and "drive out" Methane gas in these spaces (Abushammala *et al.*, 2015). All these factors together govern the maximum distances that Methane can migrate horizontally/laterally. For instance, coarse (porous) soils such as sand and gravel will stimulate lateral transportation of Methane, at greater distances away from the solid waste disposal site boundary, than would fine grained soils (Pitchel, 2005). Very few studies have investigated the maximum distances to which the Methane can migrate; though, it is believed that the migration has a high spatial and temporal variability (Kjeldsen, 1996).

It is hard to foretell the distance that Methane gas will travel because so many factors affect its ability to migrate underground; conversely, travel distances greater than 457 meters have been observed (Kjeldsen, 1996). Computer models that use data about the landfill and surrounding soil conditions can predict the approximate migration patterns from existing solid waste disposal site. A study conducted by the New York State Department of Health found that of 38 landfills, Methane migrated underground up to 305 meters at 1 landfill, 152 meters at 4 landfills, and only

76 meters from the landfill boundary at 33 landfills (Agency for Toxic Substances and Disease Registry, 1998).

Methane gas migrating from a solid waste disposal site/landfill may finally reach buildings and homes. Foundation cracks and gaps, Pressure differences between the inside and outside of the building or home, mechanical ventilation systems, and leakage areas (for example utility entry points, construction joints, or floor drain systems) provides entry points for Methane gas. Buildings and houses with basements generally provide the easiest entrance for the gas migrating in the soil. The Methane gas concentration in indoor air also depends on the building or home design, the rate of air exchange, and the distance of the building or home from the landfill/solid waste disposal site (USEPA, 1992).

In order to ensure that Methane does not migrate to structures such as buildings on the solid waste disposal site and its surroundings, it must be regularly monitored. The frequency of Methane monitoring is determined by identifying the possible gas pathways based on soil conditions, geology, hydrogeology and location of facility structures (Hooker and Bannon, 1993; Pitchel, 2005). The frequency of monitoring should be sufficient to detect Methane migration based on changing solid waste disposal site conditions.

2.2.4 Modelling the potentials of Methane emission

Degradation processes in solid waste disposal site and the succeeding Methane generation is complex and not easy to analyze. There are a large number of undefined parameters and factors affecting the rate of decay, the total amount organic material available for putrefaction and so on. This section presents the basic theory used in Methane gas assessment models.

Nevertheless, if the term recovery signifies the amount of Methane collected, the Methane emissions from a solid waste disposal site/landfill can be described in equation 1 as follows:

emissions = generation – recovery – oxidation ……. (1)

A part of the Methane gas formed in the solid waste disposal site/landfill is oxidized to Carbon dioxide in the upper of the solid waste disposal site (Avfall, 2012). Modelling of the size of oxidation process in solid waste disposal site has not received as much attention as modelling of gas formation. In most of the cases, 10 % of the total Methane through the top layer is presumed to be oxidized (Oonk, 2010).

The environmental influence from solid waste disposal site emissions is dominated by the Methane content, which typically is about 75 % (Amini and Reinhart, 2011; Mescia *et al.*, 2011). Organic material is not a homogeneous material, but includes a wide range of different molecules with varying biodegradability. Some molecules are easily degraded, such as simple sugars and fats, while others are hardy to anaerobic biodegradation (for example lignin, cellulose).

Basically, the Methane production in a solid waste disposal site/landfill depends on:

i. the amount of waste dumped

ii. quantity of degradable organic carbon (DOC) in the deposited waste.

iii. How much of the fraction of DOC which essentially donate to gas generation (DOC_f)

A simple way to theoretically describe the Methane production at a solid waste disposal site is revealed in equation (2) (First Order Decay (FOD) equation as written in IPCC's waste model) (IPCC, 2006).

$Q = L0 \times R \times (e\text{-}kc \times e\text{-}kt)$ ……..(2)

Where,

Q = Methane generated in current year (m^3/year)

L0 = Methane generation potential (m^3/Mg of waste)

R = average annual waste acceptance rate during active life of solid waste disposal site (Mg/year)

k = Methane generation rate constant (yr^{-1})

c = time since the solid waste disposal site closed

t = time since the solid waste disposal site opened.

A first order decay process as in equation (2) is characterized by a fixed half-life for the degradation process. For instance, a predicted half-life of 7 years proposes that Methane generation after 7 years is 50% of the initial generation. The generation after 14 years would then be 25 % etc. IPCC (1996) declared that the results from investigations and measurements in the United States, New Zeeland, the United Kingdom, Argentina and the Netherlands indicate half-life in the range of 3 to 35 years. The half-life is represented by the k-value in equation (2). Slow decay rates (k=0.02, half-life 35 year) are valid for slowly degradable waste for instance wood and or paper and dry site conditions. Rapid decay rates (k=0.2 or approximately 3 years' half-life) holds for high moisture conditions with rapidly degradable waste such as food waste. Oonk (2010) stated that this type of representation does not consider that the waste decomposes continuously rather than separately which is proposed by equation (2).

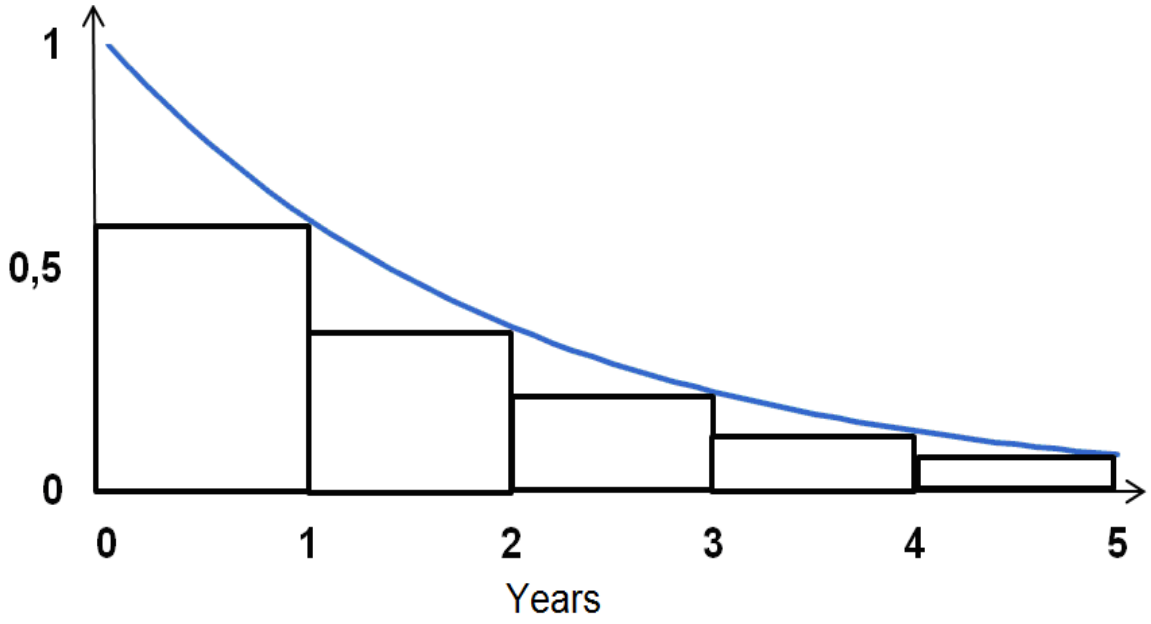


Figure 2.2: Approximation Error in First Order Model

This error can be controlled in diverse ways. For instance, LandGEM reduces the error by calculating generation each 1/10 of the calculation year (Alexander *et al.*, 2005).

The result is an underestimated Methane generation (Figure 2.2). The area below the curve indicates Methane generation assuming an uninterrupted drop. The areas within the blocks signify the case of different decline. The difference between the two areas correspond to the model error.

The IPCC has provided another way where by the real generation curve is realized by amalgamation. For example, if conditions are constant, the rate of Methane is anticipated to depend uniquely on remaining carbon (IPCC, 1996). One more simplification in the model presented so far is that the total waste in the solid waste disposal site is considered homogeneous. In the actual sense, waste dumped at municipal solid waste disposal site is often highly diverse. Some fractions are degraded gradually while others are degraded almost instantly after deposition. A solution of this issue is to introduce several phases, which is the idea of multi-

phase models. Frequently notable three portions are indicated: slow, moderate and fast degrading waste. Calculations are made with specific half-time for each portion. Single-phase models imply that different types of waste degrade dependent of each other. That is, the decay of slowly degrading waste such as wood products are enhanced by the presence of fast degrading waste such as food waste. Multi-phase models suggest that each fraction in the solid waste disposal site degrades independently of other slower or faster degrading fractions present. Oonk (2010) argues that actual production probably lies somewhere in between these two models.

2.2.5 Mathematical Modeling for Methane Emissions

Majority of Methane production and emission models are established purposely for municipal solid waste. They are therefore not automatically appropriate for conditions with reduced quantities of organic waste (Oonk, 2010). The modeling Methane emission is the way of appraising its generation and recovery based on past and future waste disposal histories and estimates of collection system efficiency. It provides an estimate of the amount of recoverable Methane that will be produced over time. A model chosen for Methane estimation from landfills/solid waste disposal sites should be based on the availability of data of waste statistics (Mali *et al*., 2012). Similarly, quantification of Methane emission from municipal solid waste disposal sites is essential in terms of not only prevention of climate change but also recovery of energy (Machado *et al*., 2009).

The development of Methane models started in the 1970's (Cossu *et al*., 1996). But earlier attempts to model Methane formation were undertaken in the 1980s (EMCON, 1980). In those days' Methane emissions was not yet recognized as a potential problem; however, one was aware of the energetic potential of Methane gas and willing to exploit this substitute energy source. Consequently, the first Methane emission formation models were made to help determine

the extent of the gas recovery projects for resource use: how much gas is formed, what are opportunities for the next 10 years and which part of it can be recovered? (Oonk, 2010). Since the mid1990s, the emphasis of modelling moved to quantification of Methane emissions, in advance of the requirement to report Greenhouse gas emissions to United Nations Framework Convention on Climate Change (UNFCCC). This leads to improved accuracy, transparency and the desire for standard emissions resulted in development of a number of emission models (Oonk, 2010).

Methane emission generation from different landfills/solid waste disposal sites can often be replicated by mathematical models, consisting of zero-order, single – phase and multi – phase models (Kittipongvises and Polprasert, 2016). These describe the decomposition of degradable organic fractions in waste and the resulting Methane generation (Cossu *et al*., 1996). However, in this study, zero-order model (IPCC default model) developed by IPCC was proposed because it is considered the simplest method and is commonly applied to a majority of countries (IPCC, 2006). Based on the equations of mass balance, the model provides default parameters to nations with little or lack of available data on solid waste statistics (Friedrich, 2013). Consequently, in view of the above, various models for estimating Methane from solid waste disposal sites/landfills are available in the literature. Nevertheless, keeping in view of the problem under investigation, the IPCC default model used in this study and some models (default method, LandGEM, GasSim lite, Triangular model, in order to evaluate Methane emissions are described individually below:

a. The IPCC Default Model

The IPCC Default model also known as IPCC tier 1 methodology, is a simple model for estimation of Methane emissions from solid waste disposal sites/landfills based on the mass

balance approach. This model was developed by Bingemer and Crutzen (1987) and is being revised in IPCC (1996) guidelines as default methodology or default model (Houghton *et al.*, 1997). Default methodology has number of numerical constants considered for developing the model. The constants vary according to the composition of waste, depth of solid waste disposal site and its management. The method is simple and emission calculations require only input of a limited set of parameters, for which the IPCC Guidelines provide default values, where country-specific quantities and data are not available (IPCC, 1996).

The default model is based on the main equation 1:

Methane emissions (Gg/yr.) =

$(MSW_T \bullet MSW_F \bullet MCF \bullet DOC \bullet DOC_F \bullet F \bullet 16/12\text{-}R) \bullet (1\text{-}OX)$ ……. (1)

Where:

MSW_T is the total MSW generated (Gg/yr)

MSW_F is the fraction of MSW disposed into solid waste disposal sites.

MCF is the Methane Correction Factor (Fraction)

This is based on the category of the solid waste disposal sites management as presented by IPCC (IPCC, 1996). The default values present the following for each site conditions factor:

Managed sites: MCF = 1.0

Unmanaged (open dump), deep sites (≥ 5 Meter waste): MCF = 0.8

Unmanaged (open dump), shallow sites (< 5 Meter waste): MCF = 0.4

Default (uncategorized SWDs); MCF = 0.6

DOC is the fraction of degradable organic carbon in solid waste disposal sites. This is obtained from equation 2.

DOC = percent DOC (by weight) = 0.4 (w) + 0.17 (x) + 0.15(y) + 0.30(z) ……..…. (2)

Where,

w is the fraction of paper and textile in MSW;

x is the fraction of garden waste, park waste or other non-food organic waste in MSW;

y is the fraction of food waste in MSW; and

z is the fraction of wood or straw in MSW

DOC_F this is the fraction of total degradable organic carbon that is based on a theoretical model where the variation depends on the Temperature in the anaerobic zone of the solid waste disposal site and it can be estimated using equation 3.

$DOC_F = 0.014T + 0.28$ …… (3)

Where,

T is waste Temperature in degree centigrade (Tabasaran's (1981) theoretical equation).

Fraction of Methane in landfill gas (F): is the fraction of Methane in landfill gas.

16/12 is the conversion factor from carbon to Methane

R is a Methane recovered value (Gg/yr.)

Oxidation factor (OX): OX is the Methanotrophic oxidation.

b. The Landfill Gas Emissions Model

The Landfill Gas Emissions Model (LandGEM) is a modelling tool for quantifying uncontrolled Methane emissions over a time period, from municipal solid waste landfills (USEPA *et al.*, 2005). The single-phase model, LandGEM was developed by the Clean Air Technology Centre of the United States Environmental Protection Agency for U.S. regulatory applications and widely used by the United States Environment Protection Agency to estimate Methane emissions from municipal solid waste based on the standards set by USEPA and rest of the World (Pelt *et al.*, 1998; Reinhart e*t al.*, 2007; USEPA, 2010). The USEPA protocols (USEPA, 2004 and 2005) states that the composition of waste used in the model replicates U.S. waste composition of municipal solid waste, non-biodegradable waste (i.e. inert materials) and other non-hazardous wastes. The model uses the mass of waste deposited and Methane generation capacity to determine the mass of Methane that is being produced (USEPA, 1998). LandGEM is a first order decay model. First order decay model assumes that Methane emission from landfills is at its uttermost shortly after early waste placement. They also assume that Methane emission from landfill then declines speedily as the organic material in the waste descents as it is degraded by bacteria in the solid waste disposal site/landfill (USEPA, 2010).

Mathematically, LandGEM can be described using the following formula, USEPA, 2005.

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

Where,

QCH4 = estimated Methane generation in the year of the calculation (in cubic meters (m^3) per year or average cubic centimeter per minute.

Mi = mass of solid waste disposed in the i^{th} year (ton)

i = 1-year time increment

n = the difference (year of the calculation) - (initial year of waste acceptance)

j = 0.1-year time increment

k = Methane generation rate (1/year)

Lo = potential Methane generation capacity (m^3 per mega gram [Mg] or cubic feet per ton)

tij = age of the j^{th} section of waste mass Mi disposed in the i^{th} year (decimal years).

i.The Shortfall of LandGEM

The modeling of Methane is done in the U.S. using the EPA's landfill Gas Emissions Model with insufficient amount of model input assumptions known as "Clean Air Act" or "inventory" values which are selected by the USEPA (USEPA, 2005). Due to inadequate input values required by the USEPA, LandGEM do not allow for accurate estimates of Methane recovery from a number of U.S. landfills containing various waste composition, landfill condition, and collection system design and operations (Scharff *et al*., 2010). The effect of this limitation is marked clearly when LandGEM was applied using U.S. regulatory values to landfills in unindustrialized countries with huge different waste characteristics and site conditions (Scharff *et al*.,2010). Equally, LandGEM was based on data from landfills sites in the U.S., it assumes that the site being modeled is an engineered sanitary landfill. Consequently, the level at which Methane in the U.S. landfills is collected will never be approached by those of unindustrialized countries due to difficulties faced at their landfills/solid waste disposal sites. These are high leachate levels, limited/lack of soil cover in most of the cases, poor waste compaction, and the failure to install wells in active disposal areas because of security concerns (Stege *et al.,* 2010; USEPA, 2012). Also, **t**he mathematics of LandGEM is sometimes labelled somewhat confusing (Reinhart *et al,*

2005). Hence, LandGEM may not be appropriate for countries with considerably diverse climates or a different mix of waste types. Besides, 50 percent of wastes in the unindustrialized countries are from food wastes which happen to decay much rapidly than other organic materials in the wastes. Immediately, when the landfill closes and disposal terminates the mean decay rate declines rapidly, leading to very low Methane generation rates within a few years. Due to all of this LandGEM have a tendency to over-predict Methane emission at closed sites. This type of shortfall becomes obvious in wet climates with huge quantities of waste decay rates (Stege *et al*., 2010).

c.The GasSim Model

The GasSim model was developed by Golder Associates for the Environment Agency of England and Wales as a risk valuation tool to be used to appraise the influence of Methane (Oonk, 2010). This model quantifies Methane emissions, the effects of utilization of Methane on local air quality, and Methane migration via subsoil to adjacent buildings (Oonk, 2010). The model uses two approaches to compute Methane emissions from landfill sites, by using a multi-phase equation (described by Van Zanten and Scheepers, 1994) and applying the LandGEM model, which is similar to the USEPA model (Gregory *et al*., 2003). GasSim is based on United Kingdom waste statistics and starts from hemicelluloses and cellulose content in the various waste fractions. For each waste fraction a DOC_f is assumed, based on research by North Carolina State University (Gregory, 2010). The basic equation for this model is:

$$Ct=Co-(C0.1e-k1t+C0.2e-k2t+C0.3e-k3t)$$

Where:

t= time between waste emplacement and LFG generation (years)

Ct=mass of degradable carbon degraded up to time t (tons)

Co= mass of degradable carbon at time t=0 (tons)

Co, n= mass of degradable carbon at time t=0 in each fraction (n=1,2 and 3i.e. rapidly, moderately and slowly degradable fractions respectively) (tons)

kn= degradation rate constant for each fraction (n=1,2 and 3) of degradable carbon (per year)

$Cx=Ct-Ct-1$

Cx= mass of carbon degraded in year x (tons).

Further, the equation based upon a multi-phase model described by Van Zantenen and Scheepers (1994) is presented as follows:

$\alpha t=ς c\Sigma\Sigma Ajni=1mj=0kiCo, i, -ki(t-j)$ (Jacobs *et al.*, 2010)

Where:

αt= landfill gas production at a given time (m^3 LFG.y-1)

ς= formation factor (-)

c=conversion factor (m3LFG.kgOMdegrade-1)

m= number of years of landfilling (-)

j= year of landfilling amount Aj (y)

n= number of fractions I (-)

i= waste fraction with degradation rate ki (kgi. kgwaste-1) (Jacobs *et al.*, 2010).

i.The Limitations of GasSim

GasSim was primarily created for the United Kingdom Environmental Agency. This demonstrates that it might have limitations when trying to estimate the Methane emissions from other parts of the globe besides the United Kingdom. Though, it is made to be conceptual by considering landfills individually with their own engineering and waste composition. Similarly, the model is a predictive tool and should not be relied upon for an exact landfill Methane generation (Jones, 2015). The model is complicated because it does not provide a complete set of equations (Scharff and Jacobs, 2006). In addition, calculation modules within the program are protected from sharing which makes it difficult to be used without purchasing the software. At present, the Methane generated is based on the United Kingdom waste statistics. The principal input for this model is the amount of waste in mega grams, with the specific breakdown of the waste into different categories and carbon content (Scharff and Jacobs, 2006). Hence, decomposable organic carbon is divided into three separate waste fractions and those that are rapidly degrading (garden wastes), moderately degrading (nappies) and slowly degrading (newspapers) with a different degradation rate constant for each fraction which is then aggregated (Gregory, 2010).

d. The Triangular Model

This model was developed by Tchobanoglous *et al.* (1993). In the model, the Methane emissions are presented in a triangular form with the area of the triangle being equivalent to the total amount of gas computed by means of the IPCC Default model, and the shape of the triangle presents the Methane emission production over time (Kumar *et al*., 2004). Nevertheless, based on the First Order Decay, the Triangular method is modelling time-dependent generation of Methane. In the model, the organic matters in the landfill site are divided into two types:

materials that decay quickly (from 3 months to 5 years) and materials that degrade slowly (up to 25 years). Quickly decompose materials are food waste and garden and park waste (leaves and grass trimmings), paper and cardboard that are decomposed in a few days after being buried in a solid waste disposal site and may take up to five years to complete decomposition. Textile, leather, rubber, and wood are the slowly biodegradable organics, beginning the decomposition about five years after being placed in the landfill/solid waste disposal site and may last up to 50 years to complete (Tchobanoglous *et al.*, 1993). The first part of the triangle is due to phase I, II and III and the second part of the triangle consists of phase IV and V of Methane generation process (Tchobanoglous *et al.*, 1993; Velinni, 2007). The volume of Methane produced for the triangular function takes the following form: (Chaudhary *et al.*, 2014)

$Lo=1/2\times tf\times Qsp \rightarrow Qsp=2Lotf$

Where:

Qsp=specific peak rate of Methane generation, in volume per mass-time

tf = time to complete degradation

The assumption is that the production of Methane starts at the end of the first complete year of the landfill operation. The total quantity of Methane produced can be determined from the following equation straight away from the municipal solid waste (Chaudhary *et al.*, 2014). Total Methane produced (m^3 kg^{-1}) =1/2(years of gas production) × (peak biogas production rate (m^3 $kg^{-1}yr^{-1}$)).

i.The Limitations of Triangular Model

The limitation factor to this model is the moisture content. Usually, the moisture content at the landfill site is inadequate. Hence, it is not capable to perform complete conversion of biodegradable organic materials into municipal solid waste. The moisture content which outfits

the conversion of biodegradable organic portion is in between 50% to 60% (Chalvatzak *et al*., 2010). The Methane production curve becomes more linear and stretching to longer time periods, is due to the uneven distribution of moisture (Chalvatzak *et al.*, 2010).

Likewise, due to a lack of detailed data on percentages of slow and rapid biodegradable organics in the solid waste stream, and hence, K and Lo for each type being unknown, the organic waste was presumed as slowly biodegradable organics. It is assumed that the waste needs 25 years for complete decomposition (Tchobanoglous *et al.,* 1993; USEPA, 1996) and the peak gas production would occur after 5 years of solid waste placement in the landfill.

2.2.6 The Climate Models

These are mathematical illustrations of the climate system, conveyed as computer codes and run on great computers. One basis of assurance in climate models derives from the fact that model basics are based on reputable physical laws for instance, conservation of mass, energy and momentum, along with a wealth of observations (IPCC, 2014). Models display substantial and increasing skill in signifying many significant mean climate features, such as the large-scale spreading of atmospheric Temperature, precipitation, radiation and wind, and of oceanic Temperatures, currents and sea ice cover (Jucker and Gerber, 2017)

These models originate in diverse forms that is, from those that just cover one specific area of the world or part of the climate system, to those that simulate the atmosphere, oceans, ice and land for the entire planet. The output from these models drives forward climate science, assisting scientists appreciate how human activity is influencing the climate of the Earth (Stocker *et al.*, 2013) In many ways, climate modelling is just an extension of weather predicting, but concentrating on changes over decades rather than hours. The greatest talked-about models of

recent years have been those connecting Temperature to emissions of Methane gas. These models project a rising trend in the surface Temperature record, as well as a more rapid increase in Temperature at upper altitudes (IPCC, 2014).

Types of Climate Models

i. Energy Balance Models

These are the earliest and most basic mathematical climate models. The modest Energy Balance Models do not simulate the climate, but rather consider the balance between the energy entering the atmosphere of the Earth from the sun and the heat released back out to space. The only climate variable they compute is the Temperature of the surface. (IPCC, 2014). These Models only need a limited line of code and can be run in a spreadsheet and they are one-dimensional in the direction of only the latitude of the Earth. They are therefore not a worldwide model but are regional or latitudinal models. This indicates that the movement of energy is considered from one latitude to the next and not at other smaller locations across the globe. The benefit of these models is that they can compute the energy of the Earth in detail (Allen *et al*., 2016).

ii. Radiative Convective Models

These are next to Energy Balance Models, which simulate the transfer of energy through the height of the atmosphere – for instance, by convection as warm air rises to the atmosphere. Radiative Convective Models can compute the Temperature and humidity of different strata of the atmosphere (Allen *et al.,* 2016). These models are characteristically one-dimensional – only considering energy conveyance up through the atmosphere – but they can also be two-dimensional. The radiative-convective models have benefits over the Energy Balance Models,

that is, they can determine the impacts of varying Greenhouse gases concentrations on actual emissivity and consequently the surface Temperature (IPCC, 2007).

iii.General Circulation Models

These models are likewise called Global Climate Models, which simulate the physics of the climate itself. This means they capture the movements of air and water in the atmosphere and/or the oceans, as well as the transfer of heat, but they did this in three dimensions, integrating many kilometers summit above sea level or depth of the oceans in dozens of model layers (Rummukainen, 2010). Their main purpose is to recognize the dynamics of the physical constituents of the climate system such as atmosphere, ocean, land and sea ice, and for making predictions based on future Greenhouse gas. The Global Climate Models continue to be widely used, and are specifically run at higher resolution for seasonal to decadal climate prediction applications in which biogeochemical (the transfer of chemicals between living things and their environment – and how they interact with the climate system) responses are not critical (Brown *et al.*, 2017).

Over time, scientists have progressively added in other phases of the Earth system to Global Climate Models. These would have once been simulated in separate models, such as land hydrology, sea ice and land ice (Flato, 2011). These "Earth System Models" can simulate the carbon cycle, Nitrogen cycle, atmospheric chemistry, ocean ecology and changes in vegetation and land use, which all upset how the climate reacts to human-caused Greenhouse gas emissions (most especially Methane gas). They have vegetation that responds to Temperature and rainfall and, in turn, changes uptake and discharge of carbon and other Greenhouse gases to the atmosphere (IPCC, 2014).

iv.Regional Climate Models

The Regional Climate Models do a related work as Global Climate Models, but for a narrow area of the Earth. Because they cover a minor area, Regional Climate Models can commonly be run more rapidly and at a greater resolution than Global Climate Models (Laprise, 2008). A model with a high resolution has lesser grid cells and as a result can yield climate information in higher detail for a precise zone (Rummukainen, 2010).

v. Earth Models of Intermediate Complexity

Earth Models of Intermediate Complexity endeavor to include appropriate constituents of the Earth system, but frequently in a perfect manner. When associated with other types of models, these models can forecast climate over longer time scales of several 10,000 years or glacial years (Claussen *et al.*, 2002). They are three-dimensional in that they denote physical processes in three dimensions, including the atmosphere, oceans, land, and the cryosphere, or sea ice and glaciers on land (Petoukhov *et al.*, 2005).

2.3 Literature Review

2.3.1 Meteorological Variables Affecting the Surface Methane emission

The importance of the meteorological variables affecting the surface emission of Methane from landfills have been perceived on site by a number of studies (Christophersen *et al.*, 2001; Galle *et al.*, 2001; Czepiel *et al*., 2003; Wang *et al*., 2012) as follows.

i.Atmospheric Pressure

Disparities in the meteorological variables, and in particular the atmospheric Pressure, has influence on amount of Methane emissions from the surface of landfill (Poulsen *et al.*, 2003; Scharff *et al.*, 2003; Gebert and Groengroeft, 2006). Higher emission rates at landfills are reported to occur at lower ambient Pressures (Scharff *et al.*, 2003; Gebert and Groengroeft, 2006). Universally, discrepancies in atmospheric Pressure occur due to a number of issues. (i) auto oscillation of air (reported to have an inconsequential consequence), (ii) daily warming and cooling of air triggered by solarization (triggering diurnal variations), and (iii) passage of atmospheric Pressure lows and highs (leading to long term variations). Consequently, short term (everyday) and long term (seasonal) differences in atmospheric Pressure should be taken into account when conducting Methane emission monitoring at a landfill site (Poulsen *et al.*, 2003).

ii.Rainfall

A number of studies (Rees, 1980; Hartz and Ham, 1983; Edward *et al.*, 1995; Reinhart and Al-Yousfi, 1996) have indicated that rainfall (moisture) is the leading factor in the rate of waste decomposition and Methane production in landfills/solid waste disposal sites (Wreford *et al.*, 2000). Sufficient rainfall in solid waste disposal sites is essential for optimum hydrolysis and decay of complex organic materials to occur (Baldwin *et al.*, 1998). Furthermore, rainfall is a vital element for the biodegradation process in solid waste disposal sites as it serves as the means of conveyance for nutrients and bacteria within the landfills/solid waste disposal sites (Edward *et al.*, 1995). Therefore, increased rainfall solid waste disposal site improves the anaerobic degradation process within the solid waste disposal site (Barlaz *et al.*, 1997). Likewise, the exothermic anaerobic degradation process rises the Temperature of the solid waste disposal site, which further boosts the biodegradation process (Wang *et al.*, 2012).

Rowe (1998), in a comprehensive study disclosed that the rainfall within solid waste disposal sites deeper than 6 meter plays a major role in Temperature rise within the disposal site. Rees (1980) stated that optimum conditions for the generation of Methane emission at a landfill/solid waste disposal site occurs when the base of the solid waste disposal site is fully saturated and a waste density of 1 ton per m^3 is achieved. A different study by Hartz and Ham (1983) reported that even at levels as low as 10% on a wet weight basis, some Methane production occurs. Consequently, even at dry sites and with no additional rainfall added, some biodegradation is expected to occur. Similarly, Edward *et al.* (1995) reported that Methane production occurs even in very dry municipal solid waste disposal sites and, as the rainfall increases, so do the degradation process and Methane generation. Farquhar and Rovers (1973) reported that waste decomposition and Methane generation in municipal solid waste disposal sites slows down at field rainfall levels above 80 wet weight basis. According to Hartz and Ham (1983), this situation can only occur at landfills/ solid waste disposal sites located in wet climates with no leachate collection system, as they concluded that rainfall at solid waste disposal site occurs at approximately 40% wet weight basis. Edward *et al*. (1995) argued that even if the solid waste disposal site's rainfall exceeds field capacity, the mobility of nutrients and bacteria provided by the moving liquid will further increase the gas production.

Correspondingly, the effect of rainfall on the surface emissions of Methane at solid waste disposal site had opposing evidences. In a study at nine solid waste disposal sites in Thailand, it was found that Methane emissions during the rainy season were about five to six times higher in magnitude associated to winter and summer season (Wang Yao *et al*., 2010). Relatively, in a study conducted at the Sudokwon Landfill in South Korea, a different reasoning was given to the higher Methane emissions during the rainy season (Park and Shin, 2001). Due to much ground

water content during the rainy season, the surface pores at the solid waste disposal site are blocked. Thus, this accelerated the Methane flux through the remaining open pores. However, when it was a sunny day, Methane is easily released through many pores on the surface and eventually escapes to the atmosphere (Park and Shin, 2001). So, quantitatively more Methane is emitted through the surface during the hot/sunny days.

iii.Temperature

The Temperature in the solid waste disposal site plays an important role in determining the long-term potential of Methane production and emissions. Wang *et al.* (2012) concluded that high Temperature (30˚C to 40˚C) enhanced waste degradation and Methane production, thus, increasing the higher possibility of surface emissions of Methane. In an earlier study by Park and Shin (2001), they had examined the diurnal and seasonal variation of Methane from landfills. Results from the diurnal variation concluded that the surface Methane emission was scarce during the minimum Temperature of the day and rose to a peak when the Temperature was at a maximum. A significant peak of Methane was generally obtained during the hottest time of the day which is around 2pm (Park and Shin, 2001). Viewing the recorded of the seasonal variation, they précised that the Methane flux rate decreased from summer to winter.

The influence of Temperature on the Methane emission was studied by researchers in the past (Attal *et al.*, 1992; Townsend *et al.*, 1996; Einola *et al.*, 2007; James *et al.*, 2008; Yesiller *et al.*, 2008) and was mostly concentrated in Temperate areas like Alaska, British Columbia, Michigan, Finland and New Mexico and so on. On the other hand, Robinson (2007) found that the rapid transition from acetogenic to the methanogenic stage of the landfills in the warmer climates were two to three times faster than that of the landfills in temperate countries. Blakey *et al.*, (1997) had summarized that Temperature is an essential factor which affects the Methane emission.

Consequently, it is important for landfills to operate under optimum Temperature for faster Methane production and refuse stabilization (Wang *et al.*, 2012).

Since it is widely recognized that bacterial degradation is enhanced with increased Temperatures within the optimum range (Maly and Fadrus, 1971; Barlaz *et al.*, 1997; Baldwin *et al.*, 1998). Therefore, one of the most well-known equations in this regard is the van't Hoff-Arrhenius equation developed in 1884 defining the Temperature dependency of the bacterial degradation process (Metcalf and Eddy, 1991). Correspondingly, the Temperature of the waste mass is constantly testified to be a major parameter affecting the rate of waste decomposition in municipal solid waste disposal sites. Optimum Temperatures within the range of 30 to 65°C are reported for methanogenic activities, whereas, the thermophilic bacteria active in the upper end of this range are more effective in Methane generation (Edward *et al.*, 1995).

The relationship between Temperature and Methane generation was also formulated by Hartz *et al*. (1982). They concluded that the Methane generation rate was enhanced at Temperatures between 30° to 41°C. That study further indicated that the decay rate decreased when Temperature was decreased and that it tripled for each 10°C rise in the Temperature (Hartz, 1983). Other studies also identified a similar range up to 45 °C as the optimum Temperature range for gas production at landfills (Rees, 1980; Mata-Alvarez and Martinez-Viturtia, 1986).

There have been only a few full-scale studies conducted on the actual Temperature within landfills/solid waste disposal sites. Nevertheless, it is a well-known belief that solid waste disposal site Temperatures in central and deeper zones do not significantly fluctuate with ambient Temperature (Bingemer and Crutzen, 1987; Edward *et al.*, 1995; Maurice and Lagerkvist, 2003; Thompson and Tanapat, 2005). Anaerobic degradation is an exothermic

process, so bacterial activity continues to generate heat until optimum Temperatures are reached (Maurice and Lagerkvist, 2003). Additionally, Edward *et al.* (1995) reported that the Temperature in the top layers of a dry solid waste disposal site may be more affected by Temperature, while deeper zones (deeper than 15 m) are unaffected by air Temperature.

2.3.2 Factors Influencing Methane Production in Solid Waste Disposal Site

The amount of Methane produced at a precise site depend on the characteristics of the waste (for example, composition and age of the waste) and a number of environmental factors are designated below (Agamuthu, 2001).

i.Waste Composition

Methane is produced by the bacteria during putrefaction of organic matter inside solid waste disposal site/landfill; consequently, greater concentrations of organic matter will produce higher concentrations of Methane ((Christensen *et al*., 1996; Agency for Toxic Substances and Disease Registry, 2001). Other issues comprise the specific types of nutrients inside the solid waste disposal site, which can either encourage or prevent bacterial growth and decay rates of organic waste. Organic waste comprises of nutrients, such as calcium, sodium, magnesium, and potassium which promote bacterial growth, thereby increasing decomposition rates. Similarly, the waste composition will also affect the rate and amount of Methane gas produced. Easily degradable materials (for example vegetable matter) support rapid startup of microbial degradation processes, while less freely degradable matter, often with the highest degradable carbon content (for example newspapers), will support the long-term production of Methane. Generally, the organic waste present in municipal solid waste can be divided into three types. The first class includes those materials that will biodegrade rapidly (within 3 months - 5 years)

for example, food waste, leaves; and the second, one involves materials that will decompose slowly (from 5 to 50 years or more) for example, wood, card board, newspapers; and, lastly are those materials that do not degrade at all, for example, glass, metals, aluminum foil (Tchobanoglous *et al.*, 1993).

ii. Age of Waste

Normally, more newly buried waste (that is, waste buried less than 10 years) produces more Methane gas through bacterial decomposition, volatilization, and chemical reactions than does older waste (buried more than 10 years) (USEPA, 1995). Solid waste disposal site generally begins to produce significant quantities of Methane inside the first three years of active operation, and reaching peak emissions in 5 to 7 years (USEPA, 2008). The bulk of Methane produced will stop after 20 years of the final dumping of organic waste, nonetheless, some solid waste disposal site will continue to emit Methane in small amounts for up to 50 or more years after a solid waste disposal site is closed (USEPA 1999; Agency for Toxic Substances and Disease Registry, 2001; Ubavin, 2008). Different parts of a solid waste disposal site might be at different stages of decomposition of waste at the same time, depending on when the waste was originally placed in each area. The amount of organic material in the waste is a substantial factor on how long Methane production lasts (World bank, 2005).

iii.Existence of Oxygen in the Solid Waste Disposal Site

Oxygen is considered as hindering for the formation of Methane. Deficiency of Oxygen is significant for the anaerobic bacteria to grow and change solid carbon to Methane and Carbon dioxide. In other words, Methane will be produced only when Oxygen is no longer present in the solid waste disposal site/landfill (Christensen *et al.,* 1996). The more Oxygen present in a solid

waste disposal site, the longer aerobic bacteria can putrefy waste in stage I (Agency for Toxic Substances and Disease Registry, 2001). If waste is lightly buried or regularly upset, additional Oxygen is obtainable, so that the bacteria that depends on Oxygen live longer and produce Carbon dioxide and water for longer periods. Conversely, when waste is extremely compressed, the aerobic bacteria will rapidly consume all of the available Oxygen and die, allowing anaerobic bacteria to take root and rapidly move into stage II decomposition, which is the start of Methane generation. At any time, Oxygen is reintroduced into the area, the current stage will return back to stage I until all Oxygen is depleted (Barlaz, 1989).

iv.Moisture Content

The moisture content of waste in a solid waste disposal site/landfill can be increased by rainfall, surface and groundwater penetration and products of waste breakdown. The presence of moisture in a solid waste disposal site limits Oxygen transport and rises Methane generation because it boosts bacterial putrefaction and transports nutrients and bacteria to all areas within a solid waste disposal site (Christensen *et al.*, 1996). Nevertheless, saturated moisture content obstructs Methane generation (Rees, 1980; Christensen *et al.*, 1996). Methane producing bacteria attain maximum production rate when the moisture content of a waste area is 40%, based on wet weight of waste (Agency for Toxic Substances and Disease Registry, 2001). Although waste compaction is necessary for depriving the area of Oxygen for Methane production, too much waste compaction slows Methane production because it increases the density of the solid waste disposal site contents, decreasing the rate at which water can penetrate the waste (Christensen *et al.,* 1996).

v. Waste Temperature

Like a lot of other bacterial processes, Methane formation is greatly affected by Temperature. The growth of bacteria rises in warmer Temperatures, thereby increasing Methane production, while low Temperatures constrain bacterial action, so that the bacterial activity descents considerably below 10ºC (Kim, 2006). The optimum Temperature for Methane production happens between 25˚C to 45˚C, which is common in deep solid waste disposal site (Agency for Toxic Substances and Disease Registry, 2001). In shallow solid waste disposal site, consequently, seasonal Temperature disparities may affect the production of Methane. At higher Temperatures, the Methane production is more energetic and produces more warmness, and as such is self-enhancing (Christensen *et al*., 1996). Solid waste disposal site will increase in Temperature as bacterial putrefaction happens, with Temperatures ranging between 21ºC and 43ºC on average during stage IV decay (Kim, 2006). Higher Temperatures create favorable conditions for volatilization and chemical reactions (Wang *et al*., 2012).

vi.Potential of Hydrogen (pH) Within Solid Waste Disposal Site

Methanogenesis (Methane generation) will go on optimally between a pH range of 6 to 8 and is only reserved when the pH value is outside this range (Abushamamala *et al.*, 2009). If the methanogens are stressed by other factors, their transformation of Hydrogen and acetic acids declines, leading to a buildup of volatile organic acids and a reduction in pH, which furthermore may hinder the Methane formation and lead to a further decrease in pH (Christensen *et al.*, 1996). Ultimately, the Methane generation may stop.

2.3.3 Effects of Methane Emissions

a. Health Effects

Methane emissions have produced numerous human health effects. It is a Greenhouse gas as well as initiator to Tropospheric Ozone. As a Greenhouse gas, it is involved in the basket of emissions under the Kyoto protocol and in the same way in the 2015 Paris Agreement. In other words, as originator to Tropospheric Ozone, it is the most abundant anthropogenic volatile organic compound contributing to Tropospheric Ozone formation (Bingemer and Crutzen, 1987; Fiore *et al.*, 2006). However, the rise in atmospheric Methane has contributed about half of the estimated increase in global Tropospheric Ozone levels since pre-industrial periods (Ehhalt and Prather, 2001; Ramaswamy *et al.*, 2001; Dentener *et al.*, 2005), which has a negative impact on the health of living organisms (Malley *et al*., 2017). Tropospheric Ozone is a serious air polluter and breathing even small quantities of this gas is associated with the harm of pulmonary and asthma attacks (Peden, 2001). Likewise, landfills all over the world release millions of metric tons of Methane into the atmosphere on a yearly basis. When Methane is released, so many other hazardous gases and chemicals are released as well, notable among them include Benzene and Volatile Organic Compounds. Volatile Organic Compounds are known to be dangerous air pollutants (Ridlington and Madsen, 2017). Benzene is identified as human carcinogen (American Cancer Society, 2017). Ethylbenzene a likely carcinogen (Agency for Toxic Substances and Disease Registry, 2011). Toluene also a neurotoxin (distressing the nervous system) that may cause miscarriages and birth defects. Furthermore, Volatile Organic Compounds are precursors to the creation of Ground-level Ozone, a hazardous air pollutant that causes everlasting harm to lung. Children are at the highest health risk from the pollution of Ground-evel Ozone (American Academy of Allergy, Asthma, and Immunology, 2017).

The key issues to Methane emission hazards are its flammability, possible explosion and the possibility of asphyxiation. Asphyxiation can be produced by inhalation air with high

concentration of Methane, because the high concentration of Methane can lessen the Oxygen level lower that which is needed for life (Stonesypher, 2010). At low concentrations, inhalation of Methane can cause nausea, dizziness, headache, vomiting and loss of coordination. At very high concentrations it may cause coma and death (Health Protection Agency, (HPA) 2011).

A current World Health Organization report recommended that any possible exposure is likely to be restricted to 1 km from landfill sites by the air pathway (WHO, 2000). For instance, at the Dompoase Landfill in the KMA of Ghana, it was discovered that there is increased occurrence of self-reported health symptoms such as nausea, fatigue, sleepiness, respiratory problems and headaches among residents near the landfill site were constantly reported (Owusu-Sekyere *et al.*, 2013).

Although Methane explosions are by no means common occurrences, a number of incidents known or suspected to have been caused by Methane originating from landfill sites have been documented in the literature (Gendebien *et al.*, 1992; Christensen, *et al.,* 1996; Agency for Toxic Substances and Disease Registry, 2001), which include the following:

i. 1999: An 8-year-old girl was burned on her arms and legs when playing in an Atlanta playground. The area was reportedly used as an illegal dumping ground many years ago. (Atlanta Journal-Constitution, 1999);
ii. 1994: While playing soccer in a park built over an old landfill in Charlotte, North Carolina, a woman was seriously burned by a Methane explosion. (Charlotte Observer, 1994);
iii. 1987: Off-site gas migration is suspected to have caused a house to explode in Pittsburgh, Pennsylvania (USEPA 1991);

iv. 1984: Methane gas migrated to and destroyed one house near a landfill in Akron, Ohio.

Ten houses were temporarily evacuated. (USEPA 1991);

v. 1983: An explosion destroyed a residence across the street from a landfill in Cincinnati, Ohio. Minor injuries were reported. (USEPA 1991);

vi. 1975: In Sheridan, Colorado, landfill gas accumulated in a storm drain pipe that ran through a landfill. An explosion occurred when several children playing in the pipe lit a candle, resulting in serious injury all the children (United States Army Corps of Engineers (USACE), 1984);

vii. 1969: Methane gas migrated from an adjacent landfill into the basement of an armory in Winston-Salem, North Carolina. A lit cigarette caused the gas to explode, killing three men and seriously injuring five others. (USACE, 1984).

viii. 1986: Methane gas explosion incidents were reported at Loscoe village in England and Skellingsted Landfill in Denmark due to Methane gas migration (Christophersen *et al*., 2001).

b. Environmental Impacts

Methane is a gas of environmental concern mainly due to its strength as a Greenhouse gas with a high Global warming potential (Park and Shin, 2001). In spite of its relatively low atmospheric concentration compared to Carbon dioxide (currently 1.75 parts per million (ppm) as opposed to 358 ppm), the higher infrared absorption potential of Methane makes its Global warming potential some 34 times higher than that of Carbon dioxide (mole for mole) (IPCC, 2013). Therefore, the most significant environmental problem associated with Methane emissions is its contribution to the increase of Global Greenhouse gas in the atmosphere which is mainly due to

the presence of large number of landfills/solid waste disposal sites globally (El- Fadel *et al.*, 1997).

The Methane molecules do not hinder with the incoming solar radiation, but they will catch part of the energy in the infrared radiation emitted from the earth's surface. As the concentration of Methane increases in the atmosphere, a larger part of the reflected radiation is caught and the Temperature in the atmosphere also increases. The increase in mean Temperature contributes to long lasting changes in the earth's climate, such as rising air and ocean Temperatures, changes in precipitation patterns, melting and thawing of global glaciers and ice, sea level rise as ice sheets of Greenland and Antarctic melts and the water thermally expands, and severe weather events could be expected even with small changes in the climate (IPCC, 2007; USEPA, 2017).

In the late 1980s, the world started to recognize several global air pollution problems that induce transboundary environmental hazards and negatively affect other areas far away from the origin of the air pollution source. Examples that fall under this category are global warming, acid rain, and destruction of the Ozone layer by chlorofluorocarbons (IPCC, 2007). Among these examples, Global warming is gaining more and more interest and has been the focus of discussion among scientists. Global warming is caused mainly due to the increase in Greenhouse gases concentration in the atmosphere.

Global warming disrupts thousands of lives in the forms of destructive of weather patterns, severe hurricane, melting of ice, availability of soil water, forest fires, soil erosion, drought, prevalent infection of diseases and pest and consequently leads to the loss of habitat and livelihoods (Mintzer, 1993; Adejuwon, 2004). These environmental problems result to low and unpredicted crop yields, which invariably makes farmer more vulnerable, especially in Africa.

2.3.5 Quantification/Monitoring of Methane Emission from Municipal Landfills

Different models/methods have been employed to quantify and monitor the levels of Methane emissions by a number of studies from various landfills/solid waste disposal sites globally. However, some of these studies include the following.

Kumar *et al.* (2004) estimates Methane emissions from municipal solid waste landfills for the year 1980 to 1999 by means of Triangular Model in India. The results of the study indicated that the national level of Methane emission from solid waste disposal sites using the triangular model varied from 119.01Gg in year 1980 to 400.66 Gg in year 1999. Nevertheless, there are certain restrictions in the inventory estimation of Methane emission estimated for the years 1980–1999 in India. The inventory estimation has been made mostly on the basis of published documents and a little on the data generated.

Kurtulus *et al*. (2006) determines the seasonal variations of Methane gas in Istanbul Kemerburgaz-Odayeri solid waste landfill. In Istanbul, the largest city in Turkey, a huge amount of solid waste is produced by the population. The putrefaction of these wastes discarded lead to the development of Methane emission. In the study, Methane emissions produced in Istanbul Kemerburgaz- Odayeri solid waste landfill were examined. However, measurements of Methane were made for one year, including the monitoring of all seasonal variations at the Kemerburgaz-Odayeri solid waste landfill. In these measurements, it was determined that Methane diversed from 0.2 to 60%. Also, 37.5% of measurements disclosed that Methane was within concentrations of 5-15% concentration, which means that the concentrations were explosive,

whereas 46.25% showed flammable limits (concentrations >15%). The average concentrations of Methane were found to be 17.66%.

Qdais *et al.* (2010) assessed the volume of Methane emanated from Al Akeeder landfill which is the second major landfill in Jordan, by means of Gas-Sim model. The results of the study revealed that Methane emissions will reach its highest value of 12 Million M^3 /year by the year 2021, one year after the landfill closure. In addition, the quantity of Methane gas emission reduction will be about 80 thousand tons of Carbon dioxide equivalent in that year.

Rahman *et al.* (2010) studied solid waste management and its impact on climate change in Dhaka city, Bangladesh, using IPCC default methodology. The results of the study pointed out that there were about 26.89 Giga gram Methane emitted from municipal solid waste of Dhaka city in 2010. It was also found from the Methane emission calculation on the basis of IPCC default methodology that there were 16.96 Giga gram and 20.50 Giga gram Methane emitted from the municipal landfill site in Dhaka city in 2001 and 2005 respectively.

Nava-Martinez *et al.* (2011) determined the surface Methane emission in a former dumpsite in Tijuana, Mexico. One of the pollution concerns at dumpsites is the emission of Methane, which has been identified as a Greenhouse gas. For the purpose of determining the surface emission of Methane in an informal settlement built on a former dumpsite, six sampling events were conducted using the Closed Chamber Method. The results of the study revealed that Methane emission is emitted from the former dumpsite and that this emission is high with a maximum average value of 2441.81 g/m^2 /h. This surface emission is four orders of magnitude greater than in other studies. Conversely, the total mass of Methane emitted is 177 and 3.5 times lower than in other studies conducted in South Korea and India, correspondingly, and approximately 300 times higher than studies conducted in Taiwan and Japan. A high inconsistency in the measured

emissions of Methane was observed; this inconsistency may be the result of continuous changes in soil conditions due mainly to the urban and social characteristics of the study site.

Ibrahim (2012) assessed the environmental and health risk assessment of Rafah landfill. Rafah landfill is situated in the eastern part of Rafah with a distance of 400 meters from the nearest residential area, approximately 5 km northeast of the former Gaza Airport and 800 meters from the occupied Palestine border wall. The landfill covered approximately an area of 33,000 m^2. Gas-Sim model was used to quantify Methane emissions from the landfill. The results of the study indicated that the global warming potential analysis revealed that Rafah landfill would have a potential of 31638 tons of Carbon dioxide equivalent of Methane emissions in the year 2012.

Kalantarifard and Yang (2012) studied Methane production by landfill gas emissions model from Tanjung Langsat municipal solid waste landfill, Malaysia. The landfill started operation in 2002 and it was expected to have lifespan of 20 years, but due to industrialization and urbanization, it is anticipated that the landfill was reach its maximum capacity at the end of 2012. Nevertheless, the result obtained showed that the rate of Methane generation from municipal solid waste landfill was 4.436E+02 (Mg/year) in 2003, first year after waste acceptance by the landfill while the maximum Methane generation rate occurred during the years 2012 to 2015 which pointed out the highest generation by about 4.17 E+03 (Mg/year).

Kodwo (2013) estimated the Methane gas emissions from two of the largest uncontrolled disposal sites (Mallam No.1 and Oblogo No.) in the Greater Accra metropolis, Ghana, from 1991 to 2035 by means of LandGEM generation estimation tool. Nonetheless, the model predicted the time of peak production as occurring in 2002 and 2008 for the Mallam No.1 and Oblogo No.1 disposal sites respectively. The total combined highest annual Methane production from the

Oblogo No.1 and Mallam No.1 disposal sites within the study time frame were estimated to be in excess of 17,000 metric tons.

Li *et al.* (2013) quantified Methane emissions using Eddy Covariance Method at the Turkey Run Landfill, Northern Meriwether County, Georgia. The landfill accepts only municipal solid waste, which includes non-hazardous household, commercial and industrial waste and construction and demolition debris. However, the results of the study revealed that the mean Methane fluxes are 5.39 μmol m^{-2} s^{-1}.

Daura *et al. (*2014) estimated Methane gas emission from four municipal solid waste disposal sites in Kano metropolis, Nigeria. The amount of Methane gas emissions from the four disposal sites from the year 2012- 2040 were projected by means of LandGEM. The maximum Methane emission from Court road disposal site is 4.655E+05 m^3/year which would be generated in the year 2016 and would drop to 1.786E+05 m^3/year by the year 2040. The maximum Methane emission from Hajj Camp disposal site is 2.995E+05 m^3/year which is estimated to be generated in the year 2018 and would drop to 1.215E+05 m^3/year by the year 2040. The maximum Methane emission from Maimalari disposal site is 4.197E+05 m^3/year which would be generated in the year 2024 and would decline to 2.206E+05 m^3/year in 2040, whereas for Ubagama disposal site the maximum emission is 6.014E+04 m^3/year which would be generated in the year 2040 and the minimum is 3.053E+04 m^3/year in the year 2012.

Akintayo and Olonisakin (2014) assessed Methane generation potential of municipal solid waste in Ibadan metropolis, Nigeria. Energy potential from municipal solid waste of two landfills serving four local government areas in Ibadan metropolis was estimated in the study. The characterization of the municipal solid waste indicated that about 74% was made up of organic materials with food wastes comprising the maximum percentage (35%). The Methane potential

of the municipal solid waste between 2012 and 2020 was valued to be 27,517 tons by means of IPCC methodology.

Hoklis and Sharp (2014) assessed Methane emission from municipal solid waste in Phnom Penh, Cambodia. In the actual condition, all the municipal solid wastes were discarded into landfill without any gases captured for electricity generation in Phnom Penh. Methane emission in this study was calculated based on the IPCC default methodology from municipal solid waste in Phnom Penh in 2009. The result of this study displays that the Methane emissions were 338.51 Gg (Carbon dioxide equivalent). Consequently, waste materials will be reused by separation of waste at landfill, and composting of organic wastes at landfill as well. The result from these scenarios revealed that Methane emission can be reduced by 5.95% for the first scenario and 27.98% for second scenario.

Ghasemzade (2015) estimateed Methane emission in municipal solid waste landfill of Rasht city, Iran, by means of LandGEM Simulation Model. The landfill of Rasht city began operation at 2014 with the purpose to accept the generated municipal solid waste of the surrounded area. The amount of Methane generation in first year was 9.514283 Mega gram/year and it was the highest gas generation.

Abdu (2016) estimated Methane gas emission from four (Court Road, Hajj Camp, Maimalari, and Ubagama) municipal solid waste disposal sites in Kano metropolis, Nigeria. The quantity of Methane gas emissions from the four municipal solid waste disposal sites from the year 2012 to 2040 were estimated by means of landfill gas emission model (LandGEM). The results of the study indicated that the maximum Methane emission from Court road disposal site was 4.655E+05 m3/year which would be produced in the year 2016 and would drop to 1.786E+05 m3/year by the year 2040. Also, the maximum Methane emission from Hajj Camp disposal site

was 2.995E+05 m3/year which is anticipated to be produced in the year 2018 and would decline to 1.215E+05 m3/year by the year 2040. The maximum Methane emission from Maimalari dumpsite is 4.197E+05 m^3/year which would be produced in the year 2024 and would drop to 2.206E+05 m^3/year in 2040, while for Ubagama solid waste disposal site, the maximum emission is 6.014E+04 m3/year which would be produced in the year 2040 and the minimum is 3.053E+04 m^3/year in the year 2012.

Abualqumboz *et al.* (2016) quantified the total likely emissions, as well as the variation in production with time of Methane from a planned El Fukhary landfill in the Gaza Strip, Palestine by means of Triangular model. The results found from the study indicated that for 25 years of placing municipal solid waste, El Fukhary landfill projected to have possible Methane emissions of 109 m^3. Triangular model showed that the greatest production in term of Methane would occur in 2043; 28 years beyond the open year. Furthermore, the model shows that 50 % of the gas will be produced approximately at the middle of the total duration of gas production.

Wajeeha *et al*. (2016) quantified Methane emissions inventory from municipal solid waste disposal sites in Oman over the years 1971 to 2030 by means of IPCC default methodology. The results of the study indicated that the total Methane emitted from municipal solid waste disposal sites in Oman in the year 1971 were 141.6 Gg/yr., which enormously increased to 1464.4 Gg/yr. by the year 2010 and is estimated to increase by 3089.1 Gg/yr. in the year 2030.

Ghasemzade and Pazoki (2017) evaluated and modeled Methane gas emissions in municipal landfills of Jiroft city, Iran. Using LandGEM model, which was based on first-rate equation analysis; the study predicted the amount and type of Methane gas, production for 30 years (from 2016 to 2045) in Jiroft. The results of the study indicated that in 2045, 3, 324, 274 tons of waste

will be disposed in municipal landfills of Jiroft and the total amount of produced Methane gas will be 587,549,454 tons/year.

Nguyen (2017) assessed Methane emissions from municipal solid waste landfill of Nam Son Landfill, Hanoi, Vietnam. Potential for Methane emissions and the disparity in generation of Methane with time for emission inventory in the Nam Son Landfill site in Hanoi, Vietnam was modelled by means of Triangular model. The study developed five scenarios (S0, S1, S2, S3, S4); wherein Scenario S0 was "business as usual" and four alternative scenarios designate options for the municipal solid waste management in Hanoi. These scenarios help to discover the probable Methane emission lessening from capturing gas with flaring (S1 – 70% of Methane captured with flaring), composting (S2 – 50% of organic waste composted), recycling (S3 – 30% of recyclable materials recycled). The integration of composting and recycling and gas capturing is central to S4. The results of the study indicated that Methane emissions are very high (201,986 mm3) for scenario S0.

Adjoumani *et al.* (2018) quantified Methane emission from Kossihouen sanitary landfill in Abidjan, Côte d'Ivoire. The emissions were measured based on the Methane generation constant K and the Methane generation potential Lo by means of LandGEM 3.02 model for Kossihouen sanitary landfill, Cote d'Ivoire. The landfill started operation in 2018 with the purpose to accept the generated solid waste in Abidjan until the year 2025. The maximum Methane generation rate would occur during the years 2025 to 2028. The results displayed that the quantity of Methane emissions was 7.97E+07 and 6.18E+07 (m3/year) respectively.

Hosseini *et al.* (2018) studied Methane emissions from a landfill positioned in Hamedan (west of Iran) from 2011 to 2030. The municipal solid wastes collected from five cities (Hamedan, Marianaj, Joraghan, Bahar, and Lalejin) were disposed in this landfill. LandGEM 3.02 model

was used to assess the Methane emission. The results displayed that organic and food wastes had the maximum amounts in the solid waste stream (over 75%). The results disclosed that $4.371\times108m^3$ Methane would be produced after 20 years, mostly ($4.053\times106m^3$) in the first year. Furthermore, Methane production capacity in Hamedan landfill site was 107 m^3/Mg. According to the results, the maximum and minimum Methane gas generation rates were in summer (the hottest season) and winter (the coldest season) respectively. The results of the LandGEM model signified that Methane generation rate will be substantial in the first 10 years. The potential of rapidly degradable organic compounds for Methane emission would be higher than that of slowly degradable organic compounds.

Rafiq *et al.* (2018) that determined Methane emissions from the Muhammad Wala open disposal site of Faisalabad, Pakistan. The site was built in 1992 and projected to have lifetime of 28 years. By means of LandGEM software, the Methane emissions were assessed with taking into consideration the 60% content of Methane, the Methane generation rate constant of 0.02125 $year^{-1}$, and Methane generation potential capacity constant of 23.25 m^3/Mg. The outcomes of the study indicated that the maximum volume of emitted Methane is at the next year after the site closure (2021). It was estimated that total volume of Methane was 2.257 × 10+08 m^3/year.

Yusuf *et al.* (2018) quantifies Methane emissions from municipal solid wastes of Johar State in Malaysia, by means of Triangular Model. The chemical composition of the organic constituents and probable amount of Methane gas that could be derived from the waste were determined. The triangular method was used to compute Methane accessible from hurriedly biodegradable waste over a 5-year period and for slowly biodegradable waste over a 15-year period. A plot was obtained for a landfill life span of 20 years. The volume of Methane for hurriedly biodegradable

waste was found to be 12.60 m^3 whereas those from slowly biodegradable waste was found to be 6.60 m^3 at standard Temperature and Pressure. For the initial deposit of 2002, the highest Methane emission rate occurred in 2007 at 0.2829 Gg/yr. with an average cumulative emission of 0.3142 Gg, while for a landfill closed after five years the highest Methane emission rate was in 2010 at 1.2804 Gg/yr with an average cumulative emission of 1.5679 Gg whereas this cumulative emission will start declining by the year 2029.

2.3.6 Variations of Methane Emission at Different Points Away from the Municipal Solid Waste Disposal Sites

A number of researches have been undertaken to assess the variations of Methane emission at different points away from the center of municipal landfills by means of monitoring equipment. Some of these studies include the following:

Ezikomwor and Obisesan (2014) studied Methane emissions in the surrounding area of Rumuolumeni landfill site, Port Harcourt, Nigeria, with a view to determining the possible influence of meteorological parameters on the concentration of Methane emissions from the landfill. Meteorological parameters examined include Temperature, relative humidity, wind speed, wind direction. These data were collected with respect to distance from the center of the dumpsite into the residential area at 200m intervals for seven days using composite sampling technique. Pearson Correlation Statistics was used to test significant influence of distance from the dumpsite on the concentrations of Methane emissions. The results of the study showed that Methane emissions were higher at the dumpsite than the residential area. The mean value of Methane at the dumpsite was 0.06 mg/m^3.

Ezekwe *et al*. (2016) measured source gas emissions and ambient air quality in and around the Eneka Landfill in Port Harcourt, Nigeria, using Portable Real-Time Monitoring Technique. Air

samples were automatically analyzed for Nitrogen, Carbon dioxide, Sulphur dioxide, low explosive limit (Methane), Volatile Organic Carbon, Ammonia and Particulate Matter (PM) content. Likewise, weather parameters were measured. Landfill gases particularly Volatile Organic Carbon, displayed high concentrations at the landfill site with 1300ppb concentration level. These concentrations declined with increasing distance from the landfill. Carbon dioxide, Ammonia, were also recognized over the landfill and in ambient air of the study area nevertheless not in concentrations that could cause any health concerns as specified by WHO and the USEPA. Particulate Matter values were highest for PM 0.3 and its mean concentrations far exceeded the standards set by World Health Organization and the USEPA. PM 5.0 values were highest at the landfill. Lastly, Methane emission in the landfill indicates no emission during the study period.

2.3.7 Diurnal and Seasonal Variability of the Levels of Methane Emissions at Solid Waste Disposal Sites

Numerous studies were conducted to examined the diurnal and seasonal variations of the levels of Methane emission at landfill sites using different measurement/monitoring equipment. Some of these studies include:

Niloufer *et al.* (2014) assessed Methane emissions from two municipal solid waste dumpsites in Vijayawada, Andhra Pradesh, India. A portable multi-gas analyzer of MODEL VEP 200 with RS 232 was used to monitor Methane emission in the two disposal sites of Vijayawada. Methane emissions were monitored for a period of three seasons i.e. winter (November 12 to February 13), summer (March 13 to June 13) and rainy (July 13 to October 13) a whole yearly round. However, Methane emission was recorded at both dumpsites, which were found within the acceptable limits of Indian Ministry of Environment.

Rees-White *et al.* (2018) estimated Methane emissions from a landfill in south-east, United Kingdom, during a six-day measurement campaign by means of the tracer method. The sensible weather conditions made it necessary to carry out measurements in the late afternoon and in the evening when the lower solar flux resulted in a firmer troposphere with a lower inversion layer. This caused a slower mixing of the gas, but allowed plume measurements up to 6700 m downwind from the landfill. The average Methane emission varied between 217±14 and 410±18 kg h^{-1} within the individual measurement days, but the measured emission rates were greater on the first three days (333±27, 371±42 and 410±18 kg h^{-1}) related to the last three days (217±14, 249±20 and 263±22 kg h^{-1}). It was not possible to completely separate the extent to which these disparities were a result of measuring objects, such as wind/measurement direction and measurement distance, or from a real change in the fleeting emission. Such emission change is known to occur with changes in the atmospheric Pressure. The higher emissions measured during the first three days of the campaign were measured during a period with an overall decrease in atmospheric Pressure (from approximately 1014 millibars on day 1 to 987 millibars on day 6). The lower emissions measured during the last three days of the campaign were carried out during a period with an initial Pressure increase followed by a period of slowly reducing Pressure. The average daily Methane recovery flow varied between 633 and 679 kg h^{-1} at standard Temperature and Pressure. The Methane emitted to the atmosphere accounted for approximately 31% of the total Methane generated.

William (2018) quantified Methane emission using mass balance approach in Keele Valley Landfill, Ontario, Canada. Emission of Methane from landfills in Canada are not well measured and in Ontario constitute the major point source emitters. However, the approach comprises measuring the downwind field of improvements at successively further distances from the source

until the integrated Methane enhancements congregate. An average emission rate of 429.199 kilo gram/hour of Methane was measured on several days.

Angaye *et al.* (2019) examined the spatial and temporal level of Methane emissions from six dumpsites by means of portable air quality meter (AEROQUAL-Series 300) in Yenagoa, metropolis, Nigeria. The results of the study indicated that the spatial level of Methane ranged from 1.00 - 6.44 parts per million. Based on temporal variation level of Methane ranged from 1.59–4.09 parts per million ($p<0.05$), with higher values in wet season. In the meantime, Methane emission was not discovered in the control station.

Chengliang *et al.* (2019) examined a temporal and spatial variation of Methane emissions from a limited controlled landfill site under a regular period for one year in China. The number and positions of static chambers were arranged according to the guidance on monitoring surface Methane emissions by the UK Environment Agency to obtain representative data from the heterogeneous surface of the landfill. Inverse distance weighting was applied to evaluate and visualize the Greenhouse gas emissions from the whole landfill surface based on the measurements of distributed static chambers. The results of the study revealed that Methane emission fluxes from the landfill area was 1324.73 ± 2005.17 mg C m^{-2} d^{-1}, Methane releases preferred to present spatial heterogeneity, while temporal heterogeneity was expected to exist in Methane emissions. The annual Methane emissions from the limited-controlled landfill was calculated to be 1.078 Gg Carbon dioxide-eq yr^{-1}, which was the least among all types of landfill sites.

Borjesson and Svensson (1997) studied the rates of Methane emission from a Swedish landfill, measured by chamber technique and permanent frames, ranged between 0.034 and 20 mmol Methane m^{-2}. h^{-1} on average. The emissions followed a seasonal form, with the maximum fluxes

happening between September and May. Methane concentrations in soil also followed a seasonal form, with a clear reduction during summers. With the means of Methane emission rates from frost-free periods, a stepwise regression model was made, that might explain 95% of the disparity. Soil Temperature turned out to be the controlling factor, explaining 85% when changed to a second-degree function. Methane emissions were negatively correlated with soil Temperature, which strongly suggests that biological Methane oxidation is a significant regulating factor. The activity of Methane-oxidizing microorganisms was highest around 0.5–0.6 m depth in the soil profile, and moisture at this level improved emissions. The propensity for Methane emissions to be greater at night was perhaps due to the inhibitory effect of low soil Temperatures on Methane-oxidizing microorganisms.

Maurice and Lagerkvist (2003) measured Methane emission at three landfills in Northern Sweden and Northern Finland. Numerous approaches for assessing Methane emission in winter conditions was verified. Static chamber seemed to be the most appropriate measurement method. The result of the study indicated that winter measurements should be done directly at the soil surface and that any snow cover should be detached beforehand. A seasonal variation of Methane emission was detected. Methane emission was measured during late winter at the three sites and during late summer at two of the same three sites. Monitoring implemented during the different seasons produces a better approximation of the annual Methane emission. Variations in Methane oxidation are probably the sources of any differences as low Temperature and low soil water content both reduce Methane oxidation activity. At low emission rates, the main Methane emission may occur during winter time because of the mitigation effect landfill cover has on Methane oxidation during summer time. A reduced Methane oxidation activity was observed during the late summer at two of the sites.

Fourie and Morris (2004) studied Methane emissions from four enormous landfills situated in the semi-arid climates of South Africa. A flux accumulation chamber technique was used and measurements were made at each site over a period of two to three days. The results of the study indicated higher emissions of Methane during the winter season compared to summer season. A common conclusion based on results from all four sites was that capping of landfills in semi-arid climates with low penetrability covers would perhaps considerably hinder the already low rate of waste degradation and thus Methane gas generation.

Wang-Yao *et al.* (2006) assessed the seasonal variation of landfill Methane emissions. Measurements for Methane emission were prepared at seven solid waste disposal sites, situated in central Thailand including three sanitary landfills, and four open disposal sites. The Methane emission measurements were done from September to November 2005 for wet season data and from January to February 2006 for dry season data. Emissions fluxes of Methane at each point were calculated in $g/m^2/d$. Nonetheless, 88.4% of sampling runs satisfied the $R^2 > 0.5$. From 188 closed flux chamber results in wet season, the spatial variability of the local emissions is rather high (fluctuating between 0 – 825.79 $g/m^2/d$) but the average spatial emissions fluctuated between 5.45 – 129.79 g/m^2 /d. The spatial variability of the local emissions in dry season is lesser than emissions in wet season (fluctuating between 0 – 686.93 g/m^2 /d) but the average spatial emissions fluctuated between 1.00 – 23.40 $g/m^2/d$ Consequently, the quantity of Methane emissions collected by extraction in wet season are much higher than dry season.

Jha *et al.* (2008) measured Methane emission from three municipal solid waste landfill areas of Delhi that is, Gazipur, Bhalswa and Okhla. The results of the study revealed that the range of Methane emission differs in winter from 12.94 to 58.41 Mg/m and in Summer from 82.69 -293

Mg/m^2 /h in these landfill areas. The paper has also revised the literature on Methane emission from India and the status of landfill areas in India.

Abushammala *et al.* (2015) studied Methane emissions and oxidation during the wet and dry seasons at two sanitary landfills and one open dumping landfill in Malaysia. The resulting levels of Methane emissions and oxidation were then modeled by means of the Inter-Governmental Panel on Climate Change 1996 default model to determine Methane generation rate and likely values. The probable value of Methane was 151.7 m^3 t^{-1} for the sanitary landfills and 75.9 m3 t^{-1} for the open dumping landfill respectively. The Methane generation rate value of the sanitary landfills during the wet season was 0.136 y^{-1}, whereas that during the dry season was 0.072 y^{-1}. The Methane generation rate values of the open dumping landfill during the wet and dry seasons were 0.008 and 0.0049 y^{-1}, correspondingly.

Abushammala *et al.* (2016) measured Methane emissions in a landfill in tropical environments in Malaysia to examine the seasonal differences in Methane emissions. The results of the study indicated that Methane emissions were fluctuated from 0 to 1,602 g m^{-2} d^{-1} during wet and dry seasons, respectively, hence, higher Methane emissions were found during the wet season than in the dry season.

2.3.8 Model Emission Results Versus Direct Monitoring Values at Municipal Landfills

Several studies were conducted by applying different theoretical models to estimate Methane emission generated in various landfill sites of the World. The results of these emissions were compared with direct monitoring values obtained by monitoring equipment. Some of the researches include the following:

Chiemchaisri *et al.* (2005) equated theoretical models (Intergovernmental Panel on Climate Change and Landfill Gas Emission Model proposed by United States Environmental Protection Agency) with the measurement results obtained from actual waste disposal sites by Close Chamber Method in the two solid waste disposal sites (Nakorn Prathom municipality landfill and Nonthaburi dumpsite) in Thailand. The sites have been working for about 5 and 10 years, which can be considered as the average operating period for sanitary landfills and open dumpsites in Thailand. The Methane emission rate from these sites was determined at 4 different locations during January 2002 to October 2002. From the information of waste generation rate and total disposed waste amounts at 142 waste disposal sites in Thailand, total Methane emission potential from these waste sources was assessed to be 138.9 Gg/year by IPCC method, largely greater than 94.7 Gg/year foretold by LandGEM of the USEPA. Temporarily, real measurement from representative landfill and open dumpsites by close chamber technique gave an average Methane emission rate of 23.95 and 1.98 g/m^2 respectively during the dry season. The emission rate was found to contrast extensively as a result of the differences in local climatic conditions, waste characteristics, waste disposal methods, the presence of cover soil and gas migration in the waste disposal site.

Chiemchaisri and Visvanathan (2008) compared Methane emission potential of the municipal solid waste disposal sites in Thailand. Open dumping and landfilling are the predominant solid waste disposal practices in Thailand. Methane emission potential at these sites was estimated by three methods (Intergovernmental Panel on Climate Change Default Method, Landfill Gas Emission Model, and Closed Flux Chamber Method). Results of the Intergovernmental Panel on Climate Change Method, Landfill Gas Emission Model, and Closed Flux Chamber Method were compared. The Methane emission potential of 366 Giga gram/year by means of the IPCC method

was higher than the estimations of the Landfill Gas Emission Model and Closed Flux Chamber Method of 115 Giga gram/year and 103 Giga gram/year, correspondingly. Nevertheless, huge difference in Methane emission rates within and between the sites was anticipated because it could be affected by waste characteristics, climatic condition, disposal methods, age of disposal site, and gas migration within and across the site boundaries.

Oonk and Boom (1994) conducted Methane gas emission measurements via a Mass-Balance Technique. The emissions of Methane were measured at about 20 Dutch landfills in the years 1993 and 1994. The Mass-Balance attested to be well appropriate for this purpose and the results of the measurement confirmed the accepted landfill gas formation model. Ratio in Methane emission suggest mean Methane oxidation in the top-layer to be about 30%, which is greater than the mean 10% oxidation used in national emission inventories.

Manju and Ramanathan (2011) assessed Methane flux from municipal solid waste landfill areas of Delhi, India. In the study, Methane emission inventory from landfills of Chennai has been generated by measuring the site specific emission factors in conjunction with important activity data as well as using the IPCC methodologies for Methane inventory preparation. In Chennai, emission flux ranged from 1.0 to 23.5mg Methane m (-2) h (-1), at Kodungaiyur and 0.9 to 433mg Methane/m (-2) h (-1), and at Perungudi. Methane emission estimates were found to be about 0.12Gg in Chennai from municipal solid waste management for the year 2000 which is lower than the value computed using IPCC, 1996 (IPCC, 1996. Report of the 12th session of the intergovernmental panel on climate change, Mexico City, 1996) methodologies.

Bhailall *et al.* (2016) compared the results of theoretical models (LandGEM, GasSim, IPCC Waste Model 2006 and the California Landfill Methane Inventory Model) with actual measured Methane yields by means of Close Chambers, at six municipal landfill sites of South Africa.

Conversely, the results of the study revealed that the theoretical models over estimate Methane emissions at the six disposal sites of South Africa. The theoretical models do not take into consideration site specific characteristics like; the effect of climatic conditions on emissions, the seasonal changeability of Methane oxidation rates in cover soils.

Siddiqui and Paranjpe (2016) estimates Methane emission from landfills site and open dumping in Jabalpur city. However, the study concentrated on the estimation of the carbon footprint of household waste produced in Jabalpur city. The results from two theoretical estimation methods, mass balance approach and default methodology, are compared with the measurement results derived from experimental values. Experiments revealed an emission of 0.013 g Methane/kg of organic fraction of municipal solid waste which is much lower compared to the Intergovernmental Panel on Climate Change method (0.036 kg Methane/kg of waste) or theoretical approaches (0.355 kg Methane/kg of waste).

García *et al*. (2017) related theoretical models for Methane estimations in order to determine reliability, accuracy and efficiency with actual data obtained in-situ in a Landfill Site in the State of Mexico, Mexico. The United States Environmental Protection Agency Model and the Mexican Model were chosen for this study. Both models are based on a first order equation for degradation of organic matter assuming that the Methane generation reaches its maximum after a period of time and then it declines exponentially whereas the organic fraction of waste is consumed. Measurement in-situ, by means of a landfill gas analyzer (GA5000), revealed lower Methane emissions than values assessed by theoretical models (United States Environmental Protection Agency Model and Mexican Model) (In-situ = 3355.99 m3/hour, USEPA Model = 4885.74 m3/hour, Mexican Model = 6780.56 m3/hour). The experiment verified substantial

dissimilarities in model estimations versus real measurements of Methane emissions from landfill site in the state of Mexico.

2.3.9 Influence of Temperature and Pressure on Methane Emission from Municipal Disposal Sites/Landfills

A number of studies were conducted to assess the influence of climatological variables (Temperature, Pressure) on Methane emission from municipal disposal sites/landfills using different monitoring equipment. Some of the studies include:

Visvanathan *et al*. (1999) examined Methane oxidizing capacity of landfill cover soils through column and batch experiments by simulating conditions that are typically come upon in tropical climates of Thailand. The rate of oxidation was examined at diverse Temperatures and moisture contents. It was detected that a low moisture content of 6% produced insignificant oxidation, while oxidation rates were at extreme at moisture contents between 15 and 20%. Temperature was found to be a leading factor which controlled the oxidation rates. The peak Temperature was between 30 and 36°C. In the column tests, the Temperature prejudiced the Methane oxidation capacity meanderingly by triggering the topsoil surface to become completely dry, causing nearly zero oxidation in spite of aerobic conditions. Although some increase in oxidation rate was observed, a higher concentration of Methane could not produce a corresponding increase in oxidation rates, indicating the restrictive capacity of the soil to oxidize Methane.

Chanton and Liptay (2000) assessed the seasonal variations in the oxidation of Methane during its transport across the soil cap of a landfill in Leon County, Florida. The study was determined in situ with a stable isotopic method. The methodology contrasted the δ13C values of emitted and anoxic zone Methane and applied quantities of the isotopic fractionation factor α, which diverse contrariwise with Temperature from 1.025 to 1.049. Anoxic zone Methane did not differ

seasonally and had a δ13C average value of −55.18 ± 0.15‰. Methane emitted from the landfill soil surface and captured in chambers ranged in δ13C from −54‰ in winter, when emission rates were high, to −40‰ in summer, when emission rates were lower. The opposed disparity between the δ13C of emitted Methane and the rate of Methane emission is reliable with control of the emission rate by bacterial oxidation. The clarification of the isotope data signposts that Methane oxidation consumed from 3 to 5% of the total flux in winter to a maximum of 43 ± 10% in summer. There was variation in the extent of Methane oxidation in soil types, with mulch/topsoil averaging 55 ± 14% and clay averaging 33 ± 13% in summer. The seasonally unified value for Methane oxidation for areas of the landfill covered with mulch/topsoil was 26 ± 4% of the flux toward the soil surface, whereas for clay soil it was only 14 ± 2%. The general annual average, which includes both types of soil, was 20 ± 3%.

Park and Shin (2001) studied the surface emission of Methane emission to assess the quantity of Methane emission efflux from solid waste landfills by means of an air flux chamber in South Korea. Methane emission efflux increased as atmospheric Temperature increased during the day, and the same pattern for the surface emission was observed for the change of seasons. Similarly, Methane emission efflux rate decreased from summer through winter. The average Methane emission efflux rates of winter, spring and summer were 0.1584, 0.3013 and 0.8597 m3 m−2 h−1 respectively. The total amount of surface emission was calculated based on the seasonal Methane emission efflux rate and the landfill surface area. From the estimates of Methane emission production, it is anticipated that about 30% of the produced Methane emission may be released through the surface without extraction process.

Molnar (2007) assessed the effect of Temperature in landfill site of Romania. The study was carried out in municipal landfill of Budapest, Romania, where the daily Temperature values

measured by meteorological station were compared with the emitted Methane. Nevertheless, the results of the study revealed that Methane content values from the landfill increased, substantially as Temperature increased.

Uyanik *et al*. (2012) examined the influence of Temperature on the composition and the energy recovery of Methane gas in Istanbul, Turkey. The data on Methane emissions and Temperature were collected from April, 2009 to March, 2010. The Artificial Neutral Network (an estimation model for solid waste) was used to analyze the effect of Temperature on Methane emissions. The analyzed results indicated that the Artificial Neutral Network was found to be successful in explaining differences of Methane content and Temperature in the landfill with correlation coefficients of 0.706 and 0.984, respectively. Further, the results show that Temperature is a very useful factor in predicting the Methane content from landfill site, more especially with respect to landfill without cover.

Wang *et al*. (2012) a demonstration pilot with seven anaerobic landfill simulators was used to study the impact of Temperature in the range of 20 - 46 °C on long-term landfill Methane emissions, characteristics and tendencies. The pilot was conducted more than 1400 days. The study indicated that higher Temperatures enhanced the waste deprivation and therefore Methane generation. Methane generation revealed the maximum Temperature sensitivity, 1.6 to 2.8 %. The Temperature coefficient of Methane generation varies significantly from the scarce values given in landfill simulation studies, but is in accordance with hydrolysis solubilisation related behavior and gives thus more detailed information of landfill behavior at different Temperatures. The results give new information for evaluation and modelling of landfill control strategies in long-term in various environmental conditions.

Yang *et al.* (2015) studied the compositions and annual variations of Methane at two large-scale sites of Chen-Jia-Chong Landfill, Wuhan China. Seventy-six wells were built and used for the gathering and measurement of Methane gas. The study revealed the similarities and differences of Methane components and variations at two sites with different phases. It was found that ambient Temperature displayed strong correlations (0.971) with Methane components at both sites.

Czepiel *et al.* (1994) studied the short-term influence of atmospheric Pressure and long-term influence of gas recovery on landfill Methane emissions at the Nashua, New Hampshire municipal landfill in the northeastern United States of America. Landfills are the largest sources of Methane emissions to the atmosphere in the United States. However, few measurements of whole landfill Methane emissions have been testified. The study presented the results of a multi-year research of whole landfill Methane emissions using atmospheric tracer methods. Emissions were measured in 1994, before the installation of a gas collection system, and again in 1996 and 1997 following the installation of a gas collection system. Both pre- and post-collection system emissions were negatively correlated with surface atmospheric Pressure. Emissions decreased approximately 2-fold before gas collection over a Pressure range of 1011 to 1028 millibars. The Pressure result was even more outstanding after the start of gas collection when emissions decreased more than 3-fold over a Pressure range of 1007 to 1023 millibars.

Czepiel *et al.* (2003) examined the influence of atmospheric Pressure by means of Eddy Covariance Technique on landfill Methane emissions at the Nashua, New Hampshire municipal landfill, United States of America, with an active vertical and horizontal gas collection system. The study revealed that surface Methane fluxes increased 300% due to decreases in barometric Pressure of 10 millibars, which occurred during passage of low-Pressure weather fronts over an

anaerobic landfill. The study further concluded that monitored emissions were negatively correlated with surface atmospheric Pressure. The results from the monitoring had a 0.93 correlation coefficient when modelled by linear regression.

Poulsen *et al.* (2003) examined the concentration and flux of Methane emission in soil adjacent to an old, in Danish municipal landfill, within 48-hour period during the passage of a low-Pressure weather system, to identify processes governing Methane emission flux and concentration. Two different methods were used (a) State-space analysis was applied to find the relation between gas flux and short-term (hourly) differences in atmospheric Pressure. (b) a numerical gas transport model was fitted to the data and used to compute short-term influences of variation in atmospheric Pressure, volumetric soil-water content, soil gas permeability, soil gas diffusion coefficients, and biological Methane deprivation rate upon landfill gas concentration and flux in the soil. Flux and concentration was found to be the most sensitive to disparities in volumetric soil water content, atmospheric Pressure variations and Methane permeability while variations in Methane oxidation rate and molecular coefficients had less effect. Flux seemed to be most sensitive to atmospheric Pressure at intermediate distances from the landfill edge. Likewise, the general Methane flux out of the soil over longer periods (years) was largest during periods with fast falling atmospheric Pressures resulting in emission of huge quantities of Methane during short periods of time.

Gebert and Groengroeft (2006) examined gas emission dynamics through high resolution measurements of Methane, Pressure, flow rate and composition as well as barometric Pressure and Temperature in an inactively vented landfill site in Northern Germany. The results of the study showed that Methane emission could be directly related to atmospheric Pressure changes on all scales as induced by the auto oscillation of air, diurnal variations and the passage of

Pressure highs and lows. Gas flux reversed every 20 h on average, with 50% of emission phases lasting only 10 h or less. During gas emission phases, Methane loads fed to a connected Methane oxidizing bio filtration unit varied between near zero and 247 g Methane h^{-1} m^{-3} filter material. Emission dynamics not only influenced the quantity of Methane fed to the bio filter but also the formation of gas composition profiles within the bio filter, thus, being of high relevance for bio filter operation. The duration of the gas emission phase emerged as most important variable for the distribution of Methane mechanisms within the bio filter.

Xu *et al.* (2010) evaluated the impact of changes in barometric Pressure on landfill Methane emissions. Landfill Methane emissions were measured continuously using the Eddy Covariance Method from June to December, 2010. The study site was located at the Bluff Road Landfill in Lincoln, Nebraska, USA. The results pointed out that Methane emissions from landfill is strongly depended on changes in barometric Pressure; increasing barometric Pressure repressed the emission of Methane, whereas, decreasing barometric Pressure improved the emission of Methane from the landfill, an occurrence named barometric pumping. There was up to a 35-fold disparity in day to day Methane emissions due to fluctuations in atmospheric Pressure. However, Wavelet coherence analysis shown a strong spectral coherency between disparities of atmospheric Pressure and Methane emission at periodicities ranging from 1 day to 8 days.

Nwachukwu and Anonye (2013) conducted a time series study to determine the influence of atmospheric Pressure on the variability of Methane concentration in a closed landfill site. An in situ data of Methane concentration and environmental parameters were collected using in-borehole gas monitor, the GasClam (Ion Science, UK). Linear regression analysis was used to determine the strength of the correlation between ground-gas concentrations and atmospheric Pressure. The result displayed Methane concentration to be variable with weak negative

correlations of 0.2691 with atmospheric Pressure over the entire monitoring period. Although the R^2 was slightly improved by considering its concentration over single periods of rising and falling Pressure, single period of rising Pressure and single period of falling Pressure, its correlations remained insignificant at 95 % confidence level. The result shown that atmospheric Pressure the commended major control on the variability of ground-gas concentration is not always so.

Aghdam *et al.* (2016) assessed the influence of barometric Pressure on extracted Methane concentrations entering the gas engine at Odense Nord and Stige Ø landfills, California, U.S.A., by means of Eddy Covariance Technique. The correlation factor R^2 for linear regression was used to study the significance of correlation. Methane concentration data revealed significant correlation factor with barometric Pressure (R^2 value of 0.4888). The correlation was also observed visually in a scatter plot. It was observed that a higher barometric Pressure, results in a lower Methane concentration entering the gas engine.

Most of the previous studies were conducted to examine the levels of Methane emissions from municipal landfills by means of LandGEM and GasSim developed by USEPA, England, and Wales respectively. However, there are some barriers to applying these mathematical Models in the municipal solid waste disposal sites of Urban areas of developing countries like Nigeria (most especially in Kano metropolis). This is because the Models were developed considering the landfills condition of United States of America, England, and Wales. These models have to be considered less accurate when applied to any other area outside these countries (Oonk, 2010). It should be noted that the landfills in United States, England, and Wales are well managed and engineered. Also, some previous studies indicated that LandGEM was used to examine the levels of methane emissions from four municipal solid waste disposal sites in Kano metropolis. But,

this study attempted to analyze the levels of methane emissions from 10 municipal solid waste disposal sites in Kano metropolis using IPCC default methodology and Crowcon-Gasman Fl

CHAPTER THREE

THE STUDY AREA AND METHODOLOGY

3.1 The Study Area

3.1.1 Location of Kano metropolis and history

The study area is located within 12^0 25′ 36.55″ to 12^0 40′ 45.48″ N, and 8^0 35′ 33.47″ to 8^0 45′ 43.54″ E and at an average height of 485m above sea level (Figure 3.1). The city is positioned at the central western part of Kano State and it is the Capital of Kano State. It is the third largest city in Nigeria, after Lagos and Ibadan (Okeagu, *et al.*, 2004). The metropolis covered an area of over 500 square kilometers (Kano Urban Planning and Development Agency (KNUPDA), 2019). It is bounded by Madobi and Tofa Local Government Areas to the South West, Gezawa Local Government area to the East, Dawakin Kudu Local Government area to the South East, and Minjibir Local Government area on the North East. It comprises of eight Local Government Areas, including the Municipal, Gwale, Fagge, Dala, Nassarawa, Tarauni, Kumbotso and Ungogo (Figure 3.2).

Kano has been an ancient city of Hausa people, long before the 10th century A.D (Okeagu, *et al.*, 2004). The man whom the city was named after, was a blacksmith as well as a hunter, by name Kano. He lived in the village of Gaya (now headquarters of Gaya Local Government Area) before his migration to Dutsen Dala (Dala hills), as well as Gwauron Dutse hill, where he used to collect iron for his work. He used to hunt animals and return to his station at Gaya. It was later he decided to leave Gaya and come to the present site Kano city and settled at Gwauron Dutse with his family.

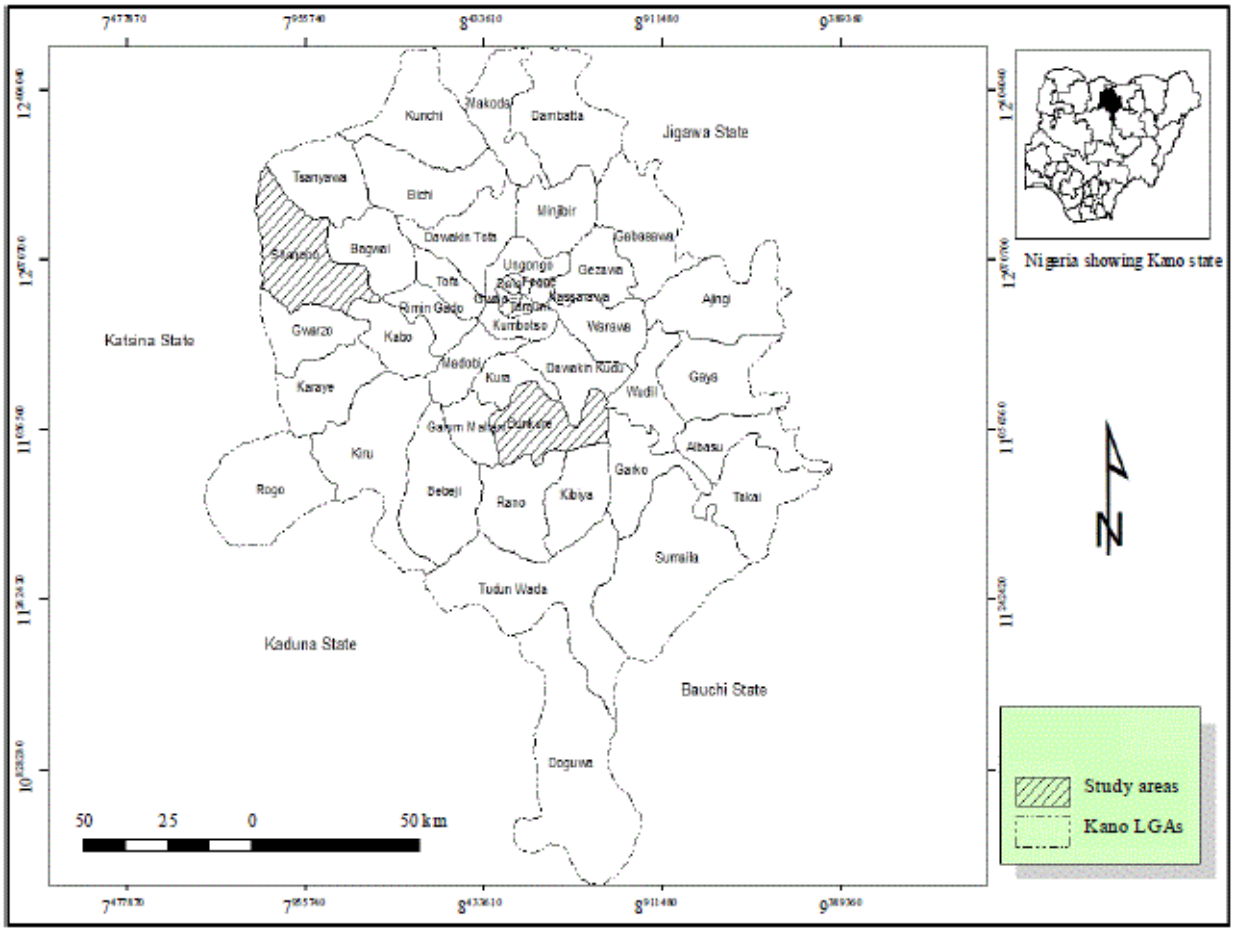


Figure 3.1: Map of Kano State
Source: Kano State Ministry of Land and Physical Planning (2017)

3.1.2 The physical setting

3.1.2.1 *Climate*

The climate of Kano is classified as Tropical wet and dry (Koppen, 1923). It is influenced by the movement of the two air masses of the Tropical maritime air masses coming over Atlantic Ocean and the Tropical continental dry air masses initiating from the Sahara Desert (Okeagu, *et al.*, 2004). As a result, the climate is characterized by four distinct seasons, namely; the dry and cool

season, which lasts from mid-November to February and marked by dusty harmattan haze; a dry and hot transitional period between the harmattan season and the wet season which lasts from March till May; the wet and warm season follows the hot season and lasts till September; and lastly the dry and warm-takes over till mid-November (Udo, 1981; Essiet and Tudun Wada, 1999). Climatic elements play an important role in the municipal waste management in Kano metropolis. For instance, during the rainy season, high Tempereture and humidity cause the municipal solid waste to decompose, and producing large amount of Methane emission (Abushammala *et al*., 2016).

The rainfall occurs during hot dry season which starts mostly from May and ends in October with rain days ranging between 90 - 100, and a mean annual of about 1000mm (Nabegu, 2018). The amount, duration, and frequency of rainfall vary widely from one year to another. The highest amount of rainfall is received usually from July ending and through August every year. The rainfall is characterized by strong wind, thunder and lightning. Showers are intense and last for short periods (Institute for Agricultural Research (IAR), 2018). Over the years, the rainy season is characterized by late annuals, early cessations and long spells of drought of up to 21 days (Nigerian Meteorological Agency (NIMET), 2018). Generally, the more moisture contents in the landfill/solid waste disposal site, the greater the microbial putrefaction and Methane emissions (Agency for Toxic Substances and Disease Registry, 2001).

The mean daily Temperature of Kano metropolis ranges between 28^0C and 44^0C. Unlike the rainfall, there is little variation in the annual Temperature, but the mean mean daily could be as low as 8^0C during the harmattan period, especially at night, and up to 44^0C in April – May. (IAR, 2018). Generally, higher Temperature induces bacterial activity, which directly results in

increase in Methane production and emission from landfills/solid waste disposal sites (Scheutz *et al.*, 2009).

3.1.2.2 *Geology and Relief*

The Kano region generally is underlain the Basement complex rocks of the Pre-Cambrian age, which include gneisses, amphibolite, marbles and the older granites (Wright, 1985). Prolonged denudation in the area have also resulted in laterite formation. Regolithic hills are out crops of the upland plains (Okeagu *et al*., 2004).

Relief ranges from lower plains of about 500metres above sea level to the highlands of over 1000metres above sea level. the landscape is characterized by picturesque grouped hills, sandy plains alluvial channels and some stand-alone rock formations (Okeagu *et al*., 2004).

3.1.2.3 *Soils*

Soils of Kano metropolis are mostly Ferruginous tropical soils and aerosols, derived from the Basement complex rocks. Most of the soils have undergone prolonged weathering, giving rise to fairly deep profiles, and inclusion of lateritic layer (Okeagu *et al.*, 2004). Perviousness is a measure of how well the Methane gas moved through joined spaces or pores in refuse dumps and soils. Dry, sandy soils are very penetrable, while saturated clay have a habit of plentiful fewer pervious. Methane have a tendency to migrate through areas of high permeability (for example,

areas of sand or gravel) rather than through areas of low perviousness (for example, areas of clay or silt) (Agency for Toxic Substances and Disease Registry, 2001).

3.1.2.4 *Vegetation*

The greatest part of the natural vegetation of Kano metropolis has been totally degraded through the extraction of fuel wood, urban encroachment, industrialization, human settlement and like activities, and are substituted with either exotic plants or built-up area. This is mainly due to urban expansion and high population density (Dakata and Yelwa, 2012). Nonetheless, the exotic trees/plants add more to the waste sector through cuttings and leaves de-shading, which lead to higher generation of Methane emissions from the disposal sites.

3.1.3 The human setting

3.1.3.1 *Population and settlement*

Kano metropolis is the second most populous urban center in the Nigeria after Lagos. The 2006 population census of the country put the total population of Kano metropolis at 2.8 million people (Official Gazette, 2009). However, the present estimated population for the eight Local Government Areas of the metropolis was put at 7,574,502 people (National Population Commission Projection for 2019), and it is among the fastest growing city in Nigeria (Nabegu, 2010). The population of the metropolis is influenced by three major factors: birth, death and migration (Olofin *et al.*, 2008). The population density at the city centers and its environs rises to about 10,000 persons per square kilometer (Okeagu *et al.*, 2004). The urban growth rate is about 5.5 % per annum at present (Olofin *et al.*, 2008).

The population of Kano metropolis is predominantly Hausa – Fulani. Nupe and Kanuri tribesmen occupy a distinct part of the old city. Yorubas and Igbos are also found in large numbers.

Koreans, Lebanese and Shuwa Arabs communities have been assimilated into the culture of the Kanawa (the people of Kano) as a result of trade, Islam and marriages. Kano metropolis, like Lagos in the south is the melting point of Nigeria ethnic diversity (Okeagu *et al.*, 2004).

The per capita solid waste generation in Kano metropolis is about 0.56kg/capita/day (Ogwueleka, 2009). This makes Kano metropolis third to Lagos and Ibadan in terms of waste generation in Nigeria. Items such as food scraps, vegetables, leaves, water packaged in plastic sachets (pure water) for human consumption, polyethylene shopping bags and plastic drink bottles constitute a convincing source of waste in the metropolis.

Kano metropolis has two distinct types of settlement pattern. These are the traditional nucleated pattern, which is prevalent within the walled city of Kano. Here, houses are irregular in shape. Some are round, while others are either rectangular or square in shape. Some of these houses are roofed with mud. Streets are inter-connected but very narrow and this have presented much problem to waste evacuation from within the old city.

The second type of settlement forms found within Kano metropolis is the modern type of nucleated settlement. Sabon Gari is one of such area. Other areas are Nassarawa, Kundila, Sharada, Danladi Nasidi etc. Although the streets here are wider, well laid, and often tarred, the population density is similarly generally high. Houses here are rectangular in shape and are roofed with corrugated iron sheets which allowed easy evacuation of waste materials by trucks to various solid waste disposal sites of the metropolis (Nabegu, 2008).

3.1.3.2 *Socio-economic activities*

Kano metropolis is the commercial nerve center of Kano State. It forms the center of commerce in the country generally, due to many markets, including Kwari, Singa, Rimi, Kofar Wambai,

Sabon Gari, Yankaba, Yan Lemo, etc. Indeed, marketing and trading has been the leading economic activity of the people of the area There are many small scale commercial, hand craft and other land use services done by individuals or groups, along the major roads and within the residential areas of Kano metropolis (Ibrahim, 2014). Further, trading activities in Kano metropolis include leather goods, soft drinks, animal feeds, food and beverages, textiles, local crafts as well as dyed textile materials (Okeagu *et al.*, 2004). However, all the commercial activities taking place in major markets, residential areas, major streets, etc. influences solid waste generation directly i.e. add more waste in to waste stream of the metropolis and produces more Methane emissions.

Industrially, Kano metropolis is one of the most developed urban center in Nigeria. The existence of raw materials, available markets, transportation networks, capital and labor had made the city one of the main industrialized urban center in Nigeria. The origin of Kano industrialization date back to 1900 when Kano emirate was conquered by the forces of British expansionism and integrated into a world capitalist economy. Kano commercial and industrial activities is felt not only within the country, but also in some neighboring countries, such as Niger Republic, Sudan, Cameroon, Chad and Benin. Prior to the imposition of British rule in Nigeria, Kano already had a long history of a leading center of cottage industries, commerce and agriculture.

Even though, before the arrival of white men, there were not many traditional industries within the Kano metropolis, from 1945 forward, many more firms, manufacturing a full variety of consumer goods, were established. The city has a number of industrial layout. Notable among them is the Bompai industrial estate. Other are the Sharada, Challawa, Hadejia Road and Dakata industrial estates. It was in 1970’s, after the oil boom, that the formation of import substitution

factories peaked. Between 1973 and 1982, not less than 165 new manufacturing plants were established in the Kano metropolis. After 1985, there were about 500 manufacturing industries engaging over one hundred thousand employees (Olofin *et al.,* 2008). These factories were set up by the indigenous and foreign private capital as well as by the State government through Kano State Investment Properties Company and the former Northern Nigerian Development Corporation and now New Nigerian Development Corporation (Beamonte *et al.,* 2007). They typically focused on the manufacture of plastic and plastic products, sweet and confectioneries, soft drinks, textile goods, metal and wooden furniture, animal feeds, rubber products, pharmaceuticals, paper and paper products, perfume, food and beverages, cosmetics and toiletry, and leather goods (Olofin *et al*., 2008). The establishment of Bompai industrial estate has enhanced the process of urbanization. There is a linked between industries and waste generation most especially waste coming from food industry, furniture industry, textile industry, unused raw materials etc. that end up in to solid waste disposal sites of the metropolis to produced more Methane emissions through the process of waste decomposition by methanogenic bacteria.

3.1.3.3 *Transport and communication*

Kano metropolis is one of the renowned center of the trans-Sahara trade with North Africa employing camel caravans across the Sahara Desert. The British occupation of Kano in 1904 changed the direction of trade. The means of communication improved as Kano became accessible by road in 1906, by rail in 1911, and by air in the late 1940s. There are direct road transport services to several state capitals and Abuja and to all the local government headquarters in the state. Kano metropolis is a major railway terminus extending to Nguru. It is also the gateway to Nigeria by air from Europe and the Middle East (Okeagu *et al.,* 2004). Nevertheless,

majority of the generated wastes in Kano metropolis are transported mostly by trucks, carts and other vehicles from either the residential areas, markets, institutions, or industries in to the solid waste disposal sites.

3.2 Methodology

3.2.1 Types of data used and their sources

Table 3.1 summarizes the data used, methods, sources, and key materials used both during the field and office works. The ancillary data used in this work includes topographic and administrative maps of the study area. Pictures of ten selected solid waste disposal sites also served as ancillary data. The image of the study area on Google Earth provided valuable materials during field work. The information on the characteristics of the respective study site covers the structural and physiographic parameters, and was acquired from field observations and measurements. The data for Methane emissions were acquired from field monitoring.

3.2.2 Methods and procedures of data collection

The methods used were selected according to the research objectives and questions. The research approach and methods used covered three main areas: pre-field work, reconnaissance and field work.

3.2.2.1 *Pre-field work activities*

The process and modalities for the research began with series of consultation with the supervisors, Kano State Refuse Management and Sanitation Board, relevant and community leaders. The aim was to collate and analyze relevant information on solid waste management in Kano metropolis. This was followed by a desktop review of relevant literature (published and

unpublished). Finally, at this stage, the basic consumable materials and equipment for the research were procured.

3.2.2.2 *Reconnaissance survey*

The fieldwork was started with a reconnaissance survey. The survey, which aimed at selection of sites for the study3 and appraisal of the environment of the study area, acquisition of more baseline information/data and pre-testing of field instruments used, took place in 2015. The suitability of the office-based design was verified during the reconnaissance survey. Thus, during the reconnaissance exercise, a global positioning system and an 8.0-megapixel camera was used for collection of information for points identified on the study area map during pre-field checks. During the survey, ten solid waste disposal sites, which were noted for heavy solid waste dumps were identified and selected for the study (Table 3.2).

3.2.2.3 *Detailed fieldwork*

The method of investigation adopted in this study involved quantification/monitoring Methane emission and measurements of meteorological variables (Temperature and atmospheric Pressure) over active solid waste disposal sites, that were some 30 to 40 years old within Kano metropolis.

Table 3.1: Data Used, Sources and Materials Used

S/N	Data required	Variables measured/estimated	Method of measurement/monitoring	Source of information	Materials used

1	Features of waste disposal sites, and characteristics of municipal solid wastes at disposal sites	Location, coverage, land use, history, meteorological conditions (Temperature, atmospheric Pressure), other physical, social characteristics of surrounding of solid waste disposal sites	Visual observation, interview of residents and physical of measurement features using Kestel 400 version 3.00 handheld weather tracker of disposal sites surrounding area. There was also interview with officials of Kano State Refuse Management and Sanitation Board	Digital map/guide of area obtained from 2015 Google Earth edition, Department of Operations, Kano State Refuse Management and Sanitation Board.	Computer Garmin GPS; Administrative map of area; Digital camera; Canon calculator; Digital map/guide of area obtained from 2015 Google Earth edition
2	Level of Methane gas emission from solid waste disposal sites	Methane emissions from the selected solid waste disposal sites.	Diurnal and seasonal monitoring/quantification of Methane emission at disposal sites using Crowcon - Crowcon – Gasman "FL" and IPCC default method	Selected solid waste disposal sites	Crowcon - Crowcon – Gasman "FL" Garmin GPS; Digital, and administrative map of area; Digital camera; Canon calculator; IPCC default method
3	General environment of the study area		Field observation and library		Digital, and administrative map of area

Source: Author's Field Work, 2019.

3.2.3 Selection of solid waste disposal sites

Ten solid waste disposal sites located in areas of high population and residential density and, therefore, largest disposal sites within Kano metropolis, were selected for the study. The size of the solid waste disposal sites selected ranged between 20,432.24 m^2 to 92,832.31 m^2 (REMASAB, 2019). The selection of the plots, as mentioned earlier, was based on size and age, being the largest within the metropolis. The ten sites were located along different road arteries in the metropolis (Figure 3.2).

Table 3.2: The GPS Readings of the Center of the Respective Solid Waste Disposal Sites Selected for the Study

S/No	Site location	Name of location	Age (years)	Size (m^2)	Coordinates
1	Court Road	Along Court Road, off Zoo Road, Tarauni Local Government Area	30	43,338.93	Easting 8^0 32′ 34.08″ Northing 11^0 57′ 59.04″
2	Ubagama	Alongside Bulukiya Road, Dala Local Government Area.	28	28,868.84	Easting 8^0 30′ 54″ Northing 12^0 00′ 54″
3	Hajj Camp	Along Airport Road, Fagge Local Government Area	27	41,855.16	Easting 8^0 31′ 16.32″ Northing 12^0 01′ 26.4″
4	Maimalari	Beside Independence Road, Nassarawa Local Government Area.	25	92,832.31	Easting 8^0 34′ 17.76″ Northing 12^0 08′ 13.44″
5	Kuntau	Alongside Kuntau Road, Gwale Local Government Area.	23	59569.85	Easting 8^0 27′ 59.04″ Northing 11^0 57′ 59.04″
6	Yankaba	Beside Hadejia Road, Nassarawa Local Government Area.	31	27,339.12	Easting 8^0 35′ 35.52″ Northing 12^0 00′ 47.52″
7	Ramin Birji	Along NNPC Road in the Tarauni GLocal Government Area.	22	24,321.34	Easting 8^0 35′ 6″ Northing 11^0 57′ 33.12″
8	Kwarin Goshi	Along Dala Road in Dala Local overnment Area.	19	30,401.17	Easting 8^0 30′ 18″ Northing 12^0 00′ 52″
9	Ramin Hassan	Alongside Sani Bello Street, Gama Quarters, Nassarawa Local Government Area.	29	20,432.24	Easting 8^0 35′ 35.52″ Northing 12^0 00′ 47.52″
10	Ramin Hussain	Beside Sani Bello Street, Gama Quarters, Nassarawa Local Government Area.	30	23,730.42	Easting 8^0 33′ 34.12″ Northing 12^0 02′ 5.28″

Source: Author's Field Work, 2019.

All sites were located with GPS for possible follow up investigation in the future Table 3.2). For each of the plots, the surrounding environment, such as geographical and geological conditions, hydrological distributions, and neighboring pollution sources, were noted. The digital map showing the location of the sites and the visual view of the respective site is given in Appendix 1. The remaining part of this subsection describes the key environmental, social and economic characteristics of the sites.

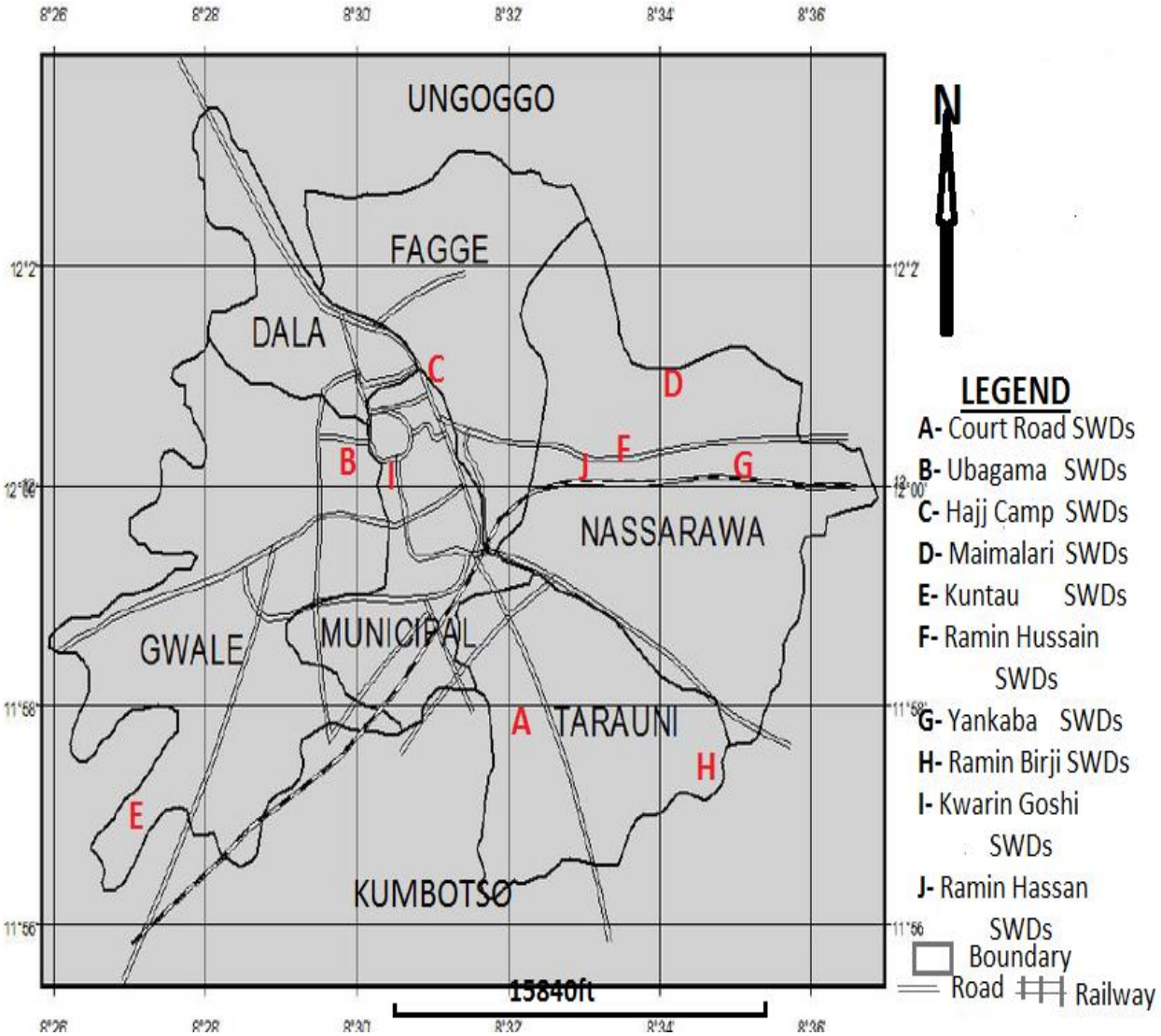


Figure 3.2: The Kano Metropolis Showing the Locations of Sampling Sites

Source: Kano State Ministry of Land and Physical Planning (2017)

3.2.3.1 *Court Road solid waste disposal site*

The Court Road solid waste disposal site (Appendix II (a)) lies at an elevation of 475 meters above sea level. The wastes here typically consist of paper, food, plastics, commercial, textiles, agricultural, ashes, and so on, from the densely populated areas of Shagari quarters, Tudun Maliki, Durimin Iya, Sheka Yarkasuwa, Durimin Zungura, Hauren Balagu, Hauren Investment (REMASAB, 2019). Also, the site is located very close to habitation and commercial buildings to the east.

3.2.3.2 *Ubagama solid waste disposal site*

Ubagama solid waste disposal site (Appendix II (b)) lies at an elevation of 476 meters above sea level. The wastes contain in this disposal site include significant quantity of human faeces. In addition, municipal solid wastes consisting of paper, food, plastics, textiles, ashes, agricultural and the rest from the densely populated areas of Makafin Dala, Kofar Wambai, Kofar Waika, Kaigama, Dandishe, Yanjakai, are also found in this disposal site (REMASAB, 2019).

3.2.3.3 *Hajj Camp solid waste disposal site*

The Hajj Camp solid waste disposal site (Appendix II (c)) lies at an average height of 461 meters above sea level. The site is situated very close to human habitation to its southern part (about 100m), Government Technical College Fagge, located at the eastern part of the disposal site (less than 50m), and commercial buildings at its western part (less than 100m) respectively. The site accept waste from densely populated areas of Sabon Gari market, Sabon Gari town, Kwakwaci, Kwari market, Kofar Wambai market, Kurna, Rijiyar Lemo, Singer market (REMASAB, 2019).

3.2.3.4 *Maimalari solid waste disposal site*

Maimalari solid waste disposal site (Appendix II (d)) is located around the industrial sites of Nassarawa Local Government Area. It lies at an average height of 459m above sea level. The Maimalari solid waste disposal site is where all manner of unsorted wastes including organic wastes, commercial wastes, industrial wastes, vegetables, ashes, textiles, paper, institutional are freely dumped into burrow pit from the heavily populated areas of Tudun Wada Yandusa, Tudun Murtala, Bompai, Dakata, Zango, Sabon Gari market, Chediya Uku, Rimin Kebe (REMASAB, 2019).

3.2.3.5 *Kuntau solid waste disposal site*

Kuntau solid waste disposal site (Appendix II (e)) is elevated at 481meters above sea level. The disposal site is very close to human habitation (less than 100m) to all of its surroundings. The collected waste is currently being disposed of at the site. Municipal solid wastes such as of paper, commercial, hospital, institutional, food, plastics, textiles, ashes, agricultural, and so forth are accepted in to a burrow pit from densely populated areas of Janbulo, Bakin Bulo, Rijiyar Zaki, Unguwar Wambai, Dorayi Babba, Dorayi Karama, Charanci, Taen, Salanta, Gaida (REMASAB, 2019).

3.2.3.6 *Yankaba solid waste disposal site*

The Yankaba solid waste disposal site (Appendix II (f)) has a slaughter house towards its northern boundary, a significant amount of animal waste is also dumped here. There is also the presence of residential, commercial properties and Yankaba Motor park within 100 meters of its neighborhood. The disposal site is located at about 457 meters above sea level, and it is still in operation. Municipal solid wastes such as food, plastics, ashes, hospital, commercial, textiles, agricultural and the rest are accepted in this disposal site. Similarly, the Yankaba solid waste

disposal site serves the densely populated areas of Badawa quarters, Walallabe, Gawon Gailo, Sauna, Tinshama, Kawaji, Yankaba town, Yankaba market (REMASAB, 2019).

3.2.3.7 *Ramin Birji solid waste disposal site*

The Ramin Birji solid waste disposal site (Appendix II (g)) is located within 50 meters of its neighborhood (residential houses). In addition, the disposal site is simply an open dumpsite where all kind of unsorted solid wastes including domestic, textiles, paper, ashes, commercial, food, institutional, vegetables, non-biodegradable wastes are freely dumped into borrow-pit. The site is located at about 479 meters above the ground surface, and it is still in operation. The site serves the densely populated areas of Danmarke, Kawo, Tarauni, Walawai, Unguwa Uku, Hotoro NNPC, Masama, Kundila (REMASAB, 2019).

3.2.3.8 *Kwarin Goshi solid waste disposal site*

Kwarin Goshi solid waste disposal site (Appendix II (h)) is also located within 100 meters of its vicinity (residential houses, driving training ground and motor garage). The disposal site is simply an open dumpsite where all kind of unsorted solid wastes containing paper, textiles, rubber, plastics, ashes, commercial, food, vegetables, and so on, are freely dumped into an open ground and borrow-pit. The site is located at about 472 meters above sea level, and it is still in operation. The site serves the heavily populated areas of Kofar Mazugal, Koki quarters, Daurawa, Koki, Gwammaja, Masaka, Federal Secretariat quarters, Ikeja quarters (REMASAB, 2019).

3.2.3.9 *Ramin Hassan solid waste disposal site*

The Ramin Hassan solid waste disposal site (Appendix II (i)) lies at an elevation of 461 meters above sea level. Heavy residential, school (Mamuda Mai Barkono Memorial Primary School),

commercial activities, mosque, are found very close (less than 50m) to the disposal site. The Ramin Hassan is an open disposal site where all kind of unsorted wastes such as organic wastes, ashes, vegetables, rubber, paper, household wastes, commercial wastes, plastics, and the rest. are easily disposed of in to the disposal site from the densely populated areas of Gama Tudu, Gawuna, Tudun Wada, Brigade, Zangeru, Kwanar Jaba, Kwana Hudu (REMASAB, 2019).

3.2.3.10 *Ramin Hussain solid waste disposal site*

The Ramin Hussain solid waste disposal site (Appendix II (j)) is situated very close to heavy residential areas of Gama quarters, and is still in operations. The site lies at an elevation of 459m above sea level. The Ramin Hussain disposal site is where all kind of unsorted wastes such as organic wastes, paper, ashes, textiles, hospital, household wastes, plastics, vegetables, commercial wastes are easily disposed of in to the disposal site from the highly populated areas of Gama Kwari, Kankaren Kutare, Jagule, Airport Road, Ahmadiyya, Mile Tara (REMASAB, 2019).

3.2.4 Quantification and monitoring of Methane emissions and other meteorological variables

In the course of this study, Methane emissions produced from the ten selected solid waste disposal sites were quantified/monitored by means of theoretical model (IPCC default methodology) (IPCC, 1996) and the Crowcon Gasman 'FL'. The details of each quantification/monitoring method were presented as follows:

i.Quantification of Methane emissions by IPCC default methodology

The Methane emission from the ten selected solid waste disposal sites were quantified using IPCC default methodology for two seasons (dry, January, 2018 and wet, August, 2018, respectively). One of the most frequently used models for the quantification of Methane emissions from solid waste disposal sites is based on Mass Balance Approach. The IPCC default methodology (IPCC, 1996). The default methodology also known as the Tier l, is actually an empirical model. The Reviewed 1996 IPCC guidelines for National Greenhouse gas inventories (IPCC, guidelines) outline IPCC methodology for quantifying Methane emissions from solid waste disposal sites (IPCC, 2000). The IPCC default method was first advanced by Bingemer and Crutzen, 1987 (Bingemer and Crutzen, 1987) and has been approved by IPCC as a recognized method for quantification of potential Methane amounts from solid waste disposal sites. Consequently, it is considered the simplest, easy to apply and the results are very transparent and it is one of the greatest obtainable tools for quantifying Methane emissions from municipal solid waste disposal sites in most countries of the world. Nevertheless, the method is recommended for countries in which comprehensive data on solid waste statistics is not obtainable, hence, a number of empirical constants have been considered while using the IPCC default methodology and therefore the emissions are calculated (Mali, 2011). This methodology computes Methane emissions based mostly on the fraction of degradable organic carbon and fraction of degradable organic carbon assimilated (Chiemchaisri and Visvanathan, 2008; Abushammala *et al.*,2009).

Based on the foregoing, the IPCC has recommended the method for quantification of Methane emissions from solid waste disposal site using the following equation I (IPCC, 1996).

Methane emissions (Giga gram/year) = **[MSW_T x MSW_F x MCF x DOC x DOC_F x F x 16/12 – R] x[1-OX) ……... (1)**

Where,

MSW_T is the total MSW generated (Giga gram/year)

The MSW_T can be determined by multiplying the solid waste generation rate in Kano metropolis (0.56kg/capita/day) (Nabegu, 2008: Ogwueleka, 2009) by the communities served by each solid waste disposal site. The 1991 population census figures were used as a base year and the current population was determined using a population growth rate of 3.2% (NPC, 2019).

MSW_F is the fraction of municipal solid waste disposed into solid waste disposal sites.

MSW_F = 0.74. The common belief in Nigeria is that about 74% of wastes produced are taken into the solid waste disposal sites (Adewumi, *et al.,* 2005). The remaining 26% is expected to be lost due to recycling, waste burning at source as well as at disposal sites, waste thrown into drains and waste not reaching the solid waste disposal sites due to ineffective solid waste management system.

MCF is the Methane Correction Factor

This is based on the category of the solid waste disposal sites management as presented by IPCC (IPCC, 1996):

i. Managed sites: MCF = 1.0
ii. Unmanaged (open dump), deep sites (≥ 5 Meter waste): MCF = 0.8
iii. Unmanaged (open dump), shallow sites (< 5 Meter waste): MCF = 0.4
iv. Default (uncategorized solid waste disposal sites); MCF = 0.6

DOC is the portion of degradable organic carbon in solid waste disposal sites. This is obtained from equation 2.

DOC = percent DOC (by weight) = 0.4 (w) + 0.17 (x) + 0.15(y) + 0.30(z) ……. (2)

Where,

w is the fraction of paper and textile in municipal solid waste;

x is the fraction of garden waste, park waste or other non-food organic waste in municipal solid waste;

y is the fraction of food waste in municipal solid waste; and

z is the fraction of wood or straw in municipal solid waste.

DOC_F is the fraction of total degradable organic carbon that actually degrades and is converted to landfill gas and it can be estimated using equation 3.

$DOC_F = 0.014T + 0.28$ …… (3)

Where,

T is waste Temperature in degree centigrade (Tabasaran, 1981).

F is the fraction of Methane in landfill gas.

16/12 is the conversion factor from carbon to Methane

R is a Methane recovered value (Giga gram/year) using an active extraction system.

OX is the Methanotrophic oxidation. It is the fraction Methane oxidized by methanotrophs.

However, the table used to collect the above information is shown Table 3.3. The information collected about the items shown above were entered into a table similar to Table 3.3 in chapter four (Table 4.1), from which the levels of Methane emissions at each solid waste disposal sites using IPCC default methodology were determined.

Table 3.3: An Example of Parameters Used for Determining Methane Emissions at the Selected Solid Waste Disposal Sites of the Metropolis

S/N	SWDs	MSW_T	MSW_F	MCF	DOC	DOC_F	F	16/12	Methane (Gg/yr.)
01	Court Road								
02	Ubagama								
03	Hajj Camp								

04	Maimalari
05	Kuntau
06	Yankaba
07	Ramin Birji
08	Kwarin Goshi
09	Ramin Hassan
10	Ramin Hussain

Source: Author's Field Work, 2019.

ii. Monitoring of Methane emissions and ambient Temperature and Pressure

The Crowcon-Gasman 'FL' was used to monitor the presence of Methane emissions from the 10 selected solid waste disposal sites of Kano metropolis in this study. The Crowcon–Gasman "FL" is a full function personal single portable gas detector that is compact and lightweight. Containing simple one button operation; it has a large easy to read display of gas concentration, and noticeable, visual and vibrating alarms. The Crowcon–Gasman "FL" is highly accurate personal monitor available in configurations for Methane. Nevertheless, the Crowcon-Gasman 'FL' was calibrated at the beginning of every monititoring season to ensure accurate readings of Methane emission in solid waste disposal sites of the metropolis. The equipment was sourced from the department of pollution control, ministry of environment, Kano State.

The reading of Methane emission, using Crowcon–Gasman "FL", was done during both the morning (0700 hours to 1000 hours' local time) and afternoon (13:00 hours to 16:00 hours' local time) periods. Firstly, for each period, and over each site, the readings were taken at about the center position of the disposal site, and then one each at 100m away from the center at the four

cardinal points (North, East, South, and West). This is because municipal landfill site Methane monitoring points are usually spaced 90m to 120m (USEPA, 2015). This makes a total reading of five per site, and per period, for each observation day. The monitoring points over a disposal sites were labeled as D1, D2, D3, D4, and D5, in which D1 is the point at the center, D2 at the north, D3 at the south, D4 at the west and D5 is the point at the east. The mean of the five readings constitute the average for each site, for each period. The geographic coordinates of the center position of the monitoring points (D1) were recorded using a portable Garmin Global Positioning System (GPS) receiver. Secondly, the Methane emission level was also read at 100m interval away from the center of disposal site (that is, at 0m, 100m, 200m, and 300m radially away). This is with a view to assessing the level of concentration of Methane emitted away from the center of solid waste disposal site.

In the monitoring, the Crowcon–Gasman "FL" was held within 30 to 60 centimeters off the ground surface. This is because anything above 60cm Methane emission to the atmosphere decreases (Bhailall *et al.*, 2016). Also, the concentration of Methane emissions was recorded in percentage (%) (lower explosive limit). The monitoring covered four seasons of the year. That is, the cool dry season of the harmattan (January, 2018); the hot dry season (April, 2018); the wet season (August, 2018); .and the harvest season (November, 2018). The monitoring took place in the first seven consecutive days of the selected months. The two meteorological variables considered along with Methane emission are Temperature and atmospheric Pressure, and these were measured using Kestel 400 version 3.00 handheld weather tracker.

3.2.5 Method of data analysis

The method of data analysis adopted for the study helped in accomplishing the stated aim and objectives in the following ways:

i. Objective One: determine the levels of Methane emissions from the selected solid waste disposal sites in Kano metropolis. To achieve this objective, simple descriptive statistics using mean and standard deviation were used to summarized the data.

ii. Objective Two: determine the variation of Methane emissions at different points away from the center of solid waste disposal sites in the study area. To accomplished this objective, analysis of variance, and t-test were employed.

iii. Objective Three: determine the diurnal and seasonal variability of the levels of Methane emissions from the solid waste disposal sites in the study area. To accomplished the objective, students' t-test and analysis of variance were employed.

iv. Objective Four: compare the modeled emission results obtained by IPCC default methodology with direct monitoring values using Crowcon-Gasman Fl in the metropolis. Students' t-test was used to achieve the ststed objective.

v. Objective Five: assess the influence of Temperature and Pressure on Methane emissions in the study area. To accomplished the objective, simple regression analysis was used. Lastly, 0.05 was used as level of significance throughout the analyses.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Levels of Methane Emissions in Kano Metropolis

4.1.1 Levels of Methane Emissions Estimated Using IPCC Default Methodology

The computed Methane emission, using the IPCC Default methodology, along with the values of the necessary input parameters, for the selected solid waste disposal sites in the Kano metropolis for both the wet and dry seasons are presented in Table 4.1. For determining the total municipal solid waste (MSW_T) from the waste disposal sites, the solid waste generation rate in Kano metropolis, estimated to be 0.56kg/capita/day (Nabegu, 2008; Ogwueleka, 2009). This was multiplied by the population serving each solid waste disposal site. For determining the fraction of municipal solid waste (MSW_F) disposed into solid waste disposal sites, it is generally believed that, in Nigeria, about 74% of wastes produced are taken into the solid waste disposal sites. The remaining 26% is assumed to be lost, due to recycling, waste burning at source and at disposal sites, waste thrown into drains and waste not reaching the solid waste disposal sites, due to inefficient solid waste management system (Adewumi *et al.*, 2005).

The value of Methane Correction Factor (MCF) reflects the position of management of the site. In other words, the Methane correction factor is based on the category of the solid waste disposal sites management as presented by IPCC (IPCC, 1996). The IPCC recommends default Methane correction factor values, ranging from 0.4 to 1.0. This corresponds to a range of unmanaged (open dump), shallow sites (≤ 5-meter waste): MCF = 0.4; Default (uncategorized solid waste disposal site): MCF = 0.6; Unmanaged (open dump), deep sites (≥ 5-meter waste): MCF = 0.8; to well Managed sites: MCF = 1.0.

Defining Degradable Organic Carbon (DOC) depends on the components or portions of waste in the municipal solid waste. Using the statistical data on waste composition, the percentage of degradable organic carbon in municipal solid waste varies across the selected solid waste disposal sites in both the wet and dry seasons.

Defining the portion of the total Degradable Organic Carbon (DOC_F) decomposing under anaerobic zone, the estimates are based on a theoretical model that depends on Temperature in the anaerobic zone of solid waste disposal site, which is assumed to be 35 °C (IPCC, 1996). Similarly, for fraction of Methane in landfill gas (F), a default value recommended by IPCC was also used. Equally, defining the conversion factor from carbon to Methane (16/12) and Methane recovered value (R), using an active extraction system, an IPCC default values were also used.

Table 4.1: Level of Methane Emissions Estimated by Means of IPCC Default Method in Kano Metropolis During Wet and Dry Seasons

S/N	SWDs	MSW_T	MSW_F	MCF	DOC	DOC_F	F	Conversion factor	Methane (Gg/yr.)
01	Court	176,832.23	0.74	0.6	0.13	0.77	0.5	1.3	**5,107.90***
	Road	176,832.33	0.74	0.6	0.07	0.77	0.5	1.3	**2,750.72****
02	Ubagama	108,552.12	0.74	0.8	0.11	0.77	0.5	1.3	**3,537.99***
		108,552.12	0.74	0.8	0.06	0.77	0.5	1.3	**1,929.81****
03	Hajj Camp	173,480.73	0.74	0.6	0.12	0.77	0.5	1.3	**4,626.15***
		173,480.73	0.74	0.6	0.07	0.77	0.5	1.3	**2,698.59****
04	Maimalari	152,017.42	0.74	0.8	0.08	0.77	0.5	1.3	**3,603.37***
		152,017.42	0.74	0.8	0.05	0.77	0.5	1.3	**2,252.11****
05	Kuntau	147,688.14	0.74	0.8	0.12	0.77	0.5	1.3	**5,251.13***
		147,688.14	0.74	0.8	0.07	0.77	0.5	1.3	**3,063.16****
06	Yankaba	47,565.81	0.74	0.6	0.06	0.77	0.5	1.3	**634.21***
		47,565.81	0.74	0.6	0.04	0.77	0.5	1.3	**422.81****
07	Ramin	75,277.46	0.74	0.8	0.09	0.77	0.5	1.3	**2,007.39***
	Birji	75,277.46	0.74	0.8	0.06	0.77	0.5	1.3	**1,338.26****
08	Kwarin	70,417.84	0.74	0.8	0.06	0.77	0.5	1.3	**1,251.87***
	Goshi	70,417.84	0.74	0.8	0.05	0.77	0.5	1.3	**1,043.23****
09	Ramin	131,051.97	0.74	0.6	0.11	0.77	0.5	1.3	**3,203.49***
	Hassan	131,051.97	0.74	0.6	0.07	0.77	0.5	1.3	**2,038.58****
10	Ramin	90,957.72	0.74	0.8	0.10	0.77	0.5	1.3	**2,695.04***
	Hussain	90,957.72	0.74	0.8	0.07	0.77	0.5	1.3	**1,886.53****

Interpretation: *wet season; ** dry season

Source: Author's Field Work, 2019.

It is clear from Table 4.1 that the values of Methane emissions during the wet season varies across the selected solid waste disposal sites of the metropolis. The results indicated that Kuntau, Court Road, Hajj Camp, Maimalari, Ubagama, and Ramin Hassan solid waste disposal sites emits the highest Methane. This is because these are the municipal solid waste disposal sites that generate high quantity of waste from the densely populated areas of Jaen, Dorayi, Rijiyar Zaki, Sheka, Yakassai, Wakilin Kudu, Rijiyar Lemo, Sabon Gari Town, Dandishe, Kofar Waika, Makafin Dala, Dakata, Gawuna, Gama, Kwanar Jaba, Brigade, Tudun Wada, Tudun Murtala, Rimin Kebe to mention but a few. Likewise, the disposal sites (Court Road, Kuntau and Hajj Camp) received heavy wastes from the major markets/commercial centers (Rimi, Sabon Gari, Kwari, Kofar Wambai, and Singer markets) of the metropolis, as well as the main hospitals (Murtala, Nassarawa and Aminu Kano Teaching Hospital) of the study area. Therefore, high volume of waste means high Methane emissions from the disposal sites.

Equally, the high Methane emissions from the sites might be attributed to a higher amount of waste moisture content during the wet season; high fraction of degradable organic carbon content (≥ 0.11) by weight, indicates the presence of vast quantity of organic or food waste in the disposal sites (Wang-Yao *et al.*, 2006; Abushammala *et al.*, 2016). High amount of organic and food waste could quicken Methane emissions from the municipal solid waste disposal sites. Normally, waste from developing countries comprises of larger amount of food and decomposable matter (Guermoud *et al*., 2009). Lastly, the low Methane emissions observed in Yankaba solid waste disposal site might be due to low fraction of degradable organic carbon (0.06) content. Similar findings were reported by Rahman *et al.* (2010), at municipal landfill of Bangledesh; Akintayo and Olonisakin (2014), study at municipal disposal sites of Ibadan,

Nigeria; Hoklis and Sharp (2014), in their study at municipal landfill of Cambodia; Wajeeha *et al.* (2016), at Oman municipal landfills; and Adjoumani *et al.* (2018), study at municipal disposal sites of Cot d Voire respectively.

Likewise, as is evident from Table 4.1, the computed value of Methane emissions during the dry season also differs across the disposal sites. However, the values for each site are generally lower than those of the wet season. This may be attributed to lack of moisture content during the dry season period. The results of these findings were in agreement with those obtained by Qdais *et al*. (2010) in their study at municipal disposal sites of Jordan; Kodwo (2013), in his study at solid waste disposal sites of Accra, Ghana; Daura *et al.* (2014), study at municipal disposal sites of Kano metropolis, Nigeria, respectively. This is a reflection, presumably, of the desiccation condition, and therefore, lower oxidative decomposition of dump materials, during the dry season.

4.1.2 Levels of Methane Emission from Solid Waste Disposal Sites, Using Crowcon-Gasman 'FL'

Table 4.1.2 summarises the result obtained from the actual Methane emissions monitoring, using Crowcon-Gasman 'FL', across the ten selected solid waste disposal sites within Kano metropolis. In the interpretation of the results obtained, the classification of the Minnesota Pollution Control Agency (2011) was employed.

Table 4.2: Level of Methane Emission from Solid Waste Disposal Sites by Means of Crowcon - Gasman 'FL'

Period	Morning		Afternoon	
SWDs	Mean (% LEL Methane)	SD	Mean (% LEL Methane)	SD
Court Road	21.75**	9.81	29.00**	12.68
Ubagama	17.00*	7.70	24.00**	15.23
Maimalari	18.25*	6.55	21.75**	7.97
Yankaba	20.00**	4.58	22.00**	3.61
Ramin Birji	13.25*	6.08	15.75*	8.50
Kwarin Goshi	15.00*	4.32	18.15*	4.20
Hajj Camp	23.75**	10.14	26.00**	10.80
Kuntau	20.50**	8.06	28.25**	12.28
Ramin Hassan	23.50**	9.15	25.25**	11.84
Ramin Hussain	20.25**	8.96	22.75**	11.29
Grand mean	**19.33***	**7.53**	**23.33****	**9.84**

Interpretation: * medium; ** high ((based on Minnesota Pollution Control Agency, 2011))

SD = Standard deviation (n=5)

Source: Author's Field Work, 2019.

The value of Methane emissions during the morning period differs considerably across the ten selected solid waste disposal sites. The emission is highest over Hajji Camp and Ramin Hassan, where the mean values are approximately the same (24%), and lowest over Ramin Birji (13.25%)

and Kwarin Goshi (15.00%). By the Minnesota Pollution Control Agency (2011) legend, four of the solid waste disposal sites (Ramin Birji 13.25%, Kwarin Goshi15.00%, Ubagama 17.00% and Maimalari 18.25%) are characterized by medium emissions of Methane, while the remaining six sites have high emissions of Methane (Yankaba 20.00% , Ramin Hussain 20.25%, Kuntau 20.50%, Court Road 21.75%, Ramin Hassan 23.50% and Hajj Camp 23.75%), which is beyond the safety concentration limit of 20% LEL or 200,000 parts per million (ppm) for confined environments where people live or work (Christensen *et al*., 1996; Swedish Environmental Protection Agency, 1999 and USEPA, 2005). It is worth pointing out, however, that there is considerable variability in the values of recorded Methane emissions within the respective solid waste disposal sites, as shown by relatively high standard deviation values. Such is a reflection, presumably, of variation of the activities of Methane producing bacteria (methanogenic bacteria), in response to vagaries in meteorological and soil influencing parameters (Czepiel *et al.*, 1996).

The emitted Methane showed consistently greater amount in the afternoon period, compared to the morning period. The mean value is highest at both the Court Road (29.00%) and Kuntau (28.25%) solid waste disposal sites, and lowest at Ramin Birji (15.75%) and Kwarin Goshi (18.15%) solid waste disposal sites, while the values for the rest solid waste disposal sites are intermediate. In term of the Minnesota Pollution Control Agency (2011) legend, values for all sites are rated as high, which is beyond the safety concentration limit of 20% LEL for confined surroundings where people live or work (Christensen *et al*., 1996; Swedish Environmental Protection Agency, 1999 and USEPA, 2005). The only exceptions are the two disposal sites with the medium values (Ramin Birji (15.75%) and Kwarin Goshi (18.15% respectively). Similar to the morning period, the emission values showed considerable variability within the respective

solid waste disposal sites, as shown by the standard deviation values, ranging between 3.61 over Yankaba and 15.23 over Ubagama.

Thus, the study indicated that waste workers, scavengers, people residing close to the disposal sites (women at home, children and elderly persons) are at risks since they are exposed to high concentration of Methane emission in most of the disposal sites more especially during the afternoon period. This is because even at low concentration, inhaling Methane can cause nausea, dizziness, headache, vomiting and loss of coordination, and at very high concentration, it may lead to coma and death due to respiratory arrest (Health Protection Agency, 2011; USEPA, 2013). Likewise, the results of the study showed that the level of Methane emissions for both morning and afternoon periods were below 5% (100% LEL Methane), but in the near future due to rapid urbanization and increase in population within the metropolis, there is the possibility of Methane emission to increase in its level particularly at the major solid waste disposal sites of (Court Road, Kuntau, Ramin Hassan, Maimalari, Hajj Camp, Ubagama) of Kano metropolis.

Studies using spatial approaches have revealed that there is a link between people living close to solid waste disposal sites/landfills and health related effects (Pukkala and Punka, 2001; Gouveia and do Prado, 2010). Greater threat to liver, occurrences of congenital abnormalities, low birth weight, abortion and neonatal death, stomach, lung, kidney and pancreatic cancer has been reported among individuals living close to solid waste disposal sites/landfills (Goldberg *et al*., 1999; Elliott *et al.*, 2001; Pukkala and Ponka, 2001; Palmer *et al.*, 2005; Elliott *et al.*, 2009, Gouveia and do Prado, 2010). Related findings were reported in a study conducted by Oonk and Boom (1994), in their study at Dutch landfills; Nava-Martinez *et al*. (2011), study at former dumpsite in Tijuana, Mexico; Kurtulus *et al*. (2006) study at solid waste landfill of Istanbul, Turkey; Li *et al.* (2013), study at landfill site of Northern Meriwether County, Georgia and

Nioufer *et al.* (2014), in their study at municipal solid waste dumpsite in Vjayawada, Andhra Pradesh, India respectively.

4.2 Variation of Methane Emission at Different Points Away from Center of Solid Waste Disposal Sites

Table 4.3 displayed the variation in the level of Methane emissions at different points away from the center of solid waste disposal sites.

Table 4.3: Level of Methane Emissions at Different Points Away from the Center of Solid Waste Disposal Sites

	N	Mean (% LEL Methane)	Standard deviation	Standard error
0M	20	18.9500	6.93940	1.55170
100M	20	12.4500	3.15353	0.70515
200M	20	6.7000	2.61775	0.58535
300M	20	3.7000	2.17885	0.48720
Total	80	10.4500	7.15276	0.79970

Source: Author's Field Work, 2019.

The findings in Table 4.3 revealed that the trend of Methane emission away from the center of solid waste disposal sites for both morning and afternoon periods appeared to have decreased according to distance travelled. This decrease might possibly be to influence of distance away from the disposal sites. The result corroborates Ubou and Nwawuike (2016) study on the onsite and offsite ambient air quality at Nakede waste dumpsite in Imo State, which revealed that Methane emissions diminished according to distance travel away from the center of the dumpsite.

Table 4.4 gives the summary of the analysis of variance employed to test for significant difference in the level of Methane emissions at different points away from the center of solid waste disposal sites.

Table 4.4: Variations in Methane Emissions at Different Points Away from the Center of Solid Waste Disposal Sites

	Sum of squares	**df.**	**Mean square**	**F**	**Sig.**
Between groups	2717.500	3	905.833	51.985	0.000
Within groups	1324.300	76	17.425		
Total	**4041.800**	**79**			

Source: Author's Field Work, 2019.

Table 4.4 confirms that these means vary significantly from each other. From Table 4.4, the sig. value (0.000) was less than the level of significance (0.05), therefore, the null hypothesis was rejected, and conclude that Methane emission differed considerably according to distance travelled away from the center (0meter) of the solid waste disposal sites during the morning and afternoon periods.

Table 4.5: Level of Methane Emission at Different Points Away from the Center of Solid Waste Disposal Sites in the Morning and Afternoon Periods

Group test

	Time	N	Mean	Standard deviation	Standard error Mean
Methane	Morning	40	8.9750	6.01062	0.95036
	Afternoon	40	11.9250	7.94012	1.25544

Independent test

	F	Sig.	T	Interpretation	Decision on Ho
Equal Variance Assumed	3.351	0.065	-1.874	Insignificant difference	Accepted
Equal Variance not Assumed		0.065	-1.874		

Source: Author's Field Work, 2019.

The level of Methane emission away from center of solid waste disposal sites in the morning and afternoon period is presented in Table 4.5 and subjected to t-test for variations. The result obtained did not showed statistically significant difference at 0.05 probability level (0.065 > 0.05).

The lack of significant differences in the Methane emission of the two periods, conversely, reveals, probably, that the meteorological variables (Temperature and humidity) for the Methane producing bacteria inside the solid waste disposal sites most probably will not change over a comparatively short period. Hence, most possibly, Methane emissions will not differ too much over a fairly short period (Kjeldsen, 1999). Nevertheless, the considerably higher mean values of Methane emissions during the afternoon monitoring compared to morning period might be due to the fact that higher Temperatures in the afternoon accelerate the degradation of waste; therefore, more Methane generation from the solid waste disposal sites (Scheutz *et al.*, 2009).

Even though the amount of Methane emitted from the solid waste disposal sites according to distance travel away from the center of the disposal sites for both morning and afternoon periods were within the safety concentration limit for confined environments where people live or work. However, in the near future, due to increase in population, rapid industrialization, and urbanization, in Kano metropolis, there is the possibility of Methane to increase in its level away from the disposal sites, and, inhaling Methane emission can cause dizziness, vomiting, headache, cough, nausea, and so on (Health Protection Agency, 2011; USEPA, 2013,). Moreover, the presence of Methane emissions in the ambient air of the study area, though, found within the safety concentration limit for confined environments, but, is an issue of concern, since Methane act as an asphyxiant by displacing air in the body and replacing Oxygen in the blood at a concentration of 2% LEL (20,000ppm) (Macklin, 2011). This is because most of the disposal sites are located within few meters away from the heavy residential areas of the metropolis.

The likely human health effects linked to residential closeness to solid waste disposal sites have been studied by a number of researches. For instance, in a multi-site study of residents of New York State, a 12% increased risk of congenital malformations in children born to families within one mile of landfill sites, fatigue, sleepiness, headaches were reported (Vrijheid *et al*., 2002; Geschwind *et al.*, 1992). Equally, studies in the Love Canal residents of U.S.A. was a study of low birth weight, prematurity and birth defects (Goldman and Paigen, 1995). The study revealed that children born in the Love Canal area were reported to be 3 times greater risk of low birth weight than children born in a different unexposed area (Montague and Pellevano, 2001). In another study conducted by Schrapp *et al.*, 2019, at Jaleeb Al-Suyoukh landfill of Kuwait, showed that there was a significant relation between people residing close to the landfill and

nausea, headaches, daily tiredness, muscle weaknesses, cough, difficulty in breathing, nasal painfulness, and so on.

Methane emission from solid disposal sites is a potential threat to the quality of the environment, this is because the emissions of Methane released in to the atmosphere is a contributor to ground level Ozone, which is associated with higher rates of asthma attacks (USEPA, 2002). Also, it contributes to the depletion of Ozone layer and leads to global warming, and consequently climate change (USEPA, 2015). In addition, the lateral migration of Methane emissions through soil beyond solid waste disposal sites boundaries can pollute the underground water, and the presence of Methane in water used for drinking may indicate a risk of other pollutants for example benzene, toluene, xylene, ethyl benzene, etc. (Osborn *et al.*, 2011). This finding corroborate with the results reported in a study conducted by Ezikomwor and Obisesan (2014), in their study at Rumuolumeni dumpsite, Port Harcourt, Nigeria; Ezekwe *et al.* (2016), study at Eneka dumpsite in Port Harcourt, Nigeria; Ubouh and Nwawuike (2016), study at municipal solid waste dumpsite of Owerri, Nigeria.

Apart from Analysis of Variance and t-test, the effect of distance on Methane emissions could be seen graphically when Methane emissions were plotted against distance (Figure 4.1).

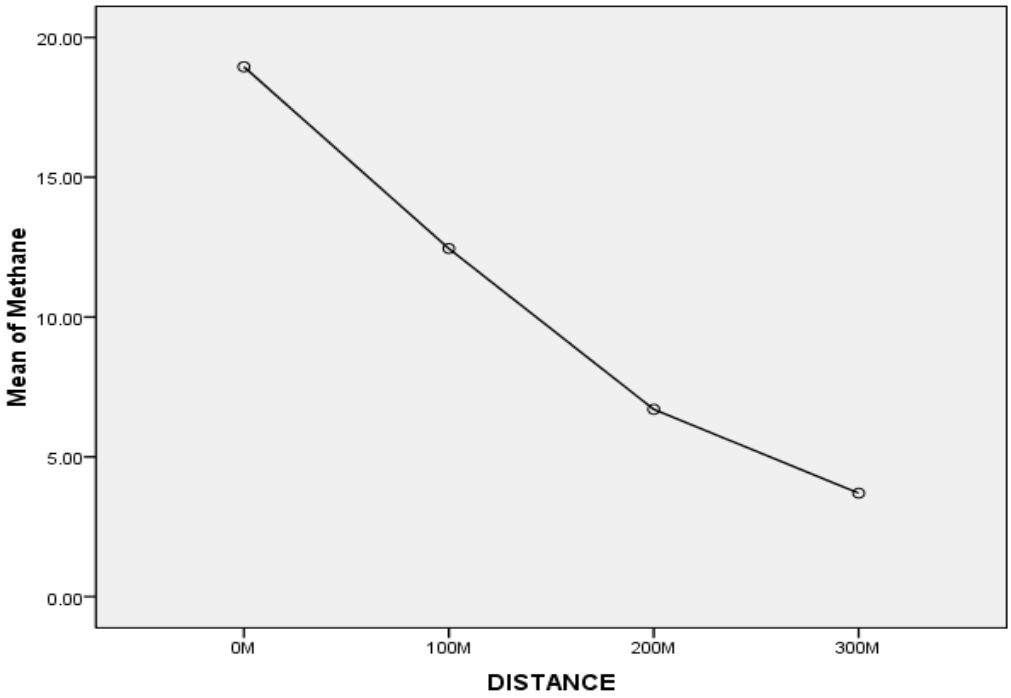


Figure 4.1: Methane Emissions Against Distance
Source: Author's Field Work, 2019.

As can be seen in Figure 4.1, it is evident that the trend of Methane emissions decreased according to distance travelled away from the center of the disposal sites. An elevated Methane emission concentration was found at 0meter and 100meter, whereas at 200meter and 300meter, the Methane emissions concentration decreased gradually. This decrease in concentration away from center of the disposal sites could be due to the fact that the migration of Methane in to the ambient air for both morning and afternoon periods may be dispersed and therefore decreased in concentration.

4.3 Diurnal and Seasonal Variability of the Levels of Methane Emissions

The results of t-test for diurnal variation of Methane emission in this study is given in Table 4.6.

4.3.1 Diurnal variation of Methane emissions

Table 4.6: Level of Methane Emissions in the Morning and Afternoon

Group test

	Time	N	Mean	Standard deviation	Standard error Mean
Methane	Morning	40	2.86	0.843	0.267
	Afternoon	40	3.40	0.900	0.340

Independent samples test

	F	Sig.	T	Interpretation	Decision on Ho
Equal Variance Assumed	17.97	0.074	-1.813	Insignificant difference	Accepted
Equal Variance not Assumed		0.074	-1.813		

Source: Author's Field Work, 2019.

From Table 4.6, it can be observed that the means of both morning and afternoon emissions do not vary much. However, when the differences in methane emission between morning and afternoon periods was subjected to t-test (Table 4.6), the result obtained did not show statistical significant difference at 0.05 probability level ($0.074 > 0.05$), therefore, the null hypothesis was accepted and it was concluded that there is no significant diurnal variation of Methane emissions.

The lack of significant differences in the methane emission of the two periods, however, reflects, presumably, the nearly similar Temperature and Pressure values recorded during the two periods.

The climatological conditions (Temperature and humidity) for the methane producing bacteria inside the solid waste disposal sites/landfills most likely will not change over a relatively short period. Therefore, most likely methane emissions will not fluctuate too much over a fairly short period (Kjedsen, 1999). That notwithstanding, the slightly lower mean values of emissions during the morning monitoring compared to afternoon time suggests slower degradation of wastes due to reduce activities of microorganisms (methanogenic bacteria). Similar findings were reported by Rees-White *et al.* (2018), at a landfill site in South-East United Kingdom; William (2018), in his study at Keele Valley Landfill, Ontario, Canada; Angaye *et al.* (2019), study at municipal solid waste disposal sites of Yenagoa, Nigeria; Chengliang *et al.* (2019), in their study at landfill site of central China.

4.3.2 Seasonal variation of Methane emissions

Table 4.7 revealed the mean variation in the level of Methane emission with the seasons of the year and Table 4.8 presents the variation in the enission.

From Table 4.8, the sig value (0.007) was less than the level of significance (0.05), hence, the null hypothesis was rejected, and conclude that Methane emissions varied according to seasons of the year.

Table 4.7: Level of Methane Emissions with Seasons of the Year

Season of the year	N	Mean (% LEL Methane)	Std. deviation	Std. error
Harvest	20	26.29	9.81	0.70711
Wet	20	20.47	5.19	0.67823
Hot dry	20	24.95	8.73	0.4000

Cool dry	20	12.20	3.82	0.49441

Source: Author's Field Work, 2019.

Table 4.8: Variation in Methane Emissions Amongst Seasons

	Sum of squares	**df**	**Mean square**	**f**	**Sig.**
Between groups	28.933	2	14.467	7.70	0.007
Within groups	22.400	12	1.867		
Total	**51.333**	**14**			

Source: Author's Field Work, 2019.

It is evident from the result that the monitoring of Methane emission using Crowcon - Gasman 'FL', varied with the seasons of the year. The highest mean value occurred during the harvest season (26.29%). This is followed by the hot dry season (24.95%) and wet season (20.24%). The least emission occurred in the cool dry season of the harmattan (12.20%). The differences in values amongst the seasons are statistically significant at greater than 0.05 probability level. The highest value obtained during the harvest season may be attributed to solubility of Methane in water. This is because Methane is water soluble (the solubility of Methane is 30 mg/l) (Bundela *et al*., 2012). In other words, the highest value obtained during the harvest season might be due to the fact that during the wet season, the rainfall would enter the body of solid waste disposal site and block the pores otherwise available for Methane gas transport, hence, significant amount of Methane gas would remain in the body of solid waste disposal site until when the wet season ceases, then Methane emission would find its way out to the atmosphere i.e. during the harvest season (Borjesson and Svensson, 1997; Christophersen *et al.*, 2001). Related finding was

reported by Kurtulus *et al.* (2006), study at municipal landfills of Istanbul, Turkey and IPCC (2007), study at landfill sites of Indian Mega cities.

The high value of Methane emission found during the hot dry season may possibly be due to the fact that high Temperature accelerates the degradation of waste; increases bacterial activity, which directly results in the increase of Methane emission from municipal solid waste disposal site (USEPA, 2003). Likewise, the high value of Methane emission obtained during the hot dry season could probably be due to the fact that the chemical processes at the body of solid waste disposal site are faster at higher energy supplies (Czepiel, et al., 1996). The result of this finding is similar to findings by Chanton and Liptay (2000), study at municipal landfills of Florida, Molnar (2007), in his study at municipal landfills of Romania, Wang *et al.* (2012), in their study at landfill sites of Finland, Yang *et al.* (2015), study at municipal landfill sites of Wuhan, China.

The comparatively lower value during the wet season may perhaps be attributed to a higher amount of moisture, which create logging conditions and, thus, anaerobic decomposition, resulting in lower Methane emission. Similarly, the lower value acquired during the wet season could be due to the fact that the start of methanogenesis and thus Methane emission may be retarded by excessive moisture (Lagerkvist *et al.*, 1999). Too much moisture in the waste was reported to obstruct waste decomposition and therefore produces low Methane emission (Oonk and Woelders, 1999; Wens *et al.*, 2001). Related findings were reported by Wang-Yao *et al.* (2006), study at municipal solid waste disposal sites of Thailand; Jha *et al.* (2008), in their study at solid waste disposal sites of India, Abushammala *et al.* (2015), and Abushammala *et al.* (2016), studies at municipal landfills of and Malaysia.

Lastly, the relatively very low Methane emission during the cool dry season of the harmattan may be attributed to slow degradation of waste, lack of sunshine, lack of moisture to help the

methanogenic bacteria to degrade the waste, hence, these might hinder Methane emission from the municipal solid waste disposal sites in the study area (Czepiel *et al.*, 1996; Bhailall *et al*., 2016). The very low amount of Methane emission during the cool dry season of the harmattan might probably be due to the fact that during the harmattan season, the production of Methane reduces and atmospheric air (Oxygen) can enter the solid waste disposal site. The solid waste disposal site contains significant amounts of Nitrogen, and with the Oxygen from the air, Methane can be oxidized. This result in Methane percentage reduction (Lawson *et al.*, 1992; Scharff *et al.*, 2003). Similar results were reported by Maurice and Lagerkvist (2003), in their study at municipal landfills of Sweden, Fourie and Morris (2004), study at landfill sites of South Africa.

The finding revealed that Methane emission during harvest and hot dry seasons have exceeded the safety concentration limit (20%) for confined environments where people live or work. Thus, most probably, the complaint on vomiting by some residents near some of the solid waste disposal sites of the metropolis, might be due to high Methane emissions from the disposal sites. Moreover, waste workers, scavengers, are at risks since they are exposed to high concentrations of Methane emissions at point source, most especially during the two seasons. The accumulation of Methane in human body through inhalation of air may cause vomiting, asphyxiation, dizziness, nausea, headache and loss of coordination (Health Protection Agency, 2009). Furthermore, Methane gas can migrate laterally away from the solid waste disposal sites via soils (Kjeldsen, 1996). The main effect of Methane in soils is believed to be due to Methane oxidation which reduces the Oxygen present, increases the Carbon dioxide levels and may also raise the soil Temperature. This may lead to plant death by enhanced asphyxiation due to a lower

solubility of gases inside the plant cells or by drying up the soil (Fischer *et al*., 1999). The variation in Methane emissions with seasons of the year is graphically presented in Figure 4.2.

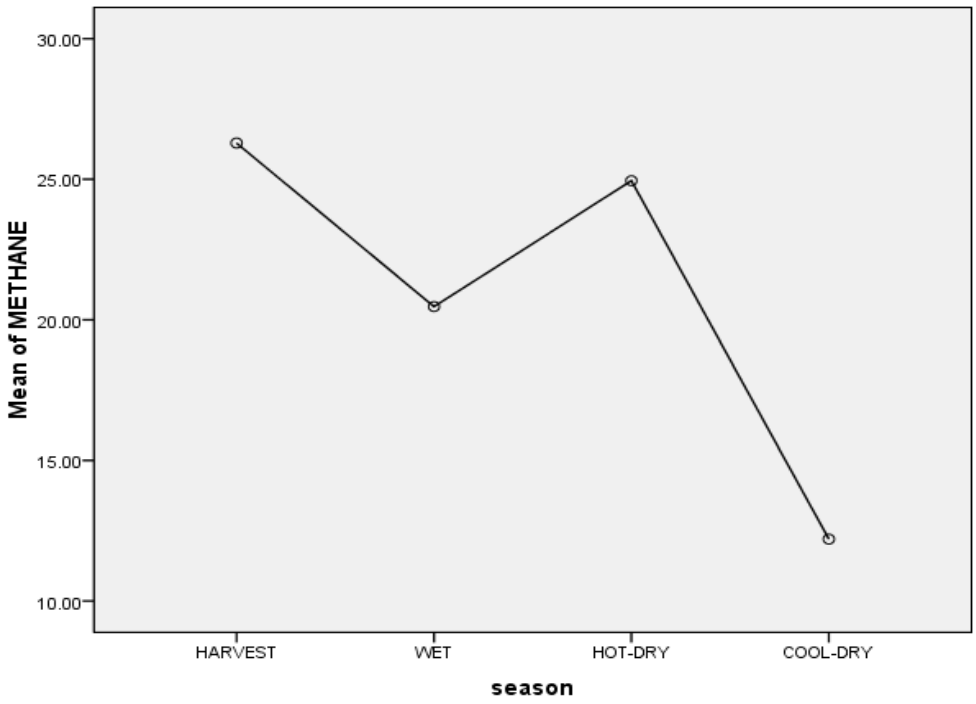


Figure 4.2: Methane Emissions Against Season
Source: Author's Field Work, 2019.

From Figure 4.2, it is obvious that the trend of Methane emissions differs across the seasons graphically. An elevated Methane emissions concentration was found during harvest season, hot dry season and wet season respectively, while in cool dry season of the harmattan, the Methane emissions declined.

4.4 Comparison of Results Obtained from IPPC Model and Field Monitoring (Crowcon-Gasman 'FL')

Table 4.9 and 4.10 presents the results of the measured and modelled Methane emissionin for both wet and dry seasons respectively. The modelled results which is in Giga gram per year was

first converted to percentage for the purpose of comparison. Hence, the two results were compared together using t-test.

Table 4.9: Comparison of Monitoring Values with Modelled Results (wet season)

Group test

	Method	**N**	**Mean**	**Standard deviation**	**Standard error mean**
Methane	Monitoring	20	40.4000	5.54176	1.75246
	Modellesd	20	9.3150E11	4.65671E11	1.64640E11

Independent Samples Test

	F	**Sig.**	**T**	**Interpretation**	**Decision on Ho**
Equal Variance Assumed	16.358	0.001	-6.376	Significant difference	Rejected
Equal Variance not Assumed			-5.658		

Source: Author's Field Work, 2019.

Table 4.10: Comparison of Monitoring Values with Modelled Results (dry season)

Group test

	Method	**N**	**Mean**	**Standard deviation**	**Standard error mean**
Methane	Monitoring	20	24.3000	5.14350	1.62652
	Modellesd	20	6.0000E11	1.87552E11	6.25173E10

Independent Samples Test

	F	Sig.	T	Interpretation	Decision on Ho
Equal Variance Assumed	25.042	0.000	-10.150	Significant difference	Rejected
Equal Variance not Assumed			-9.597		

Source: Author's Field Work, 2019.

It is clear from Tables 4.9 to 4.10 that, for both the wet and dry periods, the independent samples test revealed that the significance values (0.000 and 0.001) are less than 0.05 probability level. This means that the null hypothesis can be rejected, and concluded that the results of Methane emissions using the two methods differed significantly in the wet and dry seasons. It can be observed from the Tables that the mean of modelled results by IPCC default methodology is significantly higher than that of direct monitoring using Crowcon– Gasman "FL". The significant variations between the monitoring values and modelled results might perhaps be due to non-uniformity of the unit measurements.

That not withstanding, the disparities between the results obtained by the IPCC default methodology and Crowcon – Gasman "FL" can be attributed to general weakness inherent in empirical models. In this particular situation, for example, data on waste amounts and composition needed in the IPCC model are lacking. The IPCC default methodology does not take into consideration site specific features, like the influence of climatic conditions on Methane emissions, seasonal variability of Methane emissions rate, as well as things like waste disposal methods, and waste characteristics; whether or not waste is compressed adequately or not. This information is important for quantifying Methane emissions from municipal solid waste disposal sites (Chiemchaisri *et al.*, 2005; Bogner *et al.*, 2014; Bhailall *et al.*, 2016). Furthermore, the

uncertainty about portion of Degradable Organic Carbon seems to lead to an overestimation of the Methane production (Bogner and Mathews, 1999). The finding corroborates with the results by Chiemchaisri *et al.* (2005), in their study at two solid waste disposal sites (Nakorn Prathom municipality and Nonthaburi dumpsite) in Thailand; Chiemchaisri and Visvanathan (2008), in the study at municipal solid waste disposal site of Thailand; Manju and Ramanathan (2011), study at landfill areas of Delhi, India; Bhailall *et al.* (2016), in their study at municipal landfill sites of South Africa; Siddiqui and Paranjpe (2016), in the study at landfll sites of Jabalpur city of central Indian state of Madhya Pradesh; Garcia *et al.* (2017), study at landfill site in the state of Mexico, Mexico.

4.5 The Influence of Meteorological Conditions (Temperature and Pressure) on Methane Emissions

4.5.1 Relationship Between Temperature and Methane Emissions

The results of simple regression analysis showing the relationship between Temperature and methane emissions in this study is given in Table 4.10.

Table 4.11: Influence of Temperature on Methane Emissions

Variable Regressed	**B**	**R^2**	**F**	**Sig.**	**Interpretation**	**Decision on Ho**
Temperature Vs Methane		.471	69.35	.000	Significant effect	Rejected
Coefficient		**Beta**	**t**			
(constant)	-5.456			.099	Insignificant effect	Accepted
Temperature	0.892	.686		.000	Significant effect	Rejected

Source: Author's Field Work, 2019.

The correlation coefficient value between Temperature and Methane emission is positive and highly significant ($r = 0.686$, $sig = 0.000 < 0.05$), thus, validating the hypothesis that Temperature has a significant and positive effect on Methane emissions over the study area. As

suggested by the coefficient of determination (R^2 = 0.471), as much as about 47.1% of the variation in Methane emission is explained by Temperature variation. The regression equation is given as y = -5.456 + 0.892 Temperature, suggesting that an increase in Temperature by one-degree Celsius result in 0.892 % Methane emission. Such positive and significant relationship can be explaining by the fact that Temperature is important in creating favorable condition or otherwise for the microbial chemical action, as well as for volatization, resulting in increased Methane emissions from the solid waste disposal sites (Einola *et al*., 2007). Besides, on a warmth day, Methane can easily release through many pores on the surface and eventually escapes to the atmosphere. So, quantitatively more Methane emission is emitted through the surface during the hot/sunny days (Park and Shin, 2001).

Apart from simple regression analysis values, the significant correlation between Methane emissions and Temperature is presented visually in a scatterplot. In this respect, Methane emissions was plotted against Temperature (Figure 4.3).

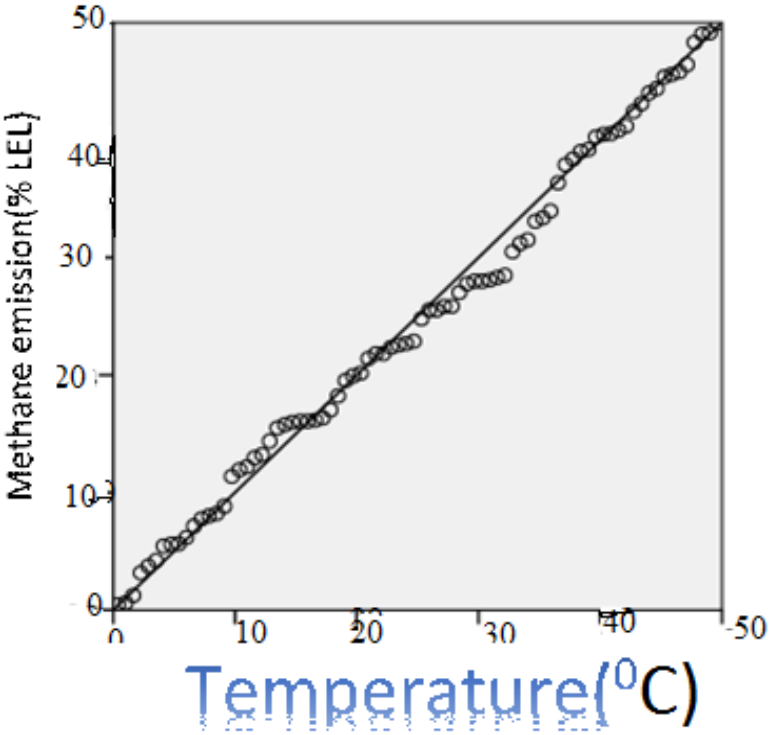


Figure 4.3: Methane Emissions as a Function of Temperature.
Source: Author's Field Work, 2019.

As observed in Figure 4.3, higher Temperature enhanced Methane emissions (Park and Shin 2001). This finding is similar to those of Visvanathan *et al*. (1999), in their study at municipal landfills of Thailand; Chanton and Liptay (2000), study at municipal landfill site of Leon County, Florida, U.S.A.; Park and Shin (2001), study at municipal landfills of South Korea; Molnar (2007), and Wang *et al.* (2012) in their studies at municipal landfills of Budapest, Romania; Uyanik *et al.* (2012), study at landfill site of Istanbul, Turkey; Yang *et al.* (2015), in

their study at two landfill sites of Chen-Jia- Chong, Wuhan China. The aforementioned studies reported that an increase in Temperature enhanced Methane emission.

4.5.2 Relationship Between Atmospheric Pressure and Methane Emissions

The results of the correlation between atmospheric Pressure and methane emissions in this study is presented in Table 4.11.

Table 4.12: Effect of Atmospheric Pressure on Methane Emission

Variable Regressed		**B**	**R^2**	**F**	**Sig.**	**Interpretation**	**Decision on Ho**
Pressure	Vs		.418	55.95	.000	Significant effect	Rejected
Methane							
Coefficient			**Beta**	**t**			
(constant)		1062.83			.000	Significant effect	Rejected
Atmospheric Pressure		-1.03	-.646		.000	Significant effect	Rejected

Source: Author's Field Work, 2019.

Similar to the trend with Temperature, the correlation coefficient value (-0.646) between atmospheric Pressure and Methane emission is highly significant, statistically ($0.000 < 0.05$). However, unlike the trend for Temperature, the relationship is negative, thus validating the hypothesis that atmospheric Pressure has a significant negative effect on Methane emissions over the study area. The linear regression equation is given as y= 1062.83 + -1.03 Atmospheric Pressure, suggesting that an increase in atmospheric Pressure by one millibar would decrease Methane emissions by 1.03 millibar. As suggested by the coefficient of determination (R^2 = 0.418), about 42% variability in the Methane emission is explained by variation in the atmospheric Pressure. This result agrees with the findings by Czepiel *et al.* (1994) and Czepiel *et al.* (2003), at the Nashua, New Hampshire municipal landfill in the North Eastern United States of America; Poulsen *et al.* (2003), study at Danish municipal landfill; Gebert and Groengroeft

(2006), study at municipal landfill of Northern Germany; Xu *et al.* (2010), study at Bluff Road Landfill in Lincoln, Nebraska, U.S,A.; Nwachukwu and Anonye (2013), in their study at closed landfill site in Manchester, UK,; Aghdam *et al.* (2016), study at Odense Nord and Stige landfills, California, U.S.A. These findings revealed that increasing atmospheric Pressure suppressed the Methane emissions, while decreasing atmospheric Pressure enhanced the Methane emission. The reason for the observed relationship in this study could possibly be due to the fact that with higher atmospheric Pressure, more air from the atmosphere flows into the body of the solid waste disposal site and dilutes the Methane gas, which decreases Methane emissions.

CHAPTER FIVE

SUMMARY, CONCLUSION AND RECOMMENDATIONS

5.1 Summary

This study assessed the spatio-temporal variability of methane emissions from ten selected municipal solid waste disposal sites noted for heavy waste dumps in Kano metropolis. The study was carried out using IPCC default methodology for two seasons (wet and dry), and Crowcon–Gasman "FL" for a period of four seasons of the year (cool dry season - the harmattan (January, 2018); hot dry season (April, 2018); wet season (August, 2018); .and harvest season (November, 2018) respectively. Firstly, for each period, and over each site, the monitoring was carried at about the center of the disposal site, and then one each at 100m away from the center at the four cardinal points (North, East, South, and West). Secondly, the Methane emission level was also read at 100m interval away from the center of disposal site. Two meteorological variables considered along with Methane emission are Temperature and Pressure, and these were measured using Kestel 400 version 3.00 handheld weather tracker.

The results obtained in the study by means of IPCC default methodology during the wet season showed that Kuntau, Court Road, Hajj Camp, Maimalari and Ubagama solid waste disposal sites recorded the highest Methane during the wet season. Likewise, the results obtained by means of Crowcon - Gasman Fl during the morning and afternoon periods are highest over Ramin Hassan, Kuntau, Court Road, and Hajj Camp respectively. Equally, it is obvious that Methane emission decreased considerably according to distance travelled away from the center of the solid waste disposal sites during the morning and afternoon monitoring.

The results obtained also indicated that there is no significant diurnal variation in Methane emissions, this is because the value of sig. (0.074) is higher than the level of significance 0.05.

Similarly, it is clear from the result that the Methane emission monitoring, by means of Crowcon - Gasman Fl, contrasts with the seasons of the year. The highest mean value occurred during the harvest season (26.29%). This is followed by the hot dry season (24.95%). The least emission occurred in the cool dry season (12.20%). The mean of modellled results by IPCC default methodology during the two seasons (wet and dry) are higher than that of direct monitoring values using Crowcon – Gasman "FL". The independent samples test showed that the value of sig. (0.000) is less than 0.05 probability level.

Lastly, the correlation coefficient value of Temperature and Methane emission is positive and very much significant ($r = 0.686$, $sig = 0.000 < 0.05$). Similar to the trend with Temperature, the correlation coefficient value (-0.646) for Pressure and Methane emission is highly significant, statistically ($0.000 < 0.05$). However, unlike the trend for Temperature, the relationship is negative.

5.2 Conclusion

In conclusion, Kuntau, Court Road, Hajj Camp, Maimalari and Ubagama solid waste disposal sites recorded the highest Methane emission by means of IPCC default methodology during the wet season period. By means of Gasman Fl, the monitoring of Methane emission is highest over Ramin Hassan, Kuntau, Court Road, and Hajj Camp. Similarly, Methane emission decreases substantially according to distance travel away from the center of the solid waste disposal sites during the morning and afternoon monitoring. Moreover, diurnal variation has no significant effect on Methane emissions, and Methane emission monitoring by means of Gasman Fl, differs with the seasons of the year. The mean of modelled results by IPCC default methodology is greater than the actual monitoring values using Gasman Fl during the two seasons (wet and dry). Lastly,

Temperature influence Methane emission positively, whereas, Pressure impact Methane emission negatively from the municipal solid waste disposal sites of Kano metropolis.

5.3 Recommendations

The ten selected solid waste disposal sites in Kano metropolis were revealed to have been the sources of Methane emission, hence, the following measures are recommended:

1. Methane gas has the potential to be used as sources of green energy, and if appropriately planned and engineered sanitary landfills are constructed at suitable sites, the Methane gas can be tapped and used as a viable source for electricity generation and domestic cooking in order to reduce its impacts on climate change. It will also creäte the much needed employment.
2. There is need for the absolute closure of the solid waste disposal sites in the metropolis, by relocating the entire disposal sites from their present positions and sited far away from the metropolitan area to reduce the impacts on vomiting, headaches, nausea, asphyxiation and so on. The challenge here is that solid waste disposal sites are known to continue to produce Methane emissions even after 50 years of their closure (Robertson and Dunbar, 2005).
3. The study suggests for continuous monitoring of Methane emissions from the disposal sites during the harvest season, hot season and wet season, this is because the amount of Methane emitted throughout these seasons are above safety concentration limit (20% lower explosive limit) for confined environments where people live.
4. There is need for the Kano State Refuse Management and Sanitation Board to initiate more 3Rs (Reduce, Recycle and Reuse) activities in solid waste management strategies,

and encourage the private sector participation in all forms of waste recycling and controlling projects.

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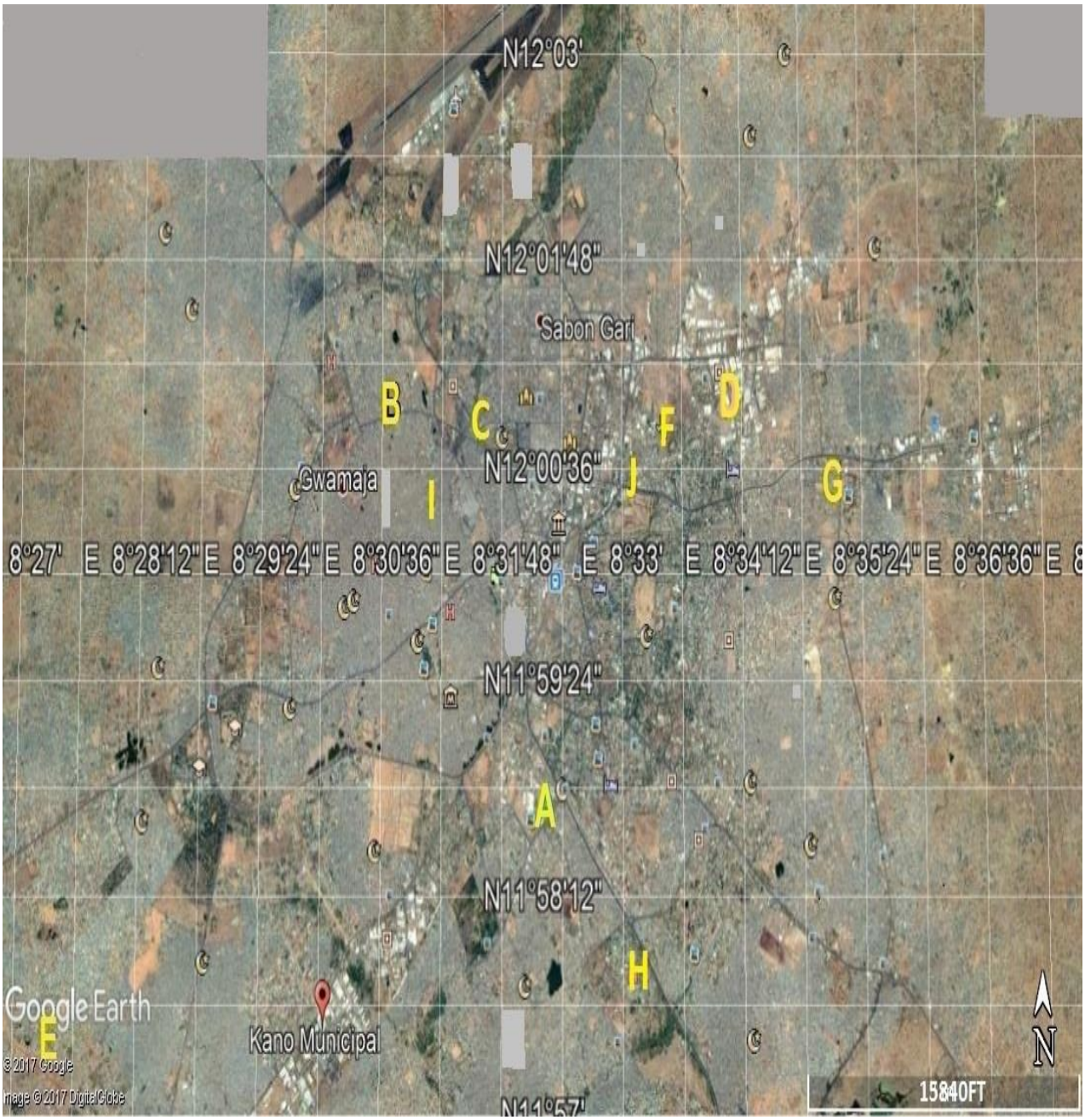
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APPENDICES

APPENDIX I: Plate I and Digital Map of Study Area



Source: Google Earth, 2018.

A- Court Road SWDs **E-** Kuntau SWDs **H-**Ramin Birji SWDs
B- Ubagama SWDs **F-** Ramin Hussain SWDs **I-** Kwarin Goshi SWDs
C- Hajj Camp SWDs **G-** Yankaba SWDs **J-** Ramin Hassan SWDs **K.** Maimalari SWDs

APPENDIX II: Plates and Location on Kano Layout Map of Respective Solid Waste Disposal Sites

a. Court Road



Plate II: Court Road Solid Waste Disposal Site
Source: Author's Field Work, 2019.



Court road – Location on Kano Layout Map
Source: Kano State Ministry of Land and Physical Planning, 2018.

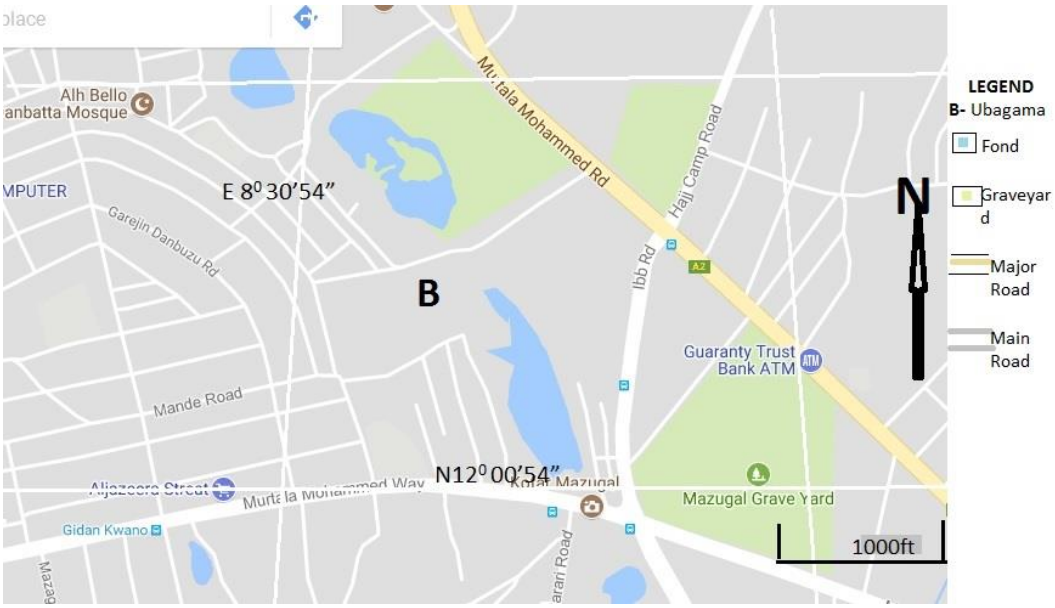


Plate III: Court road - Location on Google Earth Image of Kano Metropolis
Source: Google Earth, 2018.

b. **Ubagama**



Plate IV: Ubagama Solid Waste Disposal Site.
Source: Author's Field Work, 2019.



Ubagama – Location on Kano Layout Map
Source: Kano State Ministry of Land and Physical Planning, 2018.



Plate V: Ubagama - Location on Google Earth Image of Kano Metropolis
Source: Google Earth, 2018.

c. Hajj Camp



Plate VI: Hajj Camp Solid Waste Disposal Site.
Source: Author's Field Work, 2019.



Hajj Camp – Location on Kano Layout Map
Source: Kano State Ministry of Land and Physical Planning, 2018.

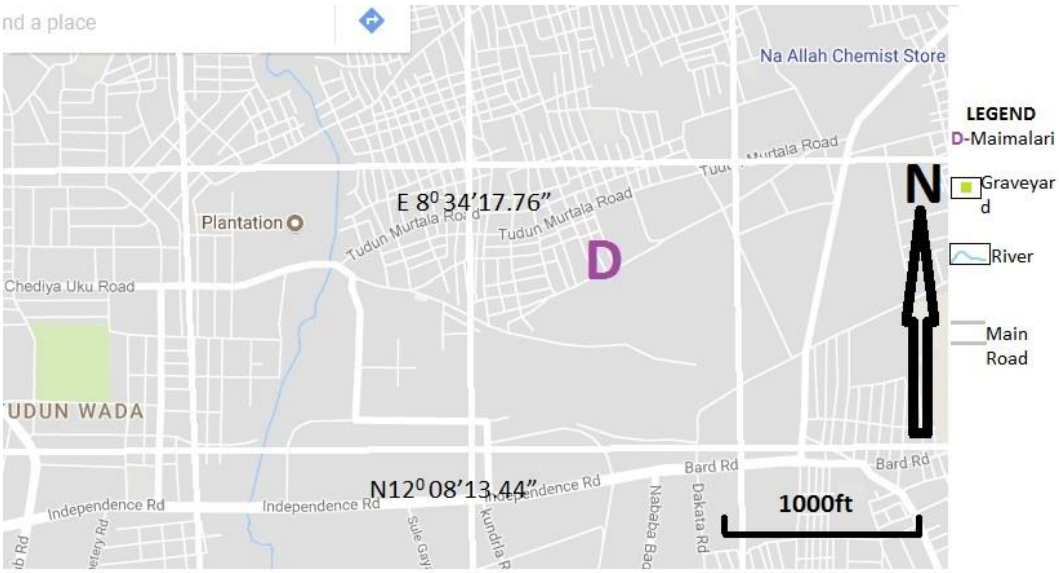


Plate VII: Hajj Camp - Location on Google Earth Image of Kano Metropolis
Source: Google Earth, 2018.

d. **Maimalari**



Plate VIII: Maimalari Solid Waste Disposal Site.
Source: Author's Field Work, 2019.



Maimalari – Location on Kano Layout Map
Source: Kano State Ministry of Land and Physical Planning, 2018.

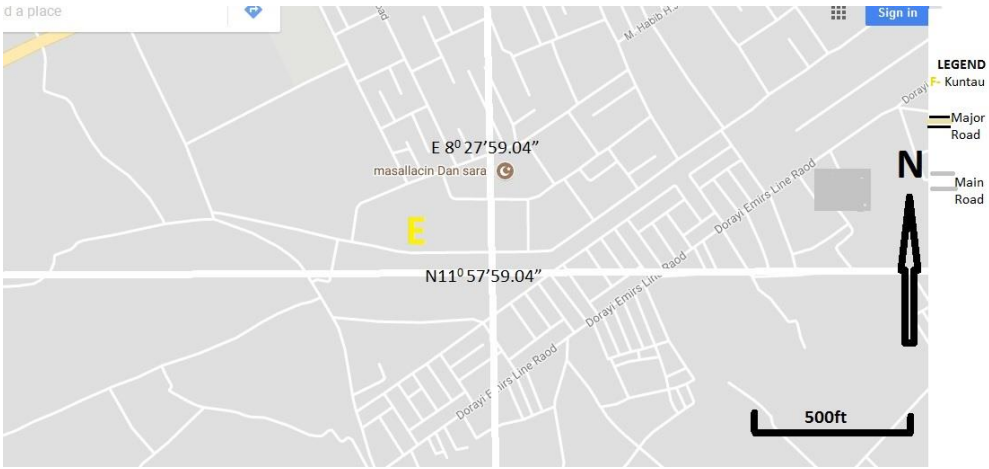


Plate IX: Maimalari - Location on Google Earth Image of Kano Metropolis
Source: Google Earth, 2018.

e. Kuntau



Plate X: Kuntau Solid Waste Disposal Site
Source: Author's Field Work, 2019.



Kuntau– Location on Kano Layout Map
Source: Kano State Ministry of Land and Physical Planning, 2018.

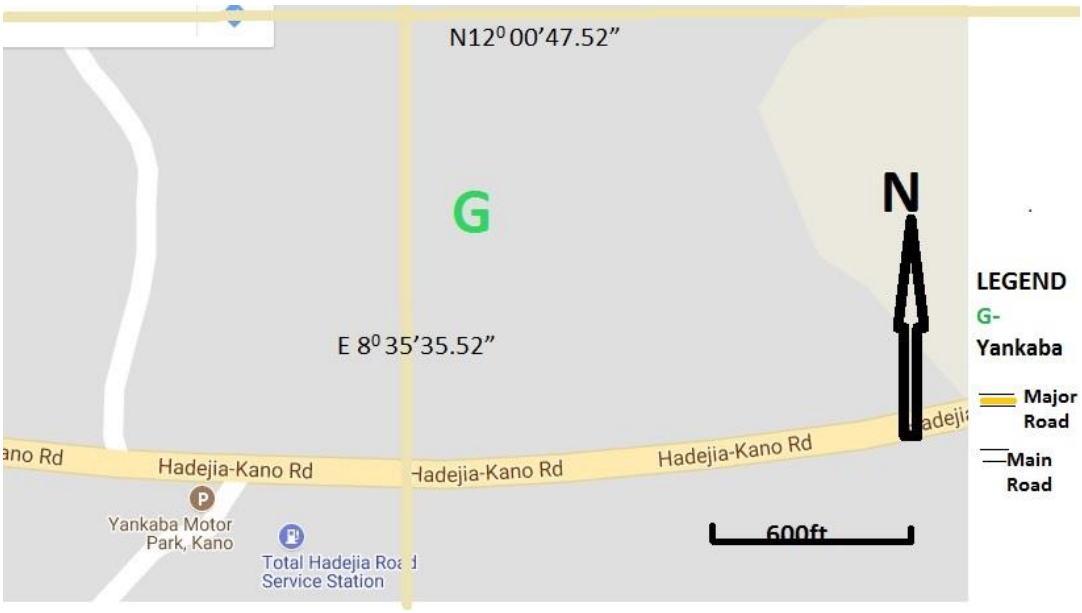


Plate XI: Kuntau - Location on Google Earth Image of Kano Metropolis
Source: Google Earth, 2018.

f. **Yankaba**



Plate XII: Yankaba Solid Waste Disposal Site
Source: Author's Field Work, 2019.



Yankaba – Location on Kano Layout Map
Source: Kano State Ministry of Land and Physical Planning, 2018.



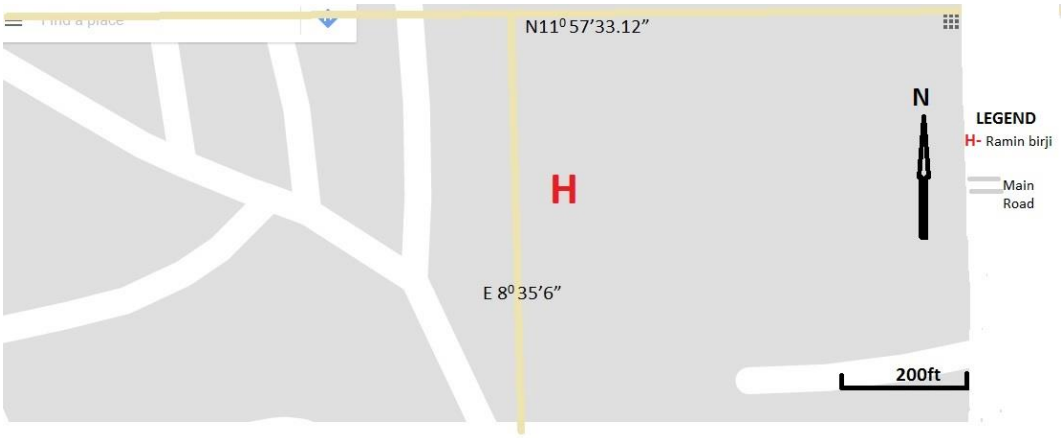
Plate XIII: Yankaba - Location on Google Earth Image of Kano Metropolis
Source: Google Earth, 2018.

g. Ramin Birji

Ramin Birji Solid Waste Disposal Site



Plate XIV: Ramin Birji Solid Waste Disposal Site
Source: Author's Field Work, 2019.



Ramin Birji – Location on Kano Layout Map
Source: Kano State Ministry of Land and Physical Planning, 2018.

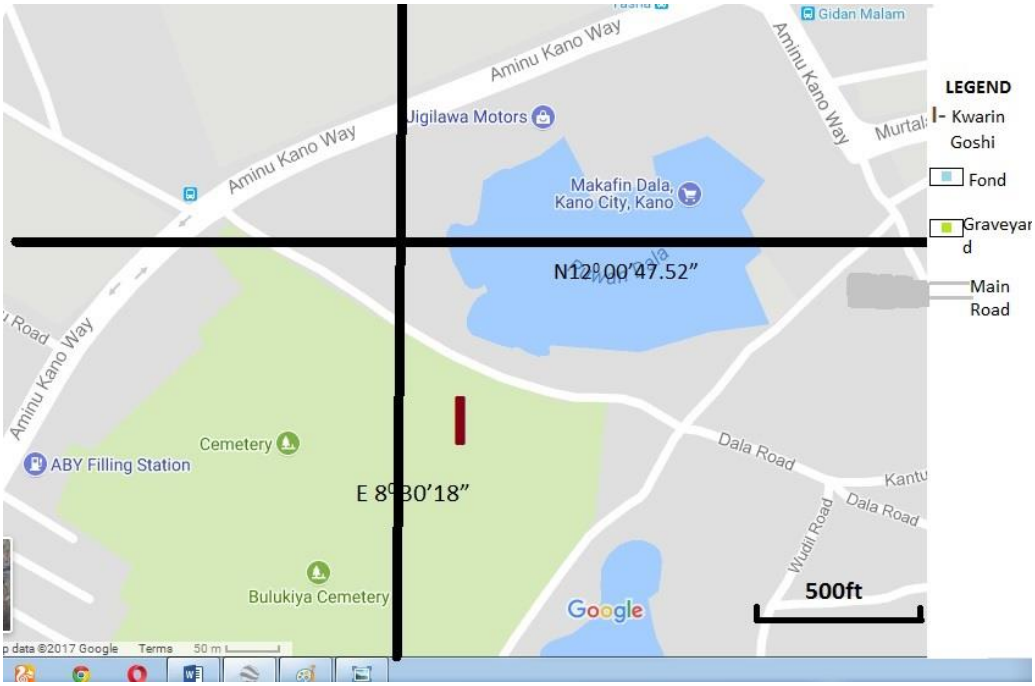


Plate XV: Ramin Birji - Location on Google Earth Image of Kano Metropolis
Source: Google Earth, 2018.

h. Kwarin Goshi



Plate XVI: Kwarin Goshi Solid Waste Disposal Site
Source: Author's Field Work, 2019.



Kwarin Goshi – Location on Kano Layout Map
Source: Kano State Ministry of Land and Physical Planning, 2018.

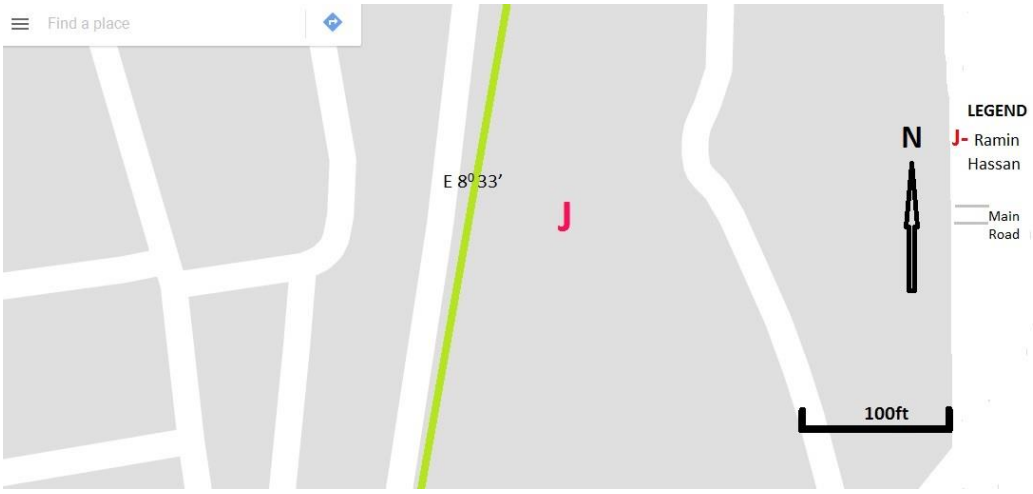


Plate XVII: Kwarin Goshi - Location on Google Earth Image of Kano Metropolis
Source: Google Earth, 2018.

i. Ramin Hassan



Plate XVIII: Ramin Hassan Solid Waste Disposal Site
Source: Author's Field Work, 2019.



Ramin Hassan – Location on Kano Layout Map
Source: Kano State Ministry of Land and Physical Planning, 2018.



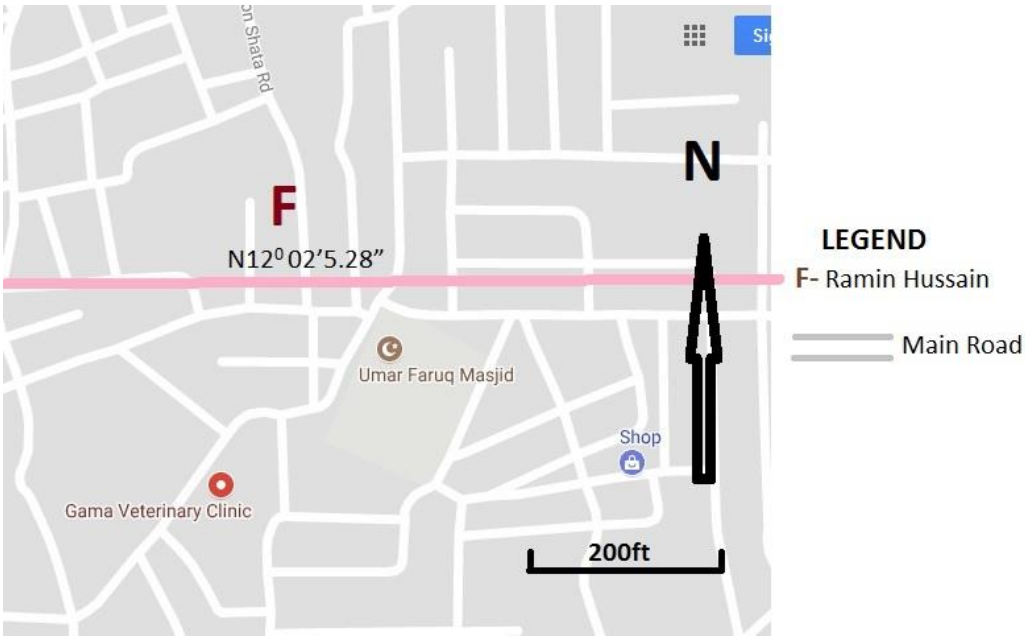
Plate XIX: Ramin Hassan - Location on Google Earth Image of Kano Metropolis
Source: Google Earth, 2018.

j. **Ramin Hussain**

Ramin Hussain Solid Waste Disposal Site



Plate XX: Ramin Hussain Solid Waste Disposal Site
Source: Author's Field Work, 2019.



Ramin Hussain – Location on Kano Layout Map
Source: Kano State Ministry of Land and Physical Planning, 2018.



Plate XXI: Ramin Hussain - Location on Google Earth Image of Kano Metropolis
Source: Google Earth, 2018.

APPENDIX III: Methane Emissions and Meteorological Conditions Field Recording Sheet Using Crowcon Crowcon – Gasman "FL" by Seasons

A. Harvest season

S/N	SWDs	Methane (% LEL)	Methane (% LEL)	Temp. (^{0}C)	Temp.(^{0}C)	Pressure (mbar)	Pressure (mbar)
		Morning	**Afternoon**	**Morning**	**Afternoon**	**Morning**	**Afternoon**
01	Court Road	36	39	31	34	1014	1008
02	Ubagama	22	46	30	35	1015	1010
03	Maimalari	19	28	30	35	1015	1009
04	Yankaba	19	25	31	35	1016	1008
05	Ramin Birji	08	10	32	35	1017	1011
06	Kwarin Goshi	13	19	31	35	1016	1009
07	Hajj Camp	26	33	30	34	1014	1011
08	Kuntau	25	38	31	35	1012	1009
09	Ramin Hassan	28	35	32	35	1015	1008
10	Ramin Hussain	29	32	32	35	1015	1008

Source: Author's Field Work, 2019.

B. Wet season

S/N	SWDs	Methane (% LEL)	Methane (% LEL)	Temp. (^{0}C)	Temp. (^{0}C)	Pressure (mbar)	Pressure (mbar)
		Morning	**Afternoon**	**Morning**	**Afternoon**	**Morning**	**Afternoon**
01	Court Road	20	14	32	23	1004	1013
02	Ubagama	25	16	33	23	1006	1014
03	Maimalari	26	17	32	24	1008	1015
04	Yankaba	25	18	33	24	1006	1014
05	Ramin Birji	19	15	33	25	1008	1013
06	Kwarin Goshi	21	14	33	23	1008	1013
07	Hajj Camp	28	20	34	24	1008	1013
08	Kuntau	27	22	34	24	1008	1012
09	Ramin Hassan	26	15	34	23	1009	1014
10	Ramin Hussain	24	12	34	23	1009	1014

Source: Author's Field Work, 2019.

C. Hot dry season

S/N	SWDs	Methane (% LEL)	Methane (% LEL)	Temp.(^{0}C)	Temp. (^{0}C)	Pressure (mbar)	Pressure (mbar)
		Morning	**Afternoon**	**Morning**	**Afternoon**	**Morning**	**Afternoon**
01	Court Road	17	40	30	41	1015	1004
02	Maimalari	18	29	31	41	1015	1004
03	Ubagama	12	22	31	40	1014	1006
04	Ramin Birji	18	28	30	41	1014	1003
05	Kuntau	21	39	31	41	1016	1002
06	Ramin Hassan	30	36	32	40	1016	1003
07	Ramin Hussain	20	33	32	41	1016	1003
08	Hajj Camp	32	37	31	41	1016	1006
09	Kwarin Goshi	15	24	32	41	1016	1008
10	Yankaba	16	23	31	41	1014	1005

Source: Author's Field Work, 2019.

D. Cool dry season.

S/N	SWDs	Methane (% LEL)	Methane (% LEL)	Temp. (^{0}C)	Temp. (^{0}C)	Pressure (mbar)	Pressure (mbar)
		Morning	**Afternoon**	**Morning**	**Afternoon**	**Morning**	**Afternoon**
01	Court Road	14	23	16	26	1023	1016
02	Maimalari	10	13	17	26	1022	1015
03	Ubagama	09	12	16	27	1023	1016
04	Ramin Birji	08	10	16	26	1021	1016
05	Kuntau	09	14	17	27	1024	1011
06	Ramin Hassan	10	15	17	26	1025	1014
07	Ramin Hussain	08	14	17	26	1024	1017
08	Hajj Camp	09	14	16	27	1024	1013
09	Kwarin Goshi	11	17	17	27	1023	1013
10	Yankaba	10	13	16	28	1026	1011

Source: Author's Field Work, 2019.

APPENDIX IV: Variation of Methane Emissions at Different Points Away from the Solid Waste Disposal Sites Using Crowcon Crowcon – Gasman "FL" During the Two Periods

A. Morning period

S/NO.	SWDs	0m away	100m away	200m away	300m away
01	Court Road	22	13	06	04
02	Ubagama	14	09	03	01
03	Maimalari	15	11	05	03
04	Yankaba	14	09	04	01
05	Ramin Birji	12	07	03	02
06	Kwarin Goshi	12	08	05	02
07	Hajj Camp	19	12	09	03
08	Kuntau	17	13	08	05
09	Ramin Hassan	20	15	09	07
10	Ramin Hussain	21	12	07	03

Source: Author's Field Work, 2019.

B. Afternoon period

S/NO.	SWDs	0m away	100m away	200m away	300m away
01	Court Road	29	17	10	06
02	Ubagama	22	15	06	03

03	Maimalari	21	12	05	03
04	Yankaba	19	13	03	01
05	Ramin Birji	15	09	06	02
06	Kwarin Goshi	12	10	05	02
07	Hajj Camp	26	14	10	05
08	Kuntau	28	17	11	07
09	Ramin Hassan	29	18	10	08
10	Ramin Hussain	25	15	09	06

Source: Author's Field Work, 2019.