ASSESSMENT OF CARBON DIOXIDE EXTRACTION IN A SOLID WASTE MANAGEMENT FACILITY, AKURE, NIGERIA

BY

ELEMILE, OLUGBENGA OLUSEUN
135390
B.Sc. Mechanical Engineering (OAU, Ife), MPH (Ibadan),
M.N.S.E., Reg. Engr.

A Thesis in the Department of Civil Engineering,
Submitted to the Faculty of Technology
In partial fulfilment of the requirement for the Degree of

DOCTOR OF PHILOSOPHY

of the

UNIVERSITY OF IBADAN

SEPTEMBER, 2016

ASSESSMENT OF CARBON DIOXIDE EXTRACTION IN A SOLID WASTE MANAGEMENT FACILITY, AKURE, NIGERIA

ELEMILE, OLUGBENGA OLUSEUN

Certification

We certify that this research work was carried out by Olugbenga Oluseun ELEMILE of the Department of Civil Engineering, Faculty of Technology, University of Ibadan, Ibadan.

…………………………………………………………………………………………

Supervisor

A. O. Coker
B.Sc. (Ib), M.Sc (Ife), Ph.D (Ib), M.N.S.E, R.ENGR
Professor, Department of Civil Engineering
Faculty of Technology
University of Ibadan, Ibadan.

…………………………………………………………………………………………..

Supervisor

M. K. C. Sridhar
B.Sc. (Andhra), M.Sc. (Baroda), Ph.D (IISC). C.Chem., M.R.S.C., F.R.S.H., M.C.I.W.E.M
Professor, Department of Environmental Health Sciences,
Faculty of Public Health,
College of Medicine,
University of Ibadan, Ibadan.

DEDICATION

This work is dedicated to the Almighty God, who is the Alpha and Omega, through whom all things are made possible. May his name be exalted forever (Amen)

And

To my late Father, Engineer Emmanuel Olufemi ELEMILE, who I know would have been well pleased with this effort if he lived to witness it.

ACKNOWLEDGEMENT

I wish to acknowledge with thanks the immense contributions of my supervisors Professor A.O. Coker and Professor M.K.C. Sridhar for the supervision of this Thesis and their desire to see me through the course successfully, by their unrelenting efforts that eventually produced the desired end results. You are deeply appreciated.

I will like to acknowledge the contributions of my examiners, Professor I.K Adewumi and Professor A.Y Sangodoyin for their timely contributions in the enrichment of this Thesis.

I will like to strongly recognize His Royal Highness, Oba (Dr) A.O Akinola for his immense contribution towards this work. He was always there when there were some knots to be untied. Professor J.O Babatola is also highly recognized for his advice.

My sincere thanks also go to Dr G.R.E.E Ana, Dr Elizabeth Oloruntoba and Dr Christianah Ijagbemi for their encouragement and advice during the course of the study.

Many thanks also go to my Lecturers at the Civil Engineering Department in persons of Professor O. A Agbede, Professor J. O Oluwoye, Dr Folake Akintayo, Dr Gbenga Ayinnuola and Dr K.K Adewole for their contributions to the work especially during the proposal presentation, conversion examination, post field presentation and abstract writing.

My special and unreserved appreciation goes to Professors G.T.A Ijaduola and E.A Bamgboye and Late Professor J.D Adeniyi for being fathers to me and without whom my admission into the Civil Engineering Department would not have been possible.

I will also like to appreciate Engr. E.A Oluwadamisi and Engr. O Adetayo who are fellow Ph.D Students for their support and comradeship especially during the programmme.

I will also like to recognize Mr. Femi Ajani formerly of the Postgraduate School now in the Undergraduate Admissions of the University, Mr. Ayobami Olajide, Mrs Anthonia Obasa and other non-academic members of Staff of the Civil Engineering, their efforts in ensuring the timely completion of the programme are highly appreciated.

Special thanks also go to Late Engr. C.O Sanusi, Engr. S.O Adesemuyi and Mr R.O Awuyo all of the Ondo State Water Corporation and Dr A. A Akinro for their role in making it possible for me to be able to undergo the programme at the University of Ibadan.

I will also appreciate Engr. K.S Adeoba, Mr. Fola Omowole and Mr Abiola Amodu all of the Ondo State Waste Management Board for their role in the conduct of the research and gaining access to the study location.

My special and unreserved appreciation also goes to my wonderful Mother, Dr. Mrs. T.T.A Elemile. Thanks for your love, concern, understanding, prayers and financial support. You shall live to eat the fruit of your labour. To my one and only sister Olufunke and her loving husband Femi thanks for your encouragement, love and tolerance and for believing in me always. I appreciate my uncle, Dr. P.O Elemile, my Aunties; late Mrs V.O Fadare, Mrs. O.O Adetuyibi and Mrs. O. Elemile for their immense contributions.

I will not fail to acknowledge Dr D.O Omole, Dr H. B Taiwo, Dr. S Aribo and Mr. M.O Morakinyo for their timely and relevant advice and contributions especially during the stage of Abstract writing.

My thanks go to Mr. A Ajadi and Mr. O. Orungbemi who were Students of the Federal University of Technology Akure for their contributions especially during the design and fabrication of the extractor.

My thanks go to Pastor O Olaniyonu, Pastor John Adetoyinbo, Pastor Tosin Adetoyinbo and the entire members of the Global Harvest Church, Akure for their prayers and encouragement during the latter part of the program.

To all who contributed in one way or the other to my life and success even though your names are not mentioned, you are remembered, God bless you all.

I owe so much to my dear wife, Mayowa and lovely boys Diekololaoluwa and Oluwadarasimi for bearing with me, missing so many things for my sake, and encouraging me during the course of this programme. You are my Heroine and Heroes. Thank you so much, I love you.

Finally and above all things, I exalt the almighty God, the Omnipotent and Omniscience for preserving me (spirit, soul and body) though the thick and thin in the course of my study. Thanks for journey mercies; thanks for preserving the house I left behind; thanks for the job I used to finance the programme; thanks for the wisdom and knowledge you gave me to pass all my courses; thanks for the people you brought my way and thanks for your glory over my life and for satisfying me with all your mercies. To you belong all the Glory, Honour, Power and Majesty. Lord, I would forever love and honour you.

TABLE OF CONTENT

Page

LIST OF FIGURES

LIST OF PLATES

LIST OF TABLES

LIST OF ACRONYMS

APC	Air Pollution Control
AC	Aerobic Composting
AD	Anaerobic Digestion
AM005	Avoided Emissions from Organic Waste through Alternative Waste Treatment Processes
BAU	Business as Usual
CCGT	Combined Cycle Gas Turbine
CCME	Canadian Council of Ministers of the Environment
CDM	Clean Development Mechanism
CER	Certified Emission Reduction
CH_4	Methane
CHP	Combined Heat and Power
CO_2	Carbon dioxide
$CO_{2\text{-}e}$	CO_2 equivalent
DAKOFA	Danish Waste Management Association (eng.)
DM	Default Method
DOC	Degradable Organic Carbon
DTIE	Division of Technology, Industry and Economics (UNEP)
EIA	Energy Information Agency
EIT	Economies in Transition
EPR	Extended Producer Responsibility
ERC	Eunomia Research & Consulting
FOD	First Order Decay
GDP	Gross Domestic Product
GEF	Global Environment Fund
GHG	Greenhouse Gas
GWP	Global Warming Potential
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
ISWA	International Solid Waste Association
JI	Joint Implementation
LCA	Life Cycle Assessment

LFG	Landfill Gas
MBT	Mechanical Biological Treatment
MCF	Methane Correction Factor
MRF	Material Recovery Facility
MSW	Municipal Solid Waste
N_2O	Nitrous Oxide
NMVOC	Non-Methane Volatile Organic Compounds
ODMOFDRS	Ondo State Ministry of Finance Department of Research and Statistics
OECD	Organisation for Economic Co-operation and Development
RDF	Refuse Derived Fuel
ROU	Recycled Organics Unit
SAS	Sorting at Source
SBC	Secretariat of the Basel Convention
SCP	Sustainable Consumption and Production
USDOE	United State Department of Energy
UNESCAP	United State Economic and Social Survey of Asia and Pacific
UNEP	United Nations Environmental Programme
UNFCCC	United Nations Framework Convention on Climate Change
USEPA	United State Environmental Protection Agency
WARM	Waste Reduction Model
WEEE	Waste Electrical and Electronic Equipment
WRAP	Waste and Resources Action Program

ABSTRACT

Carbon dioxide (CO_2) emissions from solid wastes is a major contributor to the acceleration of global warming. In Nigeria, CO_2 capture has been limited to the energy sector only. There is need to explore the reduction of CO_2 emissions from solid wastes through appropriate technologies. This study, therefore was designed to assess CO_2 extraction by adsorbents in a Municipal Solid Waste (MSW) management facility in Akure, Nigeria.

An exploratory study design with an intervention component was adopted. For a year, wastes brought to the MSW facility from three locations viz: markets, residences and roadside, were characterised and quantified monthly. Chemical characteristics of the wastes were determined using standard methods. Carbon-dioxide emissions were estimated from the MSW composition using the Intergovernmental Panel on Climate Change tools. Air CO_2 levels were monitored during the dry and wet seasons using a P-Sense Plus CO_2 meter AZ-7755(PSPCM) and seasonal variations computed. A CO_2 extractor which uses adsorbents consisting of Sawdust + Potassium Hydroxide (SKH), Sawdust + Sodium Hydroxide (SSH) and Sawdust + Calcium Hydroxide (SCH), all at ratio1:1, was designed and fabricated. The adsorbents were integrated into the equipment to capture CO_2 from 5 kg samples of solid wastes burnt under controlled conditions with five replicates for each adsorbents during each test. The potential CO_2 in the solid wastes was determined by ultimate analysis, while the concentration of CO_2 adsorbed was obtained by finding the difference between the concentration of the CO_2 at the inlet and outlet chambers of the extractor measured with the PSPCM. The effectiveness of the extractor combined with the adsorbents was determined by comparing the adsorbed CO_2 with the potential CO_2. Data were analysed using descriptive statistics and ANOVA at $\alpha_{0.05}$

The mean monthly wastes generation from the three locations were 1,004,130.8±742,394.6 kg (biodegradable wastes), 1,322,831.0±810,634.9 kg (plastics) and 1,330,813.5±400,412.4 kg (paper). The mean values for the chemical constituents of these wastes for the three locations, residential, roadside and market respectively were Nitrogen 2.7±0.6, 2.1±0.8 and 3.4±0.7%; Phosphorus 0.10±0.03, 0.10±0.03 and 0.10±0.04% and Carbon 53.2±1.4, 53.1±1.8 and 53.1±1.5%, with no significant difference within the groups. The estimated CO_2 emissions was 1.2 Gg/Yr.

The ambient CO_2 levels ranged between 438.0±7.2 and 630.0±124.5 ppm in the dry season, and 407.3±11.3 and 506.9±71.1 ppm for the wet season. The mean potential CO_2 in the solid wastes was 160.0± 42.0 ppm. The mean CO_2 adsorbed were 99.0±24.0 ppm, 45.0±24.1 ppm and 30.0±13.0 ppm for SKH, SSH and SCH respectively. The effectiveness of SKH in the capture of CO_2 was 61.9 % as against 20.8 % and 18.8 % by SSH and SCH, respectively.

The selected adsorbents were effective in capturing carbon dioxide. Incorporation of Sawdust + Potassium Hydroxide improves the effectiveness of carbon dioxide extraction in the solid waste management facility.

Key Words: Municipal solid wastes, Solid wastes characterisation, Carbon dioxide emissions, Carbon dioxide adsorption

Word count: 459

CHAPTER ONE

INTRODUCTION

1.1 Background of the study

Global warming has become a matter of public concern in the last few years. This could be mainly attributed to the trapping of enormous quantities of typical gases (termed as ‘‘greenhouse gases’’) in the earth’s atmosphere resulting in greenhouse gas (GHG) effect thereby increasing the ambient temperatures. Methane is regarded as one of the most important GHGs because its global warming potential has been estimated to be more than 20 times of that of carbon dioxide and atmospheric methane concentration has been increasing in the range of 1–2% yr^{-1} (IPCC, 2006).

Waste landfills have been recognized as the large source of anthropogenic methane emission and an important contributor to global warming (IPCC, 2006). Methane emissions from landfills is estimated to account for 3–19% of the anthropogenic sources in the world (IPCC, 2006). The estimation has been made from mere calculation using national statistics on waste generation. In many countries, especially the developing economies of the world, the available data on waste generation are not consistent, leading to a large uncertainty in the estimates.

Carbon dioxide emissions to the atmosphere have risen steadily since the beginning of the industrial revolution. Furthermore, conservative estimates suggest that the world energy demand will double by the middle of this century (OECD/IEA, 1998). Energy demand in the developing countries is growing by 3.5% per year, much faster than in the developed world, with these developing countries currently emitting 30% of the global total. Worldwide, carbon dioxide emissions are expected to exceed 36 billion tons of carbon dioxide per year by the year 2020 (IEA, 2000). Even though these forecasts may not be very accurate, the fact remains that tens of billions of tons will be emitted on an annual basis. It is reasonable to expect that, if there is a reduction, it will occur gradually and may not start in earnest before 2020. Carbon dioxide emissions will continue for the foreseeable future.

1.2 Problem statement

Municipal solid waste is a significant contributor to greenhouse gas emissions through decomposition and life-cycle activities processes. The majority of these emissions are a result of landfilling, which remains the primary waste disposal strategy internationally (Lou, 2009). In particular, the disposal of waste in landfills generates methane that has high global warming potential. Effective mitigation of greenhouse gas emissions is important and could provide environmental benefits and sustainable development, as well as reduce adverse impacts on public health (Papageorgiou, 2009).

In the last few decades, the greenhouse gases produced by human activities have been predominating over those of natural origin (Hansen, 2004). The waste sector is a significant contributor to greenhouse gas (GHG) emissions accounting for approximately 5% of the global greenhouse budget (IPCC, 2006). This 5% consists of methane (CH_4) emission from anaerobic decomposition of solid waste and carbon dioxide (CO_2) from wastewater decomposition (IPCC, 2006).

According to recent estimates, the waste sector contributes about one-fifth of global anthropogenic methane emissions (IEA 2005) and methane contribution to climate change is about one-third to a half of that of carbon dioxide (Hansen and Sato 2001). Waste sector emissions have grown steadily globally and are expected to increase in the forthcoming decades especially in developing countries like Nigeria. This is because of increase in population and GDP (IPCC 2000). In recognition of this, the Clean Development Mechanism (CDM) established by Kyoto Protocol in 1997, recognized waste and its disposal as one of the sectors identified for green house gas reduction.

Carbon dioxide (CO_2) is considered as a major contributor of greenhouse gas (GHG). Scientists found that CO_2 emission plays a critical role in the acceleration of global warming trends (USDOE, 1993). Furthermore, the global model suggests that an increase in CO_2 level leads to increasing oceanic vaporization resulting in a warming cycle (USDOE, 1993). Land filling is one of the most common ways of municipal solid waste (MSW) disposal. MSW is made up of different organic and inorganic fractions such as food, vegetables, paper, wood, plastics, glass, metal and other inert materials. In cities, it is collected by respective municipalities and transported to designated disposal sites. The insanitary methods adopted for disposal of waste cause serious health and environmental problems. The poorly maintained landfill sites are prone to groundwater contamination because of leachate percolation (Mor *et al,* 2006a). Furthermore they cause bad odours and risks of explosion of methane gas that can accumulate at the landfill site (Tchobanoglous *et al,* 1993). Typically the landfill gas consists of 50-60 Volume % of methane and 30-40 Volume % carbon dioxide with numerous chemical compounds such as aromatics, chlorinated organic compounds and sulfur compounds (Khalil, 1999). Landfills comprise the principal source of anthropogenic methane emission and are estimated to account for 3-19% of anthropogenic emission globally (US EPA, 2006).

1.3 Justification/rationale for the study

When solid waste (SW) is disposed in waste dumps and landfills, most of the organic material will be degraded over a longer or shorter period, ranging in a wide span from less than one year to 100 years or more. The majority of this process will be bio-degradation. Strongly depending on conditions in the site where the SW is disposed, this biodegradation will be aerobic or anaerobic. The main degradation products are carbon dioxide (CO_2), water and heat for the aerobic process and methane (CH_4) and CO_2 for the anaerobic process. The CH_4 produced and released to the atmosphere contributes to global warming and the emissions need to be estimated and reported in national greenhouse gas inventories under the United Nations' Framework Convention on Climate Change (UNFCCC, 2000). Fortunately in Nigeria, some works have been reported about the greenhouse gas emissions contributed by the wastes management sector, but it is imperative to look into the estimation of carbon emission potentials of open dumps which is the major method of disposal of solid wastes in Akure and in many Nigerian cities.

Also most of the work on carbon dioxide capture from the atmosphere had been focused on the energy and transportation sector. Little or nothing has been done in the developing countries especially in the solid wastes disposal sector. There is therefore the need to look into the possibility of achieving the prevention or substantial reduction of carbon dioxide emissions to the atmosphere from the waste sector through the development of a Carbon Dioxide Extractor (CDE) using locally available materials. The success can be replicated in other sectors with problems of uncontrolled carbon emissions directly to the atmosphere. This can help in reducing global warming.

1.4 Aim of the study

The major aim of this study was to develop a carbon dioxide extractor and assess the extractability of carbon dioxide emissions using various adsorbents in a solid wastes management facility, in Akure, Ondo State, Nigeria.

1.5 Specific objectives

The specific objectives of this study were to:

1. characterize the solid wastes generated in Akure brought to the Solid Wastes Management Facility into various physical components and chemical composition;
2. estimate the Carbon Emissions Potential of the solid wastes over wet and dry seasons to check if there are seasonal variations in the environmental carbon-dioxide levels emitted at the Solid Wastes Management Facility;
3. design and fabricate a Carbon Dioxide Extractor for carbon dioxide extraction in the solid wastes management facility; and
4. model and evaluate the effectiveness of Carbon Dioxide Extractor using economically viable adsorbents sourced locally

1.6 Scope of study

The scope of the study was limited to the characterization of solid waste into physical composition and chemical components, monitoring of environmental carbon-dioxide (CO_2) emissions with a view to examining the relationship if any between carbon-dioxide emissions in the wet and dry seasons and determination of the carbon emissions potential; all were carried out within one seasonal replication. The study also mitigated the CO_2 emissions by designing, constructing, modeling and evaluating the performance of a carbon dioxide extractor. The intervention was limited to a mechanically assisted CO_2 adsorption unit for solid waste burnt in an enclosed surface area so that the emissions were adsorbed adequately and prevent release into the atmosphere. The intervention is useful for transfer stations and not adequate for adsorption of emissions in an open dump. The modelling was limited to a laboratory scale analysis in a solid waste management facility receiving municipal wastes.

CHAPTER TWO

LITERATURE REVIEW

2.1 What is solid waste?

Solid wastes are wastes arising from all human and animal activities that are normally solid and that are regarded as useless or unwanted (Tchobanoglous *et al,* 1993). According to Sridhar (1998) wastes may be regarded as any unavoidable materials resulting from domestic activities and industrial operations for which there are no economic demand and which must be disposed of. All aspects of human endeavours are associated with waste generation (Adesida and Igbuku, 1998). Leton and Omotosho (2004) defined solid wastes as non-liquid and non-gaseous products of human activities, regarded as being useless. It could take the forms of refuse, garbage and sludge. Solid waste is broadly defined as that including non-hazardous industrial, commercial and domestic refuse which includes household organic trash, street sweepings, hospital and institutional garbage, and construction wastes; generally sludge and human waste is regarded as a liquid waste problem outside the scope of Municipal Solid Waste (MSW).

2.2 Classification and sources of solid wastes

Tchobanoglous *et al,* (1993) classified wastes into (1) Residential wastes which include generated food wastes, rubbish, ashes and special wastes; (2) Commercial Wastes generated from restaurants, institutions, offices, hotels, motels; (3) Municipal wastes which is a combination of Residential and Commercial wastes; (4) Industrial wastes which include wastes from construction, fabrication, light and heavy manufacturing, refineries, mining, power plants etc. (5) Agricultural Wastes which include wastes from field and row crops, orchards, vineyards etc.

Another type of wastes which was not classified above is Biomedical Wastes. Coker *et-al*, (2000) defines biomedical wastes as largely infectious wastes generated from health care establishments, medical institutions, diagnostic laboratories, veterinary clinics, hospitals and research facilities. Savas (1977) also classified solid wastes into municipal waste which include; garbage, rubbish (combustible and non combustible solid waste of households, institutions, commercial activities, ashes, abandoned vehicles, agricultural wastes (crop residues, animals), industrial wastes, hazardous wastes, construction wastes, sewage treatment wastes (sludge). etc. (Peavy *et al*, 1985) divided solid wastes into three general categories namely municipal wastes, industrial wastes and hazardous wastes.

Solid wastes may be broadly classified as hazardous wastes and non- hazardous wastes. Non-hazardous wastes have little or no potential to produce harmful consequence or toxic leachates when stored, while hazardous wastes pose immediate and/or latent hazards to plant, animal and ecological environment. Hazardous wastes such as tissues/cultures, sulfuric and/or hydrochloric acids, cyanides, cadmium, copper, chromium, organic solvents and lubricating oils which produce toxic leachates and harmful fall-out when stored or disposed in the environment (Peavy *et al*, 1985).

2.3 Variations in the characteristics of solid waste

2.3.1 Seasonal variation

Variations in the characteristics of solid wastes arise from seasonal factors with respect to both climates, cultural and religious events. During the wet season, the waste becomes moist and denser and total tonnage increases. Quantities of solid waste may also increase during cultural and religious festivals. Climate affects the generation of vegetative waste (yard and garden) or plant growth responds to favourable temperatures and soil while in tropical areas, where temperatures are always favourable, maximum growth is during the raining season. At the end of the growth season (autumn dry season) leaves may comprise a significant proportion of the solid wastes (Bhide and Sundereasan, 1983). Seasonal variations in waste quantities must be accommodated by the management system.

2.3.2 Locational variation

Wastes generated in countries located in humid, tropical, and semitropical areas usually are characterized by a high concentration of plant debris; whereas those generated in areas subject to seasonal changes in temperature or those in which coal or wood are used for cooking and heating may contain an abundance of ash (Diaz and Golueke, 1985). The concentration of ash may be substantially higher during winter. Regardless of climatic differences, the wastes usually are more or less contaminated with night soil (Diaz and Golueke, 1985). These differences prevail even in wastes generated in large metropolitan areas of a developing country (Diaz and Golueke, 1985). Normally due to differences in seasonal variation in different parts or areas of the country, specific wastes will be produced. For example, industrial wastes will produce waste resulting from the raw materials or products in the course of production, while paper mill will produce paper as waste and residential areas will produce basically domestic waste. Institutions will produce wastes related to the functions of such institutions (Tchobanoglous *et al*, 1993).

2.4 Solid wastes management situation in Akure and some south western cities in Nigeria

In most cities in Nigeria, waste management issues have become a glaring challenge. In recent years, there has been a phenomenal increase in the volume of wastes generated daily in the country (Olanrewaju and Ilemobade, 2009). This is due to the huge volume of waste generated in the cities on a daily basis which calls for proper handling in order to protect the environment and the population. Hoornweg (1999) emphasized that waste is inseparable from life because as long as man is alive, he stores up, uses, and disposes off materials and the complexity of waste which modern civilization produced is directly related to the living standard, socio-economic and cultural attributes of that particular environment

Over the years, concerted efforts have been made to adequately solve the problems created by the emanation of wastes. Adewumi et al, (2005) examined the typology, characteristics and future trends of solid waste and asserted that the major components of waste are degradable materials (food remnants, paper, and rags) and non-biodegradable plastics, tins, metals, bottles, glass, and bones. The study asserted that in several Nigerian cities, garbage contributes substantially more than other components, this could be explained by the fact that most activities which affect the environment stem from the need for food; its production, processing and preparation as shown in Table 2.1. It could also be observed that the generation of waste components in Akure does not vary much as compared to other cities in south western Nigeria. The only components where the generation varies significantly is the generation of plastics which is very low, while glass and metal scraps are far above the mean generation of the components. This could be attributed to the fact that the recycling of glass and metal scraps is not rampart in Akure as compared to other cities such as Ibadan and Ile-Ife. For the low generation of plastics in Akure, it could be attributed to the fact that the practice of reuse of plastics is very much in vogue which makes it difficult for the component to be easily disposed of. Moreover, the high proportion of food remnants could be looked at from the fact that this component of waste encompasses all forms of food waste from both domestic and commercial origins. Oreyomi, (1998) maintained that improper disposal of solid waste poses serious danger to the handlers and the people living around the wastes as disposal sites carry along rodents, insects and other vermin, which could transmit diseases such as typhoid fever, dysentery, diarrhea, cholera, yaws, and other diseases.

In another study exploring the average composition of solid waste generated in the urban areas of Akure by Adewumi and Babatola, (2006), it was revealed in Table 2.2 that generally, paper was the most highly generated while bones was the least generated. It could also be observed that the component of waste generated was determined by location. In the Alagbaka area, paper was the most highly generated. Other components of waste such as food waste, plastics, nylon and metals are generated more in other areas than Alagbaka. This is because the area is where most Government offices are domiciled and also a high income area and most workers usually go to their individual homes for their waste generation activities.

A study carried out by Ogedengbe and Oyedele, (2006) showed that the rate of change in domestic waste quantities and composition in developing and developed countries is unprecedented. It further asserted that generally the greater the economic

Table 2.1: Average composition of solid wastes generated in eleven southwestern Nigerian Cities

City	(%)					
	Garbage	Paper	Sand (grit)	Plastic	Glass	Metal Scraps
Ile-Ife	77.9	5.3	7.5	7.3	1.1	0.8
Oyo	62.1	18.5	4.3	10.6	1.4	3.1
Ijebu-Ode	58.7	19.6	4.7	14.7	1.8	0.5
Akure	**59.7**	**14.5**	**11.0**	**1.7**	**6.3**	**7.2**
Ado-Ekiti	60.4	21.4	11.5	4.3	2.2	0.2
Abeokuta	57.8	26.2	3.4	8.7	2.2	1.6
Ibadan	64.9	14.2	6.5	9.9	1.7	2.9
Oshogbo	58.2	17.8	9.9	12.1	0.6	1.4
Iyin-Ekiti	60.9	15.3	18.6	14.1	0.8	0.4
Igede- Ekiti	58.1	19.3	17.7	3.6	1.1	0.2
Odeomu	47.8	37.7	12.3	1.2	0.4	1.4
Mean	60.5	19.1	9.8	7.1	1.7	1.8

Source: Adewumi et al, (2005)

Table 2.2: Average weekly percentage composition of solid wastes generated in six zones in Akure urban

	%						
Parameter	**Zone 1**	**Zone 2**	**Zone 3**	**Zone 4**	**Zone 5**	**Zone 6**	**Mean**
Paper	11.4	10.8	12.0	11.9	18.0	50.7	15.3
Food waste	12.1	23.0	19.6	13.8	9.7	8.1	14.3
Metals	16.7	2.1	13.0	19.0	21.6	10.5	13.9
Plastic	14.6	12.2	6.1	23.1	9.2	5.7	12.8
Nylon	10.7	9.4	9.1	13.1	11.2	7.2	10.2
Wood	6.0	13.0	17.4	9.0	7.2	4.7	8.6
Glass/Bottles	15.3	11.5	14.1	3.6	11.2	6.1	12.7
Can	8.8	13.0	4.3	4.4	7.4	2.9	8.1
Bones	4.4	5.0	4.3	2.0	4.5	4.0	4.3
Total	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**

Source: Adewumi and Babatola, (2009)

- Zone 1: FUTA Area to Ilesha Garage
- Zone 2: Okuta Elerinla Towards Adegbola
- Zone 3: Ondo Road to Ondo Garage
- Zone 4: Oja Ona Area to Araromi, Central Mosque
- Zone 5: Shagari Village to Shebi Area
- Zone 6: Alagbaka Area

prosperity and the higher percentage of urban population, the greater the amount of solid waste generated. According to Akinola and Salami (2001), waste disposal is one of the important aspects of urban management crises in Nigeria. The study noticed that management of solid waste generated within the urban centers has become one of the most intractable problems of development due to a phenomenal increase in the volume and range of waste generated in many developing countries of the world, Nigeria inclusive. This is a direct consequence of urbanization and lack of political will on the part of the administrators.

Adewumi et al, (2005) asserted that domestic waste constitutes the highest percentage of waste generated in Akure. The situation in several other South-Western Nigerian cities also shows that the percentage of domestic wastes is considerably high compared to wastes from other sources. This could be attributed to fact that Akure is not as commercialized and industrialized as cities such as Ibadan. The percentage of agricultural waste is on the average based on the fact that agricultural activities are high because of the surrounding villages from whom their products are brought to Akure to be sold off. Domestic wastes is different from other types of waste because it is directly related to households as shown in Table 2.3. The contents of household wastes are majorly food materials. Others are papers, broken furniture, plastic materials, disposable diapers, worn-out fabrics, etc. Most household wastes are biodegradable, hence attract organisms, insects and rodents that can transmit diseases to humans and this spreads very fast when in close proximity to residences. (Ogedengbe and Oyedele, 2006). Adewumi et al (2005) estimated quantity of domestic wastes generated in Akure and other South-Western Nigerian cities as revealed in Table 2.4.

Akure, the capital city of Ondo State in Nigeria has been experiencing expansion in terms of population density and explosion and this phenomenon is concomitant with multiplication of waste. Hence, the issue of waste management becomes a greater challenge. Over the years, the way and manner in which refuse is disposed in the city has consistently lacked monitoring and control. The resultant effect is deterioration of the environment which culminates in pollution.

Table 2.3: Main sources of municipal solid wastes in Akure and south western Nigerian cities

City	(%)			
	Domestic	**Commercial**	**Agricultural**	**Industrial**
Abeokuta	73.90	17.50	8.20	0.50
Ado-Ekiti	78.90	14.30	4.10	2.70
Akure	**70.30**	**18.60**	**6.30**	**4.80**
Ibadan	66.10	20.30	2.20	11.40
Igede-Ekiti	75.10	11.00	12.40	1.00
Ijebu-Ode	79.50	14.00	3.50	3.00
Ile-Ife	67.40	28.40	1.00	1.10
Iyin Ekiti	79.60	2.20	11.60	6.60
Ode-Omu	91.20	1.80	5.90	1.10
Osogbo	68.20	23.50	2.10	6.20
Oyo	90.50	6.50	2.00	3.00
Mean	76.42	14.37	5.39	3.76

Source: Adewumi et al, (2005)

Table 2.4: Biodegradable solid wastes in Akure and some south western Nigerian cities

City	Population (2013)	Biodegradable Wastes (Metric tons (T) per week)
Akure	316,925	46,271
Ibadan	1,650,806	33,050
Ijebu-Ode	330,799	54,773
Osogbo	253,430	38,852
Oyo	371,355	69,128

Source: Adewumi et al, (2005)

When residents dispose wastes close to residences, as is the case with some residents in Akure, the organisms in contact with such refuse can act as agent of degradation. This will make the residential environment to be of poor quality, hence, the buildings will require renovation or maintenance more frequently. The quality of man's environment is an integral contributor to the overall quality of families and individuals quality of life (Adedeji, 2005). It is expected that when the environmental sanitation standards of a city improves, there will be improvement in the living conditions and health status of the inhabitants.

2.5 Inventory of Green House Gases (GHGs) in Nigeria

Article 4 of the United Nations Framework Convention on Climate Change (UNFCCC, 2000) requires each Party to periodically report the emissions of greenhouse gases (GHGs) including CO_2, CH_4, N_2O and non-methane volatile organic compounds (NMVOC) in their National Communication. In fulfillment of the article, Nigeria's national communication based on emission per unit human population (based on gross population of 96.7 million for the year 1994) indicates a gross per capita CO_2 emission of 0.5 t C/cap. Per capita, non-CO_2 GHG and precursor gases are between 2 to 4 orders of magnitude lower than CO_2 per capita emissions.

An overview of gross carbon emissions by sources and removal by sinks indicate gas flaring, transportation, and electricity generation as the most significant energy consumption processes leading to GHG emissions. Energy and land use change sectors were the main contributors to CO_2 emissions, while energy, agriculture and solid waste are the main contributors to CH_4 emissions.

Nabegu, (2011) indicates that the total methane emission in Nigeria is 5.9 Tg CH_4. The energy production and consumption sector with a total emission of 1.48 TgCH_4 contributed 25% of gross national emissions with agriculture contributing the rest. Municipal solid wastes and waste water treatment contributed 0.21 and 1.88 Tg CH_4. These respectively represent 4 and 32% of gross national emissions. The gross emission of nitrous oxide was 11.95Gg N_2O. The energy sector principally petroleum refining, small combustion and transport sub-sectors generated 7.47 Gg N_2O representing 63% of gross national emissions for the year 2011. This was closely followed by emissions from savannah burning (28%), field burning of agricultural wastes (6%), burning of solid wastes (2%) and on-site biomass burning from forest conversion (1%) Nabegu, (2011).

The total CO_2 emission was 17.05 Tg CO_2. Out of these, the energy sector generated 13.1Tg CO_2 with the following major energy sub-group emissions: transport 4.73 Tg CO2 or 28% of the gross national emissions; small combustion sources and gas flaring each representing about 25% of the gross national CO_2 emissions. The agricultural sector emitted 3.59 Tg CO_2 or 28% of the gross national emissions for 1994, while the other energy sub-sectors, solid waste and land use change emitted 33.2 Gg CO_2, 171 Gg CO_2 and 162 Gg CO_2.

The total generation of GHGs based on the data for Nigeria is low when compared to emissions from the United States and other developed economies. However, Nigeria's gross emissions may approach those of these countries if its population continues to grow at the rate of 3.5% per annum since per capita emissions is also likely to increase. The current population of Nigeria is put at over 160 million, representing 20% of the entire population of Africa. The United Nations projected a population of 289 million for the Nigeria by 2050 (UNFCCC, 2000). Apart from population growth, Nigeria has been experiencing increased urbanization over the last five decades. The proportion of the population living in the urban centers has risen from 15% in 1960 to 43.3% in 2000 and is projected to rise to 60% by 2015 (NPC 2004). Furthermore, current economic growth of 7% per annum since 2005 has been projected to continue and would invariably fuel increase in the generation of solid waste

2.6 Solid waste disposal and CH_4 and CO_2 emissions

Akpovi and Sridhar (1985); UNCHS/UNEP (1997) asserted that the practice of open dumping and burning could lead to the leaching out of organic and inorganic components of the solid wastes when left to decay in refuse depots on open dumps, while localized air pollution arise due to the open burning practised. Most of the organic materials will be degraded over a longer or shorter period, ranging in a wide span from less than one year to 100 years or more. The majority of this process will be by bio-degradation. Strongly depending on conditions in the site where the solid waste is disposed, this biodegradation will be by both aerobic and anaerobic. The main degradation products are carbon dioxide (CO_2), water and heat for the aerobic process and methane (CH_4) and CO_2 for the anaerobic process.

The CH_4 produced and released to the atmosphere contributes to global warming and the emissions need to be estimated and reported in national greenhouse gas inventories under the United Nations' Framework Convention of Climate Change (UNFCCC). The CO_2 produced originates from biogenic sources (e.g., food, garden, paper and wood waste) and the emissions need therefore not be considered in national inventories. The estimated global annual emissions from solid waste disposal sites (SWDS) are in the range of 20 - 40 million tonnes of CH_4, of which the most comes from industrialized countries (UNFCCC, 2000). This contribution is estimated to be approximately 5-20 percent of the global anthropogenic CH_4, which is equal to about 1 to 4 percent of the total anthropogenic greenhouse gas (GHG) emissions. The emissions from developing countries and countries with economies-in-transition will increase in the near future due to increased urban population, increased specific (pro capita) municipal solid waste (MSW) generation due to improved economy and improved solid waste management practices. From the developed countries, the emissions are estimated to remain stable or decline over the next 10 - 20 years.

A recent compilation of reported emissions to the UNFCCC (UNFCC, 2000) indicate emissions of 24 million tonnes CH_4 from developed countries in 1990. In the year 1998, these emissions had been reduced to about 20 million tonnes. The reduction is due to increased recycling and alternative treatments and increasing implementation of landfill gas extraction and recovery systems.

2.7 Primary causes of climate change

A review of the factors reported to be responsible for climate change will reveal that climate change is inevitable. The primary cause of climate change is the variation of the solar radiation retained by the earth's surface (Pidwirny, 2006). Routinely, variation in the quantity of solar radiation reaching the earth is controlled by three cycles known as the Milankovitch cycles. They are the *eccentricity* which has a 100,000 years cycle and has to do with the shape (elliptical or circular) of the earth at any time; *precision of the equinoxes* which has a cycle of 26,000 years and has to do with earth's rotation; and *obliquity* which has a 41,000 years cycle and has to do with the inclination or tilt of the earth (Pidwirny, 2006). Other occasional factors which may lead to short-lived climatic variations include: volcanic eruptions, variation in solar outputs, variation in orbital characteristics and variation in atmospheric CO_2 (Pidwirny, 2006).

Apart from variation in atmospheric CO_2 on which man has a substantial influence, the other factors, to a large extent, are independent of anthropogenic factors. So much sensitization has been going on about the role of burning of fossil fuel in climate change, however it must be noted that burning of fossil fuel does not initiate climate change, rather it only amplifies it (Pidwirny, 2006). This is to say that without burning fossil fuel, climate change would still have taken place but what remains to be ascertained is by how much the burning of fossil fuel has *hastened* and *aggravated* climate change.

Research efforts have shown that deforestation and burning fossil fuel have increased atmospheric CO_2 from 280ppm to 380p pm between early 1700's and 2005. This represents 35.7 % increase in about 300 years and all things being equal, 100% increase in the next 530 years (Monni et al, 2006). The greenhouse gases that are making the largest contribution to global warming besides carbon dioxide (CO_2) are methane (CH_4) and nitrous oxide (N_2O) both of which are produced during the management and disposal of wastes.

2.8 Climate change and environmental health

Climate change has a lot of implications for the environment and consequently public health. While it has been estimated that for 1m rise in sea level, 3.7 million people will be displaced from the coastal regions of Nigeria (Awosika *et al*, 1992), droughts in the hinterlands will lead to unhealthy sanitary conditions. Additional application of fertilizer may be needed to take advantage of the potential for enhanced crop growth that can result from increased atmospheric CO_2. This can pose a risk, for additional use of chemicals may impact water quality with consequent health, ecological, and economic costs (Rosenzweig *et al,* 2002). The two most important climatic elements determining the occurrence and localization of pests and diseases appear to be moisture and temperature. In general, pests and disease vectors do better when the temperature is high under conditions of optimum water supply. Global warming is therefore likely to extend the range of distribution of certain pests and diseases of crops pole wards (Adejuwon, 2004). In general, climate change is associated with (i) variability and changes in rainfall patterns; (ii) changes in water levels in lakes, rivers, seas, ponds, streams and groundwater; (iii) frequency of storms and droughts; (iv) increased desert encroachment, and (v) excessive heat. Almost all of these have serious implications for the environment and public health.

2.9 Solid waste management and environment

Nature exists in a balance. The most difficult challenge facing man is not exploiting nature, but maintaining critical balance while doing so. Massive exploitation of the earth crust has provided man with endless natural resources which are constantly being transformed into products that are discarded as waste after serving their purpose. Unfortunately, man cannot return these waste products to their crude state in the earth crust; hence the easiest route of escape is to release these materials to the atmosphere in gaseous forms or bury them. The accumulation of these gases in the atmosphere over many years has upset a critical balance of nature. The issue of global warming and climate change will continue to be a threat until man learns to return used or waste products to their crude states. Obviously, this is impossible and the closet that man can ever come to that is recycling and reuse. The most popular contributor to global warming via gaseous emission into the atmosphere is the burning of fossil fuel.

Recently, concerted efforts are being made, especially in developed nations, to reduce dependence on fossil fuel as a means to reduce global warming. However, a silent but massive contributor to greenhouse gases is waste management. A recent report by the United States Environmental Protection Agency estimates that 42% of total greenhouse gas emissions in the US are associated with the management of waste materials (USEPA, 2009). Figure 2.1 shows the contributions of these gases to global

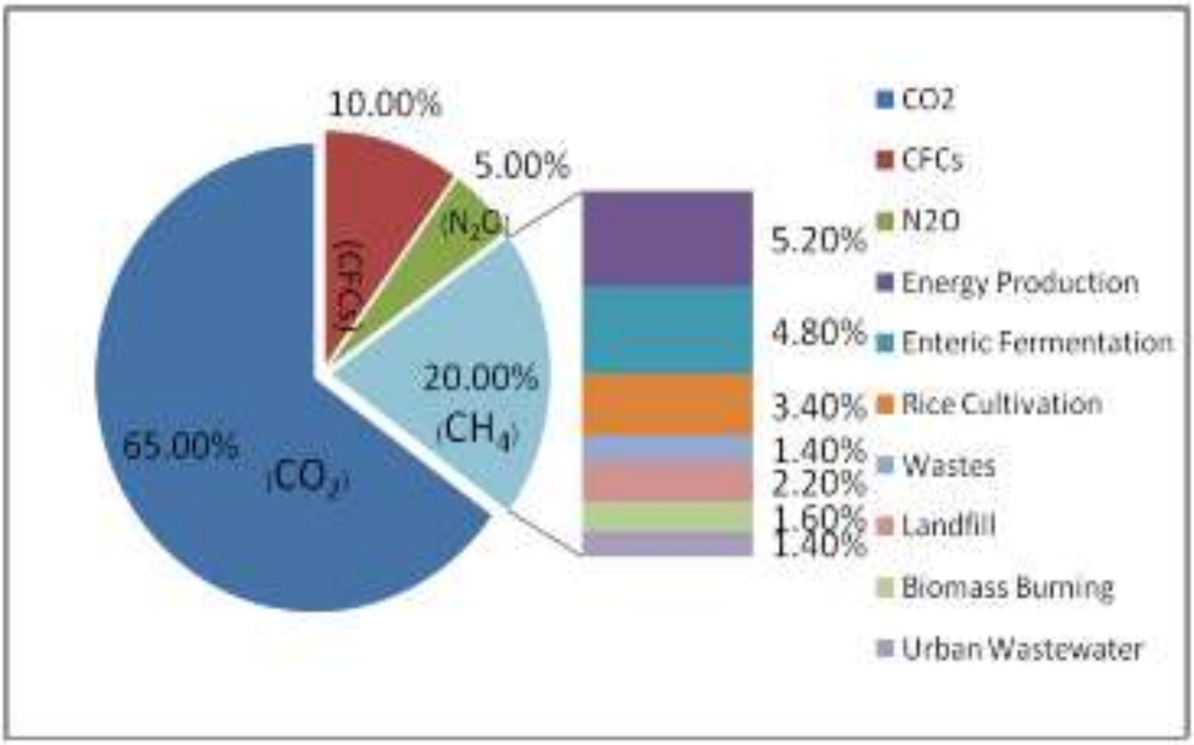


Fig 2.1: Contribution of different gases to global warming
Source: Baldasano and Soriano, (2000)

warming and a simple analysis reveals that activities associated with waste and waste management contribute a total of 57% of CH_4 emission compared with 26% contributed by energy production. It would seem that CO_2 is the most critical greenhouse gas by looking at the Fig but a large portion of CO_2 emission comes from treating food waste and is of no consequence to global warming because it is biogenic meaning that it was atmospheric CO_2 before it was fixed by plants. Waste management options such as landfill, composting, incineration/ mass burns and anaerobic digestion / biogas plants collectively emit substantial amount of greenhouse gases. Composting makes use of micro-organisms to oxidize biodegradable wastes (especially food and garden waste) to CO_2 and water vapour, using oxygen in the air as the oxidizing agent. Anaerobic decomposition converts biodegradable carbon to biogas, which consists of about 65% CH_4 and 34% CO_2 with traces of other gases. In landfills, microbes gradually decompose organic matter over time producing roughly 50% of CH_4 and 50% of CO_2 and trace amount of other gaseous compounds (UNEP, 2009).

Methane emissions from landfill represent the largest source of greenhouse gas emissions from the waste sector, contributing around 700 Mt CO_2-e for 2009 followed by incineration, estimated to contribute around 40 Mt CO_2-e (UNEP, 2009). Global warming potential of waste management can be reduced by a combination of sorting, bio-gasification, incineration and landfilling (Figure 2.2). Figure 2.2 shows vividly that the global warming potential of both incineration and landfill can be reduced by employing a wholesome waste management strategy involving sorting. Sorting ensures that waste materials are segregated into generic forms for ease of recycling, treatment and subsequent disposal.

In the case of incineration, sorting helps ensure that recyclable combustible materials such as plastics, tyres and paper are excluded from the incinerator, hence lowering global warming potential. Global warming potential (GWP) is a factor that allows the concentrations of greenhouse gases to be expressed in terms of the amount of CO_2 that would have the same global warming impact (Smith et-al, 2001). GWP is expressed as carbon dioxide equivalent (CO_2 e) over a specific time horizon, say 21 years, 100 years or 500 years. Methane (CH_4) is estimated to have a GWP of 21,

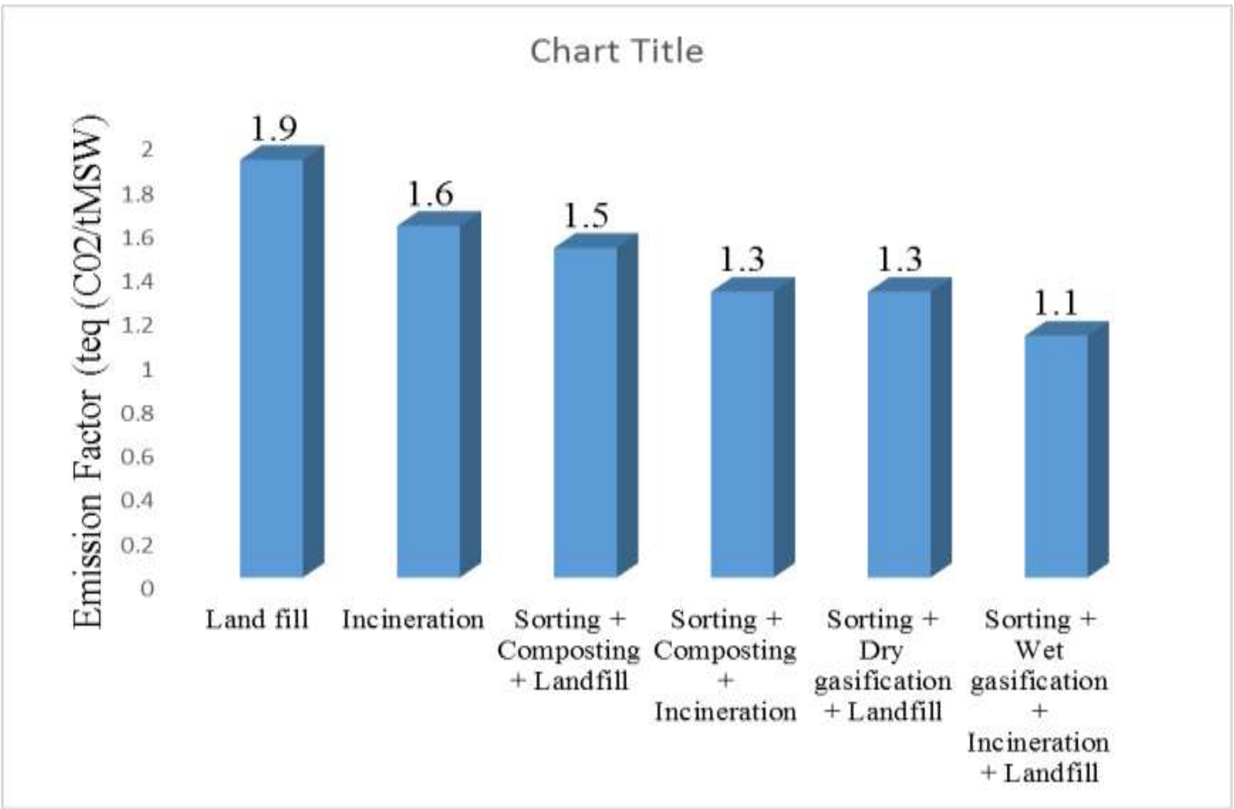


Fig 2.2: Reduction of emission factor of landfill and incinerators
Source: Baldasano and Soriano, (1999)

whereas carbon dioxide (CO_2) and Nitrous oxide (N_2O) have GWPs of 1 and 310 respectively (Table 2.5).

GWP is estimated using Equation 1.

$$GWP_i = \frac{\int_0^{TH} a_i x_i(t)dt}{\int_0^{TH} a_{CO_2} x_{CO_2}(t)dt} \qquad (1)$$

Where a_i and a_{CO2} represent the radiative forcing of the chemical specie in question and CO_2 respectively; x_i represents the time-dependent concentration of the chemical specie in the atmosphere after the time of release; x represents the time dependent concentration of CO_2 in the atmosphere after the time of release; and TH is the time horizon over which GWP is desired. The radiative force is the amount of energy Adsorbed by the chemical specie as infrared energy attempts to leave the earth.

Incineration has a lower global warming potential because, the heat generated can be diverted as a source of energy in the place of fossil fuel. Even though the global warming potential of landfill can be reduced by trapping the methane and using it as a source of energy, some of the gas will still escape and, of course, the accompanying CO_2 has no energy potential (Figure 2.3). There is also additional capture of carbonaceous materials by the soil and plants (sequestration). Use of compost may also have beneficial effects on greenhouse gas fluxes by replacing other products like fertilizer and peat; and may also lead to increased storage of carbon in the soil. Furthermore, the major greenhouse gas from incineration is CO_2 while the major greenhouse gases in landfill are CH_4 and CO_2. CH_4 has a global warming potential which is twenty one times higher than that of CO_2, hence the higher emission factor of landfill. It can be clearly seen from Table 2.5 that the CO_2 from incineration and decomposition of organic matter in landfills and composting plants is short cycle and has no global warming potential as opposed to the CO_2 from burning of fossil fuel. Figure 2.3 shows the interaction between selected waste management options and global warming. Positive sign implies contribution to global warming while negative

Table 2.5: Global warming potential of greenhouse gases from waste management (CO$_{2}$-e)

Emission	Origin	Trend in Atmospheric Concentration	Effective Global Warming Potential (100 Years)	
			Emission	Carbon Sequestration
CO$_2$ (fossil C)	Combustion of Plastics	Increasing	1	0
CO$_2$ (Short-cycle)	Combustion and respiration of biomass	Stable	0	-1
CH$_4$ (Short-cycle)	Methane-forming decomposition under anaerobic conditions	Increasing	21	(not applicable)
N$_2$O	Combustion process, nitrogen metabolism in the soils, fertilizer manufacture	Increasing	310	(not applicable)
CFC-12	Refrigerant insulation foam	Increasing	8100	(not applicable)
CFC-11	Refrigerant insulation foam	Increasing	3800	(not applicable)
HFC-134a	Refrigerant insulation foam	Increasing	1300	(not applicable)
HFC-141b	Refrigerant insulation foam	Increasing	600	(not applicable)
CF$_4$	Primary aluminum smelting	Increasing	6500	(not applicable)

Source: Smith *et al*, (2001)

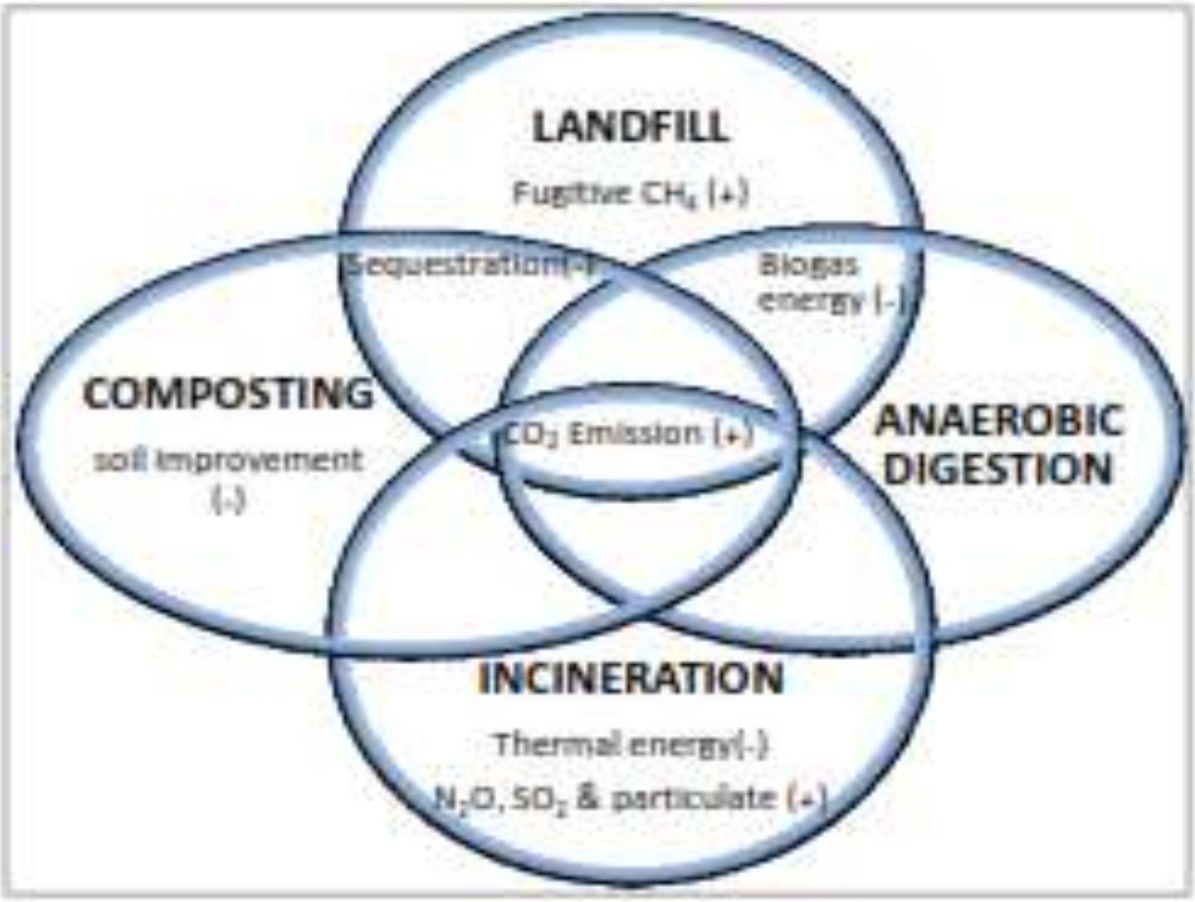


Fig 2.3: Interactive contribution of waste management options to global warming Source: Smith *et al,* (2001)

sign indicates a counteracting effect on global warming. It should be noted that CO_2 emission is common to all four options viz: landfill, composting, incineration and anaerobic digestion. Landfill and composting technologies offer exceptional advantage of carbon sequestration. Carbon sequestration is a viable means of replenishing carbon composition of the earth crust as well as reducing greenhouse gas emission. The global warming potential associated with landfills depends on whether biogas is captured or not. Biogas which is a combination of methane and carbon dioxide is a replacement for fossil fuel. Methane from landfills is of organic origin and therefore has low global warming potential compared to other greenhouse gases. It is obvious that composting has no global warming potential because the CO_2 released during decomposition is of organic origin and is therefore biogenic. In many developing countries compost is sold to farmers for soil amendment. Incineration provides energy in the form of heat thereby reducing requirement for fossil fuel, but it has the disadvantage of releasing greenhouse gases of high global warming potentials into the atmosphere.

2.10 Effect of climate change on waste treatment facilities

A landfill is usually a depressed portion of the earth where decomposable refuse is dumped and allowed to decompose. A sanitary landfill is an engineered waste disposal site with geotechnically lined impervious base and sides into which sorted wastes are dumped and compacted before covering with compacted inert materials daily to reduce vermin and scavenging intrusion. Sanitary landfills incorporate systems for gas collection and for sorting of reusable and recyclable materials. Sorting of reusable and recyclable materials help to minimize the quantity of waste dumped on the site and provide raw materials for industries. In Nigeria, however, landfills take the form of poorly maintained open dumps overflowing with all sorts of refuse – putrescible and non-putrescible. No sorting or gas collection is done. This waste management facility is used to achieve two principal aims viz: elevation of depressed areas and disposal of waste. Its operation relies on the interaction between putrescible matter, moisture and temperature. It gives rise to the release to the atmosphere of methane (CH_4), carbon dioxide (CO_2), trace compounds, leachate and residual matter into the atmosphere. Rise in temperature will alter decomposition rates and thus affect the landfill gases generated, length of active gassing phase, site settlement; closure and completion (Figure 2.4). However, since decomposition processes are complex, higher temperatures will not necessarily imply higher decomposition rates – where higher temperatures and high moisture content will accelerate decomposition, higher temperatures combined with low moisture content will hamper decomposition (Beb and Kersey, 2003). According to Beb and Kersey (2003), higher temperature will also lead to higher evaporation losses which will lead to the production of less but stronger leachates. In addition, increased precipitation and rise in sea levels could lead to the inundation of landfill sites leading to the dispersion of untreated waste to the surrounding.

2.11 Reducing emissions through holistic waste management

In many Nigerian cities and communities, solid waste is usually sent to open dumps scattered all over the city. There is no systematic approach to solid waste management. Wastes arriving at the open dumps are usually unsorted. However, recyclable materials such as plastics, bottles, metal scraps, cans rubber and leather are retrieved from the dumps by scavengers who earn a living by selling recovered materials (Figure 2.5). Some of the waste items such as plastic cans and bottles are sold to families while the rest are sold to the industry as raw materials for new products.

Unfortunately, these scavengers are largely uneducated and sometimes constitute a nuisance to the society. A study conducted in three states of Nigeria (Lagos, Akwa Ibom and Borno) revealed that about 44% of scavengers did not go beyond primary school and none had a tertiary education (Okudo, 2010). Cases of thefts by scavengers are common. The ultimate goal of these scavengers is to earn a living rather than promote environmental sanitation or public health; hence their role in solid waste management is still primitive. The municipal waste management authorities are saddled with the responsibility of evacuating residual waste from the open dumps. Waste remaining at dump sites after the activities of scavengers are collected and finally disposed at landfills which are usually poorly maintained with no provisions for compaction, gas collection and leachate control. Most municipal waste authorities are understaffed and ill equipped, and therefore cannot keep pace

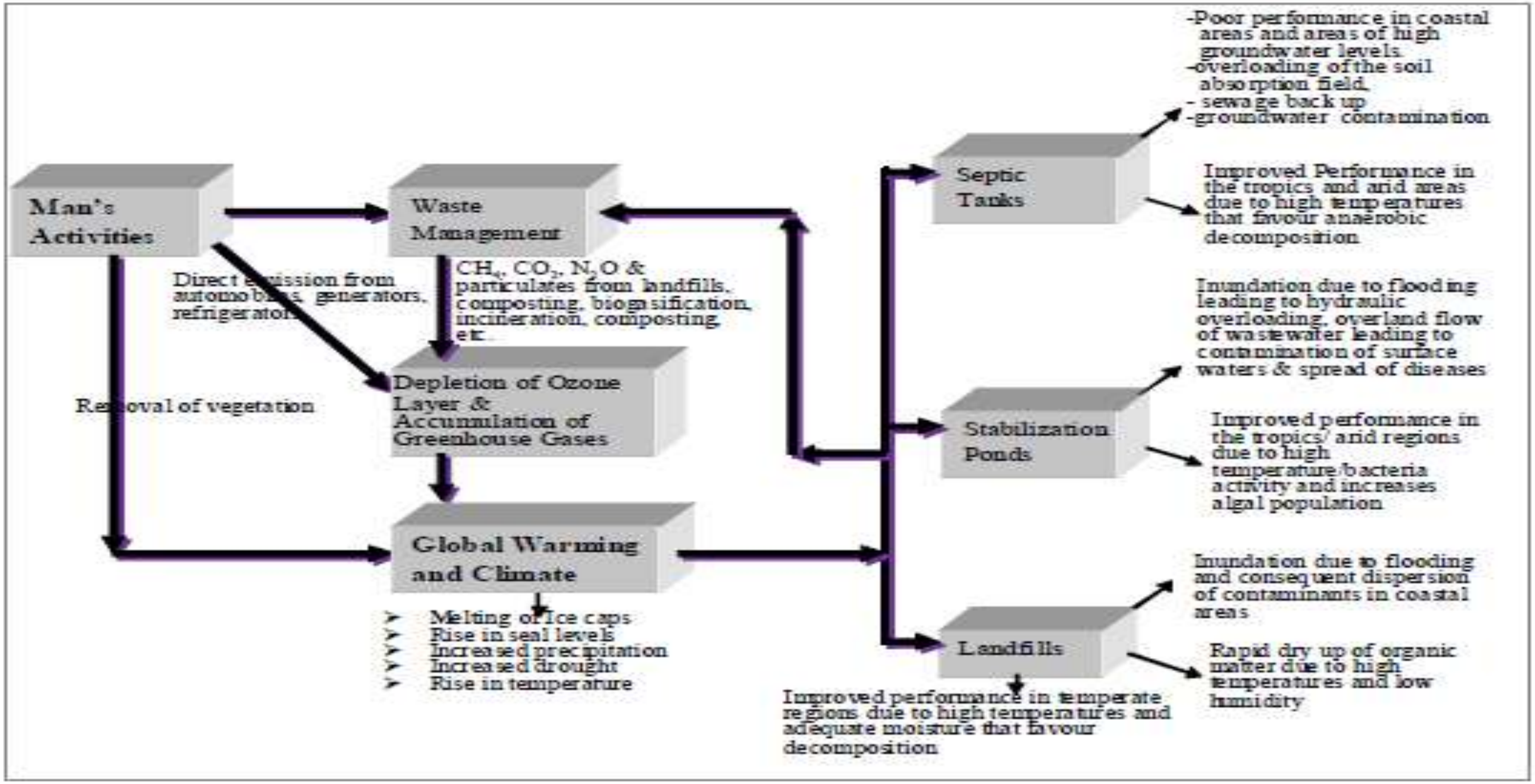


Fig 2.4: Interaction between Selected Waste Treatment Options and Climate Change
Source: Utsev, (2011)

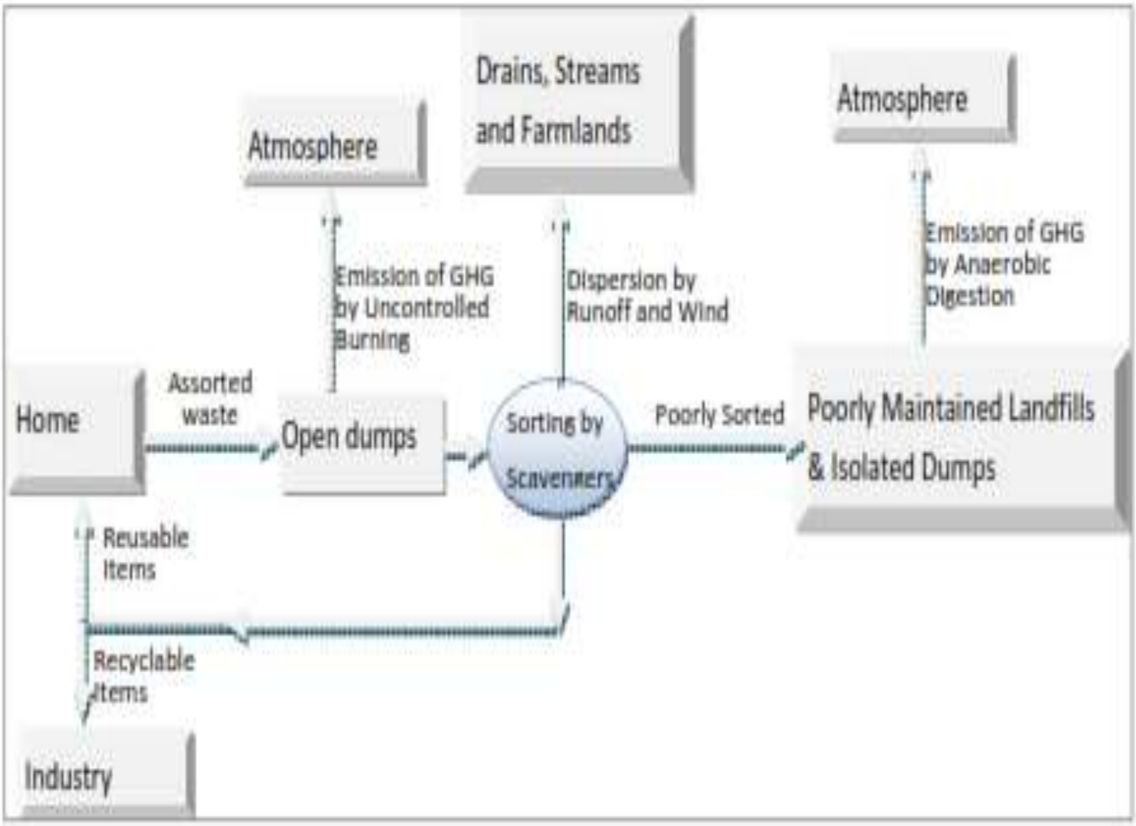


Fig 2.5: Prevailing solid waste footprint in Nigeria
Source: Utsev, (2011)

with the rate of waste generation. It is not uncommon in Nigeria to see open dumps overflowing with waste to the extent that drains are blocked and traffic is obstructed. This situation often prompts people to set the dumps ablaze, in an attempt to create space for more waste, leading to massive release of greenhouse gases (Plate 2.1). Most times these dumps are set ablaze before all reusable and recyclable materials are recovered by scavengers, resulting in huge loss of potential raw materials for industry. The dumpsites can also be set ablaze by some scavengers who specialize in picking metals in order to reduce the rigour of going through heaps of waste.

In order to promote environmental health and sanitation as well as reduce greenhouse gas emissions in a developing country like Nigeria, a waste management flow chart (Figure 2.6) has been proposed. The flow chart is aimed at engendering sustainable development through environmental sanitation, maximum resource and energy recovery, and reduction of greenhouse gas emission. Given the level of development in Africa, it is not easy to eliminate open dumps. However, existing open dumps can be converted to transfer stations operated and maintained by municipal authorities. These transfer stations should have walls and gates to check unauthorized access and provide a boundary for waste materials. This will further reduce dislodging of waste materials by runoff and wind as well as prevent uncontrolled burning and obstruction of traffic. Scavengers could be formally employed for sorting of waste in the absence of mechanized options. In the proposed waste management strategy, sorting has been given a cardinal and indispensable role. It has been shown earlier (Figure 2.2) that the emission factors associated with incineration and landfill can be reduced by sorting. Sorting provides enormous resources for the industry; and renders waste amenable to easy handling, treatment and disposal. After sorting, recyclable items such as paper, metals, glass and plastics are sent to the industry. A cursory survey revealed that some items such as paper, bottles and plastic cans are reused by low income earners. Waste papers are used for wrapping food items in local markets; or they can be used in the place of tissue papers. In addition, waste tyres are used for making shoe polish and soles for foot wears; waste papers are used for the production of toilet tissues; plastic and nylon

Plate 2. 1: Picture of a waste dump set ablaze by scavengers
Source: Utsev, (2011)

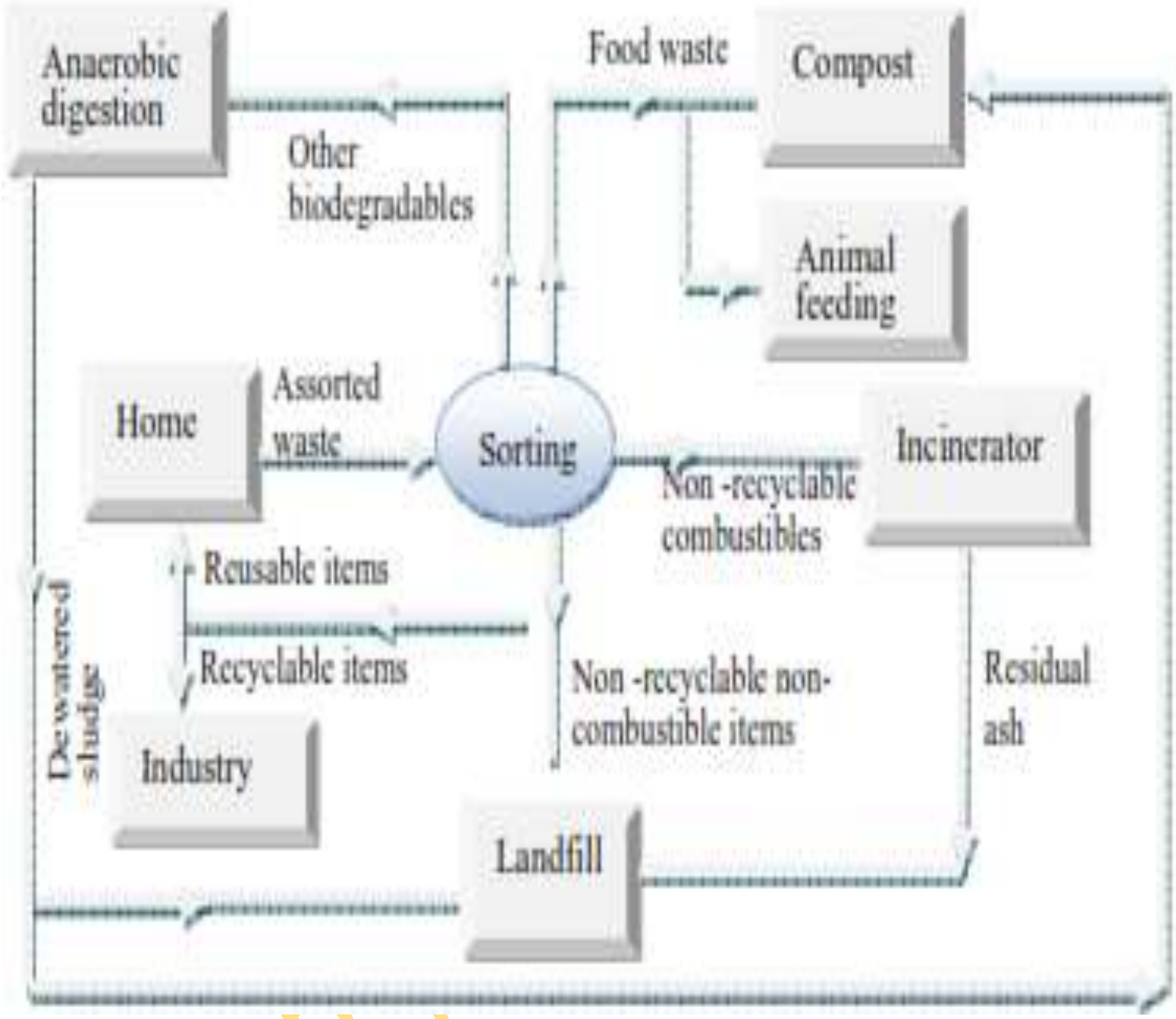


Fig 2.6: Best waste management practice flow charts for minimization of greenhouse gases and maximum resource recovery

Source: Utsev, (2011)

materials are converted into pellets and then used for production of car bumpers, car mirror holders, rubber slippers and shoes, plastic buckets, plates and cups; metal scraps are converted into cutlasses, hoes, spades, metal plates and steel rods (Okudo, 2010). Figure 2.6 suggests that sorting should be done at the transfer station but a better option is ‘sorting at source’ (SAS). Families could also be mandated to deliver their wastes in sorted forms. This will require that families have different waste bins for different categories of waste such as: (i) recyclable and non-recyclable, (ii) biodegradable and non-biodegradable, (iii) compostable and non-compostable, (iv) combustible and non-combustible, etc. A more elaborate but less practicable option is to sort them into generic forms such as food waste, plastic, glass, paper, nylon, textile, metals, etc. This is more difficult because it requires that each family will have about seven waste bins for different categories of waste.

In developing countries, organic waste constitutes over 70% of waste generated which can be composted to provide manure for increased agricultural productivity. Composting is a natural process that requires no artificial raw material. The CO_2 released during the process is biogenic and therefore has no net climatic impact. With a bit of advanced technology, organic waste can also be digested anaerobically to generate biogas. The replacement of fossil fuel with biogas is a positive step in curbing climate change. Food waste can also be fed to domestic or farm animals as illustrated in Figure 2.6.

2.12 Impact of waste management practices on greenhouse gas emissions

Every waste management practice generates GHG, both directly (i.e. emissions from the process itself) and indirectly (i.e. through energy consumption). However, the overall climate impact or benefit of the waste management system will depend on net GHGs, accounting for both missions and GHG savings.

2.12.1 Landfill

In the majority of countries around the world, controlled and uncontrolled landfilling of untreated waste is the primary disposal method. According to the estimate for the year 2009 methane emissions from landfill represent the largest source of GHG emissions from the waste sector, contributing around 700 Mt CO_2-e (Bogner *et al*, 2007). In comparison, the next largest source of GHG emissions from the management of solid wastes is incineration, estimated to contribute around 40 Mt CO_2-e Bogner *et al*, (2007). Landfills may also be a source of nitrous oxide; however the contribution to global GHG emissions is believed to be negligible, and related to the management of both wastewater bio-solids disposed at landfills and landfill leachate (Bogner *et al*, 2008). Table 2.6 provides a qualitative summary of the indirect and direct GHG emissions and savings associated with landfilling. To provide a complete picture, all GHGs are noted, including biogenic CO_2.

2.12.2 Thermal treatment

Thermal waste treatment refers to mass-burn incineration, co-incineration (i.e. replacing fossil fuels with refuse-derived fuel (RDF) in conventional industrial processes, such as cement kilns), pyrolysis and gasification. Mass-burn incineration is the most commonly applied thermal treatment. Pyrolysis and gasification may be considered as emerging technologies, with limited success in treating mixed waste streams. The majority of studies assume that energy is recovered from the thermal treatment of waste, either as heat or electricity, which can equate to a considerable GHG saving (depending on the type of energy displaced). Metals are also recovered from incinerator ash, and this contributes to further GHG benefits.

Approximately 130 million tonnes of waste are currently incinerated across 35 countries (Bogner *et al*, 2007). Japan, Denmark, and Luxembourg treat >50% of the waste stream through incineration. France, Sweden, the Netherlands and Switzerland also have high rates of incineration (Bogner *et al*, 2007). Incineration is only applied in a limited capacity in the remainder of the Organization for Economic Co-operation and Development (OECD) countries. There is no incineration of mixed waste practiced in either Australia or New Zealand, largely due to public opposition. Australia, New Zealand, Canada and the US do not have legislation in place that limits landfilling (i.e. as is the case with the EU Landfill Directive); therefore landfill remains the cheapest and thus preferred disposal option.

Incineration of mixed wastes is a largely unfeasible option in non-OECD countries due to cost and often unsuitable waste composition (as discussed below). Thermal

Table 2.6: Summary of indirect and direct GHG emissions and savings from landfills

Upstream (indirect)	**Direct (operating)** **Downstream (indirect)**	**Direct (operating)** **Downstream (indirect)**
CO_2, CH_4, and N_2O emissions from: production of fuel used on site, electricity consumption, and production of materials (i.e. liner material, soils)	Fugitive emissions of CH_4, trace NMVOC *, N_2O and halogen-containing gases; biogenic CO_2 from waste decomposition; CO_2, CH_4, N_2O, trace CO and NMVOC from fuel combustion in equipment; biogenic CO_2, CO_2, CH_4, and N_2O from leachate treatment	Energy produced from combustion of captured LF CH4 substitutes fossil energy: avoided CO_2 Long-term carbon stored in landfill (organic materials largely recalcitrant in anaerobic conditions): avoided CH_4 and biogenic CO_2

* NMVOC refers to non-methane volatile organic compounds.

Source: Scheutz *et al*, (2009)

treatment with energy recovery may be eligible for Clean Development Mechanism (CDM) funding. The CDM methodology AM0025 (‘Avoided emissions from organic waste through alternative waste treatment processes’) is applicable to projects that derive energy from waste. Much of the waste in the non-OECD region is characterized by a high percentage of putrescible waste (Table 2.7) with consequent high moisture and low calorific value, making it unsuitable for incineration without considerable pre-treatment, such as pressing or drying (Lacoste and Chalmin, 2006; UNEP, 2009).

At the global level, the climate impact of incineration is minor compared to that of landfilling, contributing around 40 Mt CO_2-e in the year 2007 (Bogner *et al*, 2007). Direct emissions from facilities are predominantly fossil and biogenic CO_2. The amounts of fossil and biogenic carbon in the waste input will vary significantly between countries, regions, and even facilities (Astrup *et al*, 2009). Typically only fossil CO_2 is counted as a GHG emission from incineration; therefore the overall climate impact of incineration will be highly influenced by the fossil carbon content of the input waste. Downstream, indirect GHG savings due to energy generation may dominate an estimate of emissions from incineration, depending on the energy assumed to be replaced.

Table 2.8 provides a qualitative summary of the indirect and direct GHG emissions and savings associated with incineration. To provide a complete picture, all GHGs are noted, including biogenic CO_2.

The estimated GHG impact of thermal waste treatment processes, such as incineration, gasification, and pyrolysis, depends in large part on the energy source(s) assumed to be replaced by energy generated through the process. A study by Dehoust *et al,* (2005) examined the impact of changing the energy source from natural gas (i.e. combined cycle gas turbine (CCGT)) to coal, and found that the GHG saving doubled: if coal is assumed to be replaced, thermal treatment receives double the carbon credit for energy produced than if natural gas is assumed to be replaced. The choice of both baseline and marginal energy mix is a key element of

Table 2.7: Characteristics of MSW in low, medium, and high GDP countries

	Low-GDP countries	Medium-GDP countries	High GDP countries
Example country	India	Argentina	EU-15
GDP US$/capita/year	<$5,000	$5,000 - $15,000	>$20,000
MSW kg/capita/year	150 – 250	250 – 550	350 – 750
MSW collection rate	<70%	70% – 95%	>95%
% putrescible waste in MSW	50% - 80%	20% - 65%	20% - 40%
Heating value kcal/kg	800 – 1,100	1,100 – 1,300	1,500 – 1,700

Source: Lacoste and Chalmin, (2006)

Table 2.8: Summary of indirect and direct GHG emissions and savings from incineration

Upstream (indirect)	Direct (operating)	Downstream (indirect)
CO_2, CH_4, and N_2O emissions from: production of fuel used in facility, heat and electricity consumption, production of materials (i.e. air pollution control (APC) systems) and infrastructure	CO_2 and biogenic CO_2 from waste combustion; trace CH_4, N_2O, CO, and NMVOC	Heat and/or electricity produced from combustion of waste substitutes fossil Recovery of metals from ash substitutes raw materials: avoided GHG emissions from material production Use of bottom ash to substitute aggregate: avoided GHG emissions from producing virgin aggregate CO_2, CH_4, N_2O, and trace CO, and NMVOC from transport of APC residues and fly ash

Source: Scheutz *et al*, (2009)

waste and climate change studies, and is often a point of debate. Many developed countries are moving towards more sustainable natural energy supply, with conventional coal-powered stations being phased-out in favour of less GHG-emitting alternatives. Therefore, at least in developed countries, the climate benefit of energy derived from waste incineration may lessen in the future.

Estimations of the climate impact of incineration with energy recovery also depend on whether electricity, heat or combined heat and power (CHP) are assumed to be produced. European waste incinerators are reported to have conversion efficiencies of 15-30% for electricity and 60- 85% for heat, with efficiency based on the percentage conversion of the lower heating value of the waste into energy (Astrup *et al*, 2009). In Northern Europe it is fairly common to find district heating networks powered by waste incinerators. Areas of Central and Eastern Europe also have the necessary infrastructure to utilise heat. The UK has examples of incinerators providing heat to adjacent industries (i.e. a latex plant) – industrial heat usage is in many cases more attractive than district heating. However, in many parts of the world, the infrastructure necessary to usefully apply the heat is often not in place and prohibits building CHP plants. An alternative use of heat energy may be for adsorption refrigeration in situations where cooling is more desirable than heating; however this is not yet a common practice. The location of thermal technologies is therefore a crucial consideration when assessing energy efficiency and the potential for thermal treatment to mitigate climate impact. The GHG impact of thermal treatment of waste biomass – such as crop residue – may be very different to that of incineration of mixed wastes. The assessment will depend on a number of factors, including:

i. Alternative life-cycle for the biomass – in the case of crop residues, an important consideration is whether they would be left in-situ, or mulched on-site, to contribute nutrients and structure to soils, or burnt (uncontrolled).
ii. Suitability of the biomass for anaerobic digestion – if the waste biomass has a composition suitable for AD (i.e. minimal lignin content) then the climate benefit of AD with energy recovery outweighs that of thermal processing with energy recovery (and typically presents a less expensive option).

iii. Whether biogenic CO_2 is considered relevant, particularly given the time-relevance of climate change.

An important, but often overlooked point is that crop residues, although not useful from the perspective of human consumption or production, contain an often significant portion of the original nutrient input to the crop. In combusting residues, there is the danger that these nutrients are removed from the agricultural ecosystem, and result in a net depletion of essential building blocks for future crops. This may perpetuate the use of 'imported' fertilizers and soil amenders, with ensuing climate impact from manufacturing and transporting soil additives. A portion of crop residues may potentially be removed in a sustainable manner (Kim and Dale, 2004); therefore individual cropping systems should be carefully assessed before waste biomass is removed to fuel power plants – even where residues are currently burnt in-situ, this may not be the most sustainable alternative.

Pyrolysis and gasification of biomass may offer higher efficiencies (of conversion of waste to energy) than mass-burn incineration, especially if operated in heat only or CHP mode, if the low emissions claims of technology suppliers are accepted. However, both gasification and pyrolysis should be considered conservatively as emerging technologies, still under development, and with variable track records. For a number of years, centralized gasification of wood (or other high-lignin content) biomass has been trial ran primarily in Japan and Europe. Independent emissions data is difficult to obtain from Japanese facilities to ascertain GHG performance, and European plants have met with mixed success. Tars produced during wood pyrolysis appear to be a major problem for gas engines attached to furnaces, causing low generating efficiencies and down-time for maintenance, and require sophisticated technical solutions to avoid. Pyrolysis and gasification should not be ruled-out as potential future technologies to produce relatively clean energy from biomass waste.

Assessments of the potential GHG benefits of the thermal conversion of biomass waste to energy should be treated with caution. Although various methods can be used to estimate the total calorific value of the biomass ('total biomass energy') there is no thermal process that will convert 100% of that calorific value into energy. Assuming

100% efficiency can lead to highly erroneous estimations of the scale of potential energy production (and GHG benefit through fossil fuel replacement) of waste biomass.

2.12.3 Pyrolysis

Pyrolysis is a thermo-chemical process in which organic material is converted into a carbon rich solid (char) and volatile matter (liquids and gases) by heating in the absence of oxygen (Demirbas and Arin, 2002). Char from biomass, termed biochar in this context, when produced and incorporated into soils under certain conditions may be stable over a long timescale. Through such a pyrolysis biochar system carbon dioxide may be removed from the atmosphere, assimilated firstly by plant growth, then stored in a stable soil-carbon pool rather than returning to the atmosphere through decomposition.

As well as this direct ‘carbon-negative’ potential of pyrolysis biochar systems there are three further related areas of benefit proposed (Lehmann and Joseph, 2009). Addition of biochar to soils can enhance fertility leading to increased crop yields or allowing reduced application of energy-intensive agrochemicals. Liquid and gas co-products of biomass pyrolysis can be used for electricity generation or other fuel use (as well as being used to power the process) thereby offsetting fossil fuel consumption and so avoiding greenhouse gas emissions. Pyrolysis can also be used to treat biodegradable wastes converting some carbon in them to a stable form and so avoiding greenhouse gas emissions from decomposition. It is the potential for multiple benefits arising simultaneously from pyrolysis biochar systems and having an overall effect of reducing the level of greenhouse gases in the atmosphere that has led recently to rapidly increasing interest in the area.

Estimates of the potential for carbon sequestration using biochar are limited but suggest that the total global scale could be large, possibly on the gigatonne scale, with one suggesting sequestration potential could exceed existing emissions from fossil fuels (Lehmann et al, 2006). Such global estimates are necessarily based on numerous assumptions and are open to criticism. It has been suggested that the efficiency of biochar systems will be strongly dependent on case-specific factors and that it is difficult to assess the overall potential without much further study (Fowles, 2007).

2.12.4 Gasification

Gasification processes involve the reaction of carbonaceous feedstock with an oxygen-containing reagent, usually oxygen, air, steam or carbon dioxide, generally at temperatures in excess of 800°C. It involves the partial oxidation of a substance which implies that oxygen is added but the amounts are not sufficient to allow the fuel to be completely oxidised and full combustion to occur. The process is largely exothermic but some heat may be required to initialise and sustain the gasification process (Zafar, 2009).

The main product is a syngas, which contains carbon monoxide, hydrogen and methane. Typically, the gas generated from gasification will have a net calorific value of 4 - 10 MJ/Nm^3.The other main product produced by gasification is a solid residue of non-combustible materials (ash) which contains a relatively low level of carbon. Syngas can be used in a number of different ways, for example:

- Syngas can be burned in a boiler to generate steam which may be used for power generation or industrial heating.
- Syngas can be used as a fuel in a dedicated gas engine.
- Syngas, after reforming, may be suitable for use in a gas turbine
- Syngas can also be used as a chemical feedstock.

Gasification plants, based on syngas production, are relatively small scale, flexible to different inputs and modular development. Producing syngas to serve multiple end-uses could complicate delivery of the plants but it could provide a higher degree of financial security.

I. Gasification of municipal solid waste

The most important reason for the growing popularity of thermal processes for the treatment of solid wastes has been the increasing technical, environmental and public dissatisfaction with the performance of conventional incineration processes. Municipal solid waste is difficult to handle, segregate and feed in a controlled manner to a waste-to-energy facility. Municipal solid waste has a high tendency to form fused ash deposits on the internal surfaces of furnaces and high temperature reactors, and to form bonded fouling deposits on heat exchanger surfaces. The products of the combustion of municipal solid waste are also very aggressive, in that the flue gases are erosive and the relatively high levels of chloride containing species in the flue gases can lead to high rates of metal wastage of heat exchange tube surfaces due to high temperature corrosion.

While evaluating gasification or other thermal technologies, the degree of pre-processing required in conversion of municipal solid waste into a suitable feed material is a major criterion. Unsorted municipal solid waste is not suitable for most thermal technologies because of its varying composition and size of some of its constituent materials. It may also contain undesirable materials which can play havoc with the process or emission control systems.

The main steps involved in pre-processing of municipal solid waste include manual and mechanical separation or sorting, shredding, grinding, blending with other materials, drying and pelletization. The purpose of pre-processing is to produce a feed material with consistent physical characteristics and chemical properties. Pre-processing operations are also designed to produce a material that can be safely handled, transported and stored

II. Advantages of gasification

There are numerous solid waste gasification facilities operating or under construction around the world. Gasification has several advantages over traditional combustion processes for municipal solid waste treatment It takes place in a low oxygen environment that limits the formation of dioxins and of large quantities of SOx and NOx. Furthermore, it requires just a fraction of the stoichiometric amount of oxygen necessary for combustion. As a result, the volume of process gas is low, requiring smaller and less expensive gas cleaning equipment. The lower gas volume also means a higher partial pressure of contaminants in the off-gas, which favours more complete adsorption and particulate capture. Finally, gasification generates a fuel gas that can be integrated with combined cycle turbines, reciprocating engines and, potentially, with fuel cells that convert fuel energy to electricity more efficiently than conventional steam boilers.

III. Disadvantages of gasification

During gasification, tars, heavy metals, halogens and alkaline compounds are released within the product gas and can cause environmental and operational problems. Tars are high molecular weight organic gases that ruin reforming catalysts, sulfur removal systems, ceramic filters and increase the occurrence of slagging in boilers and on other metal and refractory surfaces. Alkalis can increase agglomeration in fluidized beds that are used in some gasification systems and also can ruin gas turbines during combustion. Heavy metals are toxic and accumulate if released into the environment. Halogens are corrosive and are a cause of acid rain if emitted to the environment. The key to achieving cost efficient, clean energy recovery from municipal solid waste gasification will be overcoming problems associated with the release and formation of these contaminants.

IV. Types of gasifiers for municipal solid waste treatment

Gasification technology is selected on the basis of available fuel quality, capacity range, and gas quality conditions. The main reactors used for gasification of MSW are fixed beds and fluidized beds. Larger capacity gasifiers are preferable for treatment of MSW because they allow for variable fuel feed, uniform process temperatures due to highly turbulent flow through the bed, good interaction between gases and solids, and high levels of carbon conversion. Table 2.9 shows the thermal capacity ranges for the main gasifier designs.

i. Fixed beds

Fixed bed gasifiers typically have a grate to support the feed material and maintain a stationary reaction zone. They are relatively easy to design and operate, and are therefore useful for small and medium scale power and thermal energy uses.

Table 2.9: Thermal capacities for different gasifier designs

Gasifier Design	Fuel Capacity
Downdraft	1 kW-1MW
Updraft	1.1 MW- 12 MW
Bubbling fluidized bed	1 MW – 50 MW
Circulating fluidized bed	10 MW – 200 MW

Source: Zafar, (2009)

The three primary types of fixed bed gasifiers are updraft, downdraft and slagging fixed bed gasifier.

i. **In a *downdraft gasifier***, air is introduced into a downward flowing packed bed or solid fuel stream and gas is drawn off at the bottom. The air/oxygen and fuel enter the reaction zone from above decomposing the combustion gases and burning most of the tars. Downdraft gasifiers are not ideal for waste treatment because they typically require a low ash fuel such as wood, to avoid clogging.
ii. **In an *updraft gasifier***, the fuel is also fed at the top of the gasifier but the airflow is in the upward direction. As the fuel flows downward through the vessel it dries, pyrolyzes, gasifies and combusts. The main use of updraft gasifiers has been with direct use of the gas in a closely coupled boiler or furnace. Because the gas leaves this gasifier at relatively low temperatures, the process has a high thermal efficiency and, as a result, wet MSW containing 50% moisture can be gasified without any pre-drying of the waste.
iii. ***Slagging fixed bed gasifier***, which is high-pressure and oxygen-injected, has commercial potential for gasifying MSW. In theory, the high temperatures crack all tars and other volatiles into non-condensable, light gases. Also under these conditions, the ash becomes molten and is tapped out, as is done in iron blast furnaces.

A. Fluidized beds

Fluidized beds are an attractive proposition for the gasification of municipal solid waste. In a fluidized bed boiler, a stream of gas (typically air or steam) is passed upward through a bed of solid fuel and material (such as coarse sand or limestone). The gas acts as the fluidizing medium and also provides the oxidant for combustion and tar cracking. Waste is introduced either on top of the bed through a feed chute or into the bed through an auger. Fluidized-beds have the advantage of extremely good mixing and high heat transfer, resulting in very uniform bed conditions and efficient reactions. Fluidized bed technology is more suitable for generators with capacities greater than 10 MW because it can be used with different fuels, requires relatively compact combustion chambers and allows for good operational control. The two main types of fluidized beds for power generation are bubbling and circulating fluidized beds.

In a *Bubbling Fluidized Bed (BFB),* the gas velocity must be high enough so that the solid particles, comprising the bed material, are lifted, thus expanding the bed and causing it to bubble like a liquid. A bubbling fluidized bed reactor typically has a cylindrical or rectangular chamber designed so that contact between the gas and solids facilitates drying and size reduction (attrition). As waste is introduced into the bed, most of the organics vaporize pyrolytically and are partially combusted in the bed. Typical desired operating temperatures range from 900° to 1000 °C.

A *circulating fluidized bed (CFB)* is differentiated from a bubbling fluid bed in that there is no distinct separation between the dense solids zone and the dilute solids zone. The capacity to process different feedstock with varying compositions and moisture contents is a major advantage in such systems.

V. Emerging trends

- *Gasification with pure oxygen or hydrogen*

Gasification with pure oxygen or pure hydrogen (or hydrogasification) may provide better alternatives to the air blown or indirectly heated gasification systems. This depends greatly on reducing the costs associated with oxygen and hydrogen production and improvements in refractory linings in order to handle higher temperatures. Pure oxygen could be used to generate higher temperatures, and thus promote thermal catalytic destruction of organics within the fuel gas. Hydrogasification is an attractive proposition because it effectively cracks tars within the primary gasifying vessel. It also promotes the formation of a methane rich gas that can be piped to utilities without any modifications to existing pipelines or gas turbines, and can be reformed into hydrogen or methanol for use with fuel cells.

- *Plasma gasification*

Plasma gasification or plasma discharge uses extremely high temperatures in an oxygen-starved environment to completely decompose input waste material into very simple molecules in a process similar to pyrolysis. The heat source is a plasma discharge torch, a device that produces a very high temperature plasma gas. Plasma gasification has two variants, depending on whether the plasma torch is within the main waste conversion reactor or external to it. It is carried out under oxygen-starved conditions and the main products are vitrified slag, syngas and molten metal. Vitrified slag may be used as an aggregate in construction; the syngas may be used in energy recovery systems or as a chemical feedstock; and the molten metal may have a commercial value depending on quality and market availability.

- ***Thermal depolymerization***

Such processes use high-energy microwaves in a nitrogen atmosphere to decompose waste material. The waste absorbs microwave energy increasing the internal energy of the organic material to a level where chemical decomposition occurs on a molecular level. The nitrogen blanket forms an inert, oxygen free environment to prevent combustion. Temperatures in the chamber range from 150 to 350^{0}C. At these temperatures, metal, ceramics and glass are not chemically affected.

2.12.5 Carbonization

Hydrothermal carbonization (HTC) is a wet thermal conversion process that has been shown to transform organic compounds (such as biomass and organic waste) to value-added products in closed systems under autogenous pressures and over relatively low temperatures (180 - 350 ^{o}C) (Berge et al, 2011). During carbonization, feed stocks undergo a series of reactions, including hydrolysis, dehydration, decarboxylation, aromatization and condensation, ultimately resulting in the generation of gas, liquid and solid (referred as hydrochar so as to differentiate it from solids generated from dry conversion processes) products. These products have garnered significant study, with the majority of studies conducted evaluating the proper ties of the generated hydrochar. Because the majority of carbon present in feedstock remains integrated within the hydrochar, the recovered solids energy density is enhanced (Berge et al, 2011; Hwang et al, 2012). In addition, the hydrochar has been reported to be attractive for use in many different applications, including soil augmentation, environmental remediation and as an alternative energy source (Goto et al, 2004; Hwang et al, 2012; Liu et al, 2010; Paraknowitsch et al, 2009). Carbonization has also been found to be more energetically advantageous than other dry thermal conversion processes (e.g., pyrolysis) for the conversion of wet materials

HTC was first experimentally explored as a means to produce coal from cellulose in 1913 by Bergius (Bergius, 1913). During the past few decades, carbonization studies have reemerged and explored as a means to create novel low-cost carbon-based nanomaterials/nanostructures from carbohydrates (e.g., Hwang et al, 2012). More recently, HTC has been proposed as a potentially attractive municipal solid waste (MSW) conversion technique. Because, during HTC, a large fraction of the carbon remains integrated within the solid material, successful carbonization of wastes has the potential to substantially reduce fugitive greenhouse gas emissions associated with current waste treatment/management processes, including MSW landfills and compost and incineration facilities (Berge et al, 2011; Sevilla et al, 2011b) (Erlach et al, 2012; Escala et al, 2013; Hao et al, 2013; Kruse et al, 2013; Liu et al, 2013; Malghani et al, 2013; Ramke et al,2009). HTC of waste streams has also emerged as a potential alternative strategy to produce a solid fuel source from waste streams. Ramke et al. (2009), Hwang et al. (2010), and Berge et al. (2011) have all reported that the produced hydrochar has an energy density equivalent to different types of coals (e.g., brown, lignite, etc.). Other advantages associated with carbonization include that emerging compounds, such as pharmaceuticals, personal care products, and endocrine disrupting compounds, may be thermally degraded or transformed during carbonization (Libra et al, 2011). In addition, HTC of waste materials has been shown to require less solids processing/treatment, such as chemical or mechanical dewatering of biosolids (Ramke et al, 2009). HTC of waste materials also results in considerable waste volume and mass reduction, ultimately requiring less ultimate storage/disposal space. Before adopting HTC as a waste management technique, it is important to understand the potential benefits and environmental application of HTC products and the influence of feedstock properties and processing parameters (such as time, temperature and processing liquid) on carbonization products.

HTC differs from combustion, gasification, and pyrolysis in that the process occurs at comparatively lower temperatures, is simpler (e.g., compared to fluidized bed gasification), and requires a wet feedstock and/or addition of supplemental liquid. During HTC, the feedstock is decomposed by reaction mechanisms similar to those in pyrolysis (e.g., hydrolysis, dehydration, decarboxylation, aromatization, and recondensation, Demirba 2000; Libra et al. 2011). In contrast to pyrolysis (and the other conversion processes), HTC produces higher solid (i.e., hydrochar) yields and more water soluble organic compounds. Gaseous oxidation products, particularly carbon dioxide, resulting from HTC are small because unlike combustion and gasification, exposure to oxygen is limited to that initially present in the reactor headspace and any dissolved oxygen in the water. It should also be noted that the total gas produced during HTC is small in comparison to other thermal conversion processes, and thus with a smaller fraction of carbon being transferred to the gas. The composition of the gas resulting from HTC has only recently been explored; results show presence of energy rich hydrocarbons.

An advantage of HTC over dry conversion processes is that heterogeneous wet organic residues and waste streams can be processed without preliminary separating and drying. Pyrolysis, gasification, and combustion require the feedstock be dried prior to conversion. Energy required to dry feed stocks can be significant, obviously depending on feedstock moisture content.

2.12.6 Mechanical Biological Treatment

Mechanical Biological Treatment (MBT) refers to a wide range of technologies that separate incoming waste into recyclable materials for recovery and an organic fraction for biological treatment (stabilization). In Europe, facilities tend to produce a refuse-derived fuel (RDF) for subsequent thermal treatment; this is not the case in other regions (i.e. Australia). MBT – in all its various configurations – has a strong track record in Europe, and the UK and Australia are increasingly embracing MBT as the cost of landfilling increases in these countries. MBT is relatively scarce in the rest of the world, therefore the majority of Life Cycle Assessment (LCA)-type studies that estimate GHG emissions from MBT are based on European, UK, and Australian conditions (Bogner et al, 2007).

The downstream, indirect GHG emissions/savings from MBT generally outweigh both upstream and direct process emissions. Table 2.10 provides a qualitative summary of the indirect and direct GHG emissions and savings associated with MBT. To provide a complete picture, all GHGs are noted, including biogenic CO_2. The overall climate impact of a particular MBT technology will depend on:

- The efficiency of front-end sorting processes – recovered materials contribute to potentially significant downstream GHG savings
- Energy consumption of system – more automated, sophisticated systems have a higher energy demand
- Energy generation – in the case of anaerobic digestion (AD)-type MBT facilities, energy produced from biogas – either heat or electricity – will account for a GHG saving
- Control of emissions during the maturation phase – best-practice for MBT involves the use of air pollution control systems, such as scrubbers and bio-filters, to prevent emissions of nitrous oxide and methane
- Carbon storage potential – compost derived from mixed waste is usually restricted in application (i.e. remediation of contaminated land or landfill), but may be credited with a GHG benefit from carbon storage
- Biodegradability of final output – the biodegradability of the final composted output will decrease with increased maturation time, and the lower the biodegradability, the less potential for the material to generate methane (if landfilled)
- The main gains in terms of climate benefit are from separation and recovery of recyclable materials and through reduction of the amount of biodegradable waste landfilled (or medium long term binding of carbon where composted output is applied to soils). Less organic material to landfill equates to fewer methane emissions. Where MBT outputs are landfilled rather than applied to land (the use of MBT compost outputs tends to be highly regulated in OECD countries), some methane will still be generated. Theoretically, an MBT process could reduce methane by 90%, compared to landfilling the equivalent quantity of waste (Bogner *et al*, 2007).

Table 2.10: Summary of indirect and direct GHG emissions and savings from MBT

Upstream (indirect)	**Direct (operating)**	**Downstream (indirect)**
CO_2, CH_4, and N_2O emissions from: production of fuel used in facility, heat and electricity consumption, and Infrastructure	CO_2, CH_4, N_2O, trace CO and NMVOC from fuel combustion in equipment Biogenic CO_2, CH_4, and N_2O from windrows Biogenic CO_2, CH_4 (leakages) and trace N_2O from reactors, and bio-filters (MBT AD)	Heat and/or electricity produced from combustion of biogas substitutes fossil energy (MBT AD): avoided CO_2 Front-end recovery of materials substitutes raw materials: avoided GHG emissions from material production Use of organic compost output to substitute soil growth media: avoided GHG emissions from producing virgin growth media Long-term carbon stored in landfill (organic materials largely recalcitrant in anaerobic conditions):avoided CH_4 and biogenic CO_2

Source: Scheutz *et al,* (2009)

MBT, with simple aerobic composting of the organic portion of the mixed waste stream, may offer an easy, relatively inexpensive solution to reduce the climate impact of landfilling waste. This may also be seen as an interim solution to gain rapid GHG benefit while waste management systems are improved (i.e. to increase source separation and recovery). The dried organic outputs from MBT may also be used as refuse-derived fuel (RDF) for incineration with energy recovery or co-combustion in industrial furnaces, typically cement kilns, paper pulp mills, and coal-fired power plants. RDF generally does not replace conventional fossil fuel on a 1:1 ratio by weight – more RDF may be required to achieve the same energy output. Conventional furnaces will have a limit to the amount of fuel calorific value they can substitute with RDF and not all industrial processes can be easily adapted to use RDF (ERC, 2008b). Emissions control at industrial plants may be less stringent than at waste incinerators – the EU has addressed this concern through the Waste Incineration Directive (WID) that stipulates emissions requirements for any plant combusting significant quantities of waste. The climate impacts from burning RDF in industrial furnaces depend in part on the conventional fuel displaced.

MBT-AD technology for mixed residual waste is largely found in Europe. Many European plants are small-scale, treating less than 20,000 tonnes per year (Kelleher, 2007). The EU Landfill Directive creates the necessary cost and regulatory incentives to support development of both MBT-AD and MBT-composting facilities. The performance of MBT-AD requires careful preparation and pre-sorting of incoming waste in order to ensure a suitable mixture is introduced to the digestion micro-organisms. European plants are equipped with sophisticated front-end sorting equipment, which makes MBT-AD a less affordable and viable solution for developing countries, or countries where landfilling is cheap.

2.12.7 Composting and anaerobic digestion of source-separated organic wastes

Composting systems treat biodegradable material such as food, animal industry wastes, green waste, wood, and agricultural residues and produce a range of organic soil amendment products that can replace manufactured fertilizers and/or peat, reduce the need for pesticides, improve soil structure, reduce erosion, and reduce the need for irrigation. Around 2,000 composting facilities treat source-separated household organic waste in Europe (Boldrin et al, 2009). Composting and anaerobic digestion of source-separated wastes requires significant investment in local community education (both households and commercial enterprises) and public awareness – this is essential to ensure proper source-separation, high quality compost products, and secure end-use markets.

Simple composting systems are an effective, low-tech solution for developing countries to reduce waste quantities and generate a valuable compost product for application to agriculture. Both composting and AD systems are found throughout non-OECD regions. There are approved methodologies for composting projects under the CDM, such as the methodology for 'avoided emissions from organic waste through alternative waste treatment processes' (AM0025). In India, the informal waste sector feeds into both small and large-scale composting facilities. In the Defense Colony neighbourhood of Delhi, waste pickers collect material from 1,000 households and compost it in a series of neighbourhood composting pits. Also in Delhi, a large-scale composting plant processes 200 tonnes of separated organic waste per day (Chintan, 2009). An estimated 9% of MSW in India is composted, and compost is a valuable and marketable product for Indian agriculture (Sharholy, 2008).

The climate impact of composting and AD systems is due to both direct process emissions and indirect upstream and downstream emissions. Table 2.11 provides a qualitative summary of the indirect and direct GHG emissions and savings associated with composting and AD processes. To provide a complete picture, all GHGs are noted, including biogenic CO_2.

Direct emissions from composting facilities result from fuel combustion in equipment (i.e. front loaders) and from decomposition of the organic material. As composting produces CO_2 from biogenic carbon sources, it does not contribute to national GHG inventories for the waste sector under IPCC accounting methods (IPCC, 2006). CH_4 and N_2O emissions will depend on the type of organic waste input, the technology used (in particular, whether the process is open or enclosed), and how the process is managed (Boldrin *et al,* 2009). The IPCC default values for reporting emissions from

Table 2.11: Summary of indirect and direct GHG emissions and savings from composting and AD processes

Upstream (indirect)	**Direct (operating)**	**Downstream (indirect)**
CO_2, CH_4, and N_2O emissions from: production of fuel used in facility, heat and electricity consumption, and infrastructure	CO_2, CH_4, N_2O, trace CO and NMVOC from fuel combustion in equipment	Heat and/or electricity produced from combustion of biogas substitutes fossil energy (**AD processes only**): avoided CO_2
	Compost processes: Biogenic CO_2, CH_4, and N_2O from windrows	Use of organic compost output to substitute soil growth media: avoided GHG emissions from producing virgin growth media
	AD processes: Biogenic CO_2, CH_4 (leakages) and trace N_2O from reactors, and biofilters	

Source: Scheutz et al, (2009)

biological treatment processes in national GHG inventories provide an indicative range of emissions levels (Table 2.12), which are also comparable to the range of values presented for open and enclosed composting systems in (Boldrin *et al,* 2009).

Once compost is applied to land, further, minimal emissions will be generated as organic compounds are gradually mineralized to biogenic CO_2. Therefore, compost applied to soil has a medium or long-term potential to store carbon; however, it does not represent a permanent solution for ‘locking-up’ carbon (Smith *et al*, 2001; Favoino and Hogg, 2008). Quantifying the climate benefit of carbon storage is extremely difficult and will largely depend on how the soil landscape is managed (cropping, tillage, irrigation, compost application rate, etc), climate, and original carbon content of the compost and soil. Estimates of GHG savings range from 2 kg CO_2-e to 79 kg CO_2-e per tonne of composted waste applied to land (Smith *et al,* 2001; Boldrin *et al,* 2009; Recycled Organic Unit (ROU), 2006). Compost applications to land may also result in emissions of N_2O, depending on the nitrogen content of the compost, and when the compost is applied (i.e. N_2O releases are likely if vegetation is not taking up nitrogen at the time of application) (Boldrin *et al,* 2009). However, compared to synthetic fertilizers, compost may in fact reduce overall N_2O emissions from agricultural land by providing a more slowly released source of nitrogen (Favoino and Hogg, 2008). Compost applied to land replaces synthetic fertilizers and soil improvers (i.e. peat) and reduces the need for pesticides, tillage, and irrigation (Favoino and Hogg, 2008; Boldrin *et al,* 2009; USEPA, 2006; Smith *et al,* 2001). The manufacture of synthetic fertilizers is energy-intensive (e.g. extraction of phosphate rock), as is the extraction of peat for use as a soil amender (note that peat extraction also generates methane emissions). Peat use is not widespread in certain parts of the world, including developing regions and Australasia. Where compost replaces either synthetic fertilizer or peat, there will be a GHG benefit due to avoided energy use. GHGs are also released during the manufacture of synthetic fertilizers: studies have reported values of 4-13 kg CO_2 per kg synthetic N, 0.5-3 kg CO_2 per kg synthetic P, and 0.4-1.5 kg CO_2 per kg synthetic K (ROU, 2006; Boldrin et al, 2009). Substitution of fertilizer has been estimated to save around 8 kg CO_2-e per tonne of composted waste applied to land, and substitution of peat has been estimated to save

Table 2.12: Default emissions factors for CH_4 and N_2O emissions from biological treatment of waste

Type of biological treatment	CH4 Emissions Factors (g CH4/kg waste treated)		N2O Emissions Factors (g N2O/kg waste treated)		Remarks
	On a dry weight Basis	60% Moisture Content Basis	On a dry weight Basis	60% Moisture Content Basis	
Composting	10 (0.08 – 20)	4 (0.03 – 8)	0.6 (0.2 – 1.6)	0.3 (0.06 – 0.6)	Assumptions on the waste treated: 25-50% DOC in dry matter, 2% N in dry matter , moisture content 60%.
Anaerobic digestion at biogas Facilities	2 (0 – 20)	1 (1 – 8)	Assumed Negligible	Assumed Negligible	The emission factors for dry waste are estimated from those for wet waste assuming a moisture content of 60% in wet waste

Source: IPCC, (2006)

between 4 and 81 kg CO_2-e per tonne of composted waste (PROGNOS, 2008; Boldrin et al, 2009). Estimates of the net climate impact of both open and enclosed composting systems in Europe are savings of around 35 kg CO_2-e per tonne of wet organic waste input (Smith *et al*, 2001; Boldrin *et al*, 2009), taking into consideration fertilizer and peat substitution, and carbon storage in soil.

Anaerobic digestion (AD) of source-separated organic wastes is an alternative to aerobic composting systems, although AD tends to accept a smaller range of materials (i.e. materials with a high lignin content, such as woody garden wastes, are generally not suitable for AD in large quantities). The biogas produced by AD tends to have a high methane content (around 60%, although it will depend on the process parameters) and therefore high energy content. Energy consumption at the AD plant results in indirect, upstream GHG emissions, although the plant's energy requirements may be partially met through heat generated 'in-house'. Diesel and electricity are the main energy sources – diesel use is minimal (i.e. 1.6 L per tonne of waste) and electricity use varies with the process. The climate impact associated with electricity use will depend on the local mix of fuels, with coal-power resulting in a higher impact than, say, natural gas. Møller, (2009) suggest a range of values from 2-45 kg CO_2-e per tonne of waste. Small quantities of fugitive emissions from leaks in the system and during maintenance account for direct process GHG emissions – the majority of biogas is contained and used to generate energy. Møller, (2009) estimated the climate impact of fugitive emissions at 0-48 kg CO_2-e per tonne of waste received at typical AD facilities, which is generally in line with IPCC indicative values (Table 2.12.)

Indirect, downstream emissions are due to energy generation and use of the digestate/compost output. Typical electricity production efficiencies of 35% are assumed for biogas in LCA-type studies (ERC, 2002; Christensen *et al*, 2009), and plants often operate in CHP mode, using the heat 'in-house' to reach the necessary AD process temperatures. This of course assumes sophisticated AD facilities, as are common in Europe – the climate impacts of simple, small scale.

AD systems that may be more applicable to developing regions are difficult to assess due to lack of data. Biogenic CO_2 emissions from the combustion of biogas range from 154-250 kg CO_2-e per tonne waste (Møller, 2009). Climate impact due to the release of small quantities of unburned methane and nitrous oxide during the combustion process result in GHG emissions of 15-24 kg CO_2-e and 0.3-0.5 kg CO_2-e per tonne of waste, respectively (Møller, 2009). Biogas can also be cleaned and either (a) used in transport, (b) used to power equipment, (c) used in local 'sour' (i.e. impure) gas networks, or (d) piped into a gas distribution network, subject to local regulation.

Depending on facility performance, assumptions regarding energy, the end-use of energy generated, and assumptions regarding use of digestate, an advanced, European-style AD facility may have a net climate impact ranging from -375 to 111 kg CO_2 -e per tonne of wet organic waste input (Møller *et al*, 2009). Higher levels of biogas production, a high-CO_2-e energy mix, and use of heat rather than electricity would all contribute to greater GHG savings.

2.12.8 Recycling

After waste prevention, recycling has been shown to result in the highest climate benefit compared to other waste management approaches. This appears to be the case not only in the OECD (ISWA, 2009; Christensen *et al*, 2009); USEPA, 2006) but also in developing countries (Pimenteira *et al*, 2004; Chintan, 2009), although limited data is available. For example, in the US, recycling materials found in MSW resulted in the avoidance of around 183 Mt CO_2-e in 2006 (US EPA, 2009). Estimates of GHG savings are generally based on the premise that recycled materials replace an equal – or almost equal – quantity of virgin materials in a closed- loop recycling system (where material is reprocessed back into the same or a similar product).

Recycling activities are not limited to closed-loop systems, but encompass open-loop recycling, down-cycling, and industrial symbiosis. Open-loop recycling occurs where recycled material is used to make a new, different product, often with a loss of material quality (which may be referred to as 'down-cycling'). Industrial symbiosis involves the exchange of resources including by-products among industrial enterprises, which may form 'recycling clusters' to facilitate sharing resources. Case studies of industrial symbiosis in both developed and developing regions have shown measurable environmental and economic benefits with respect to air, water, and waste (Chertow and Lombardi, 2005; Ashton *et al*, 2009; Harris, 2007). GHG savings may be associated with reduced use of raw materials, reduced transportation (i.e. of wastes to landfill), and fossil fuel substitution in CHP facilities (i.e. where there is an industrial use for the heat) (Ashton, 2009; Harris, 2007). Since 2005, the UK's National Industrial Symbiosis Programme has diverted more than five million tonnes of waste from landfill and eliminated more than five million tonnes of carbon emissions through its activities (Chertow, 2009). Table 2.13 provides a qualitative summary of the indirect and direct GHG emissions and savings associated with recycling processes. To provide a complete picture, all GHGs are noted, including biogenic CO_2. Generally, emissions relating to the indirect downstream processes far outweigh the combined operating and upstream emissions in recycling processes (for example, see analyses in Merrild *et al*, (2009); Larsen *et al*, (2009); Astrup *et al*, (2009), and Damgaard *et al*, (2009)).

The GHG benefits of recycling specific materials, such as metals, plastics, glass, and paper products, are well documented (Smith *et al*, 2001; WRAP, 2006; US EPA, 2006), and are shown to vary with material, recovery rates, and the type of fossil fuel avoided (where energy savings are calculated). In particular, the magnitude of estimated GHG savings from recycling is highly dependent on the energy assumptions applied to both reprocessing facilities and substituted virgin material plants. Recycling GHG savings have been estimated for countries and/or regions using LCA. Table 2.14 compares values applied in Northern European, Australian and US studies. The variations in the amounts of GHG credited to the materials shown in the table will largely be due to the energy assumptions of the individual LCA studies.

The range of values for paper presented in Table 2.14 also reflects different paper types, and each study's assumptions regarding un-harvested wood stocks. For example, paper recycling reduces the demand for wood – some studies assume that this 'saved' wood would be used as an energy source (and therefore generate energy GHG savings), whereas others assume that the wood remains un-harvested, and thus has a carbon sequestration benefit. Merrild *et al*, (2009) estimate that the downstream GHG impact of paper recycling in Northern Europe could range from +1,500 kg CO_2-

Table 2.13: Summary of indirect and direct GHG emissions and savings from recycling processes

Upstream (indirect)	Direct (operating)	Downstream (indirect)
CO_2, CH_4, and N_2O emissions from: production of fuel used in facilities (i.e. material recycling facilities and reprocessing plants), heat and electricity consumption, and infrastructure	CO_2, CH_4, N_2O, trace CO and NMVOC from fuel combustion in equipment	Recovery of materials substitutes raw materials: avoided GHG emissions from material production. Recovery of paper avoids use of harvested wood: wood biomass replaces fossil fuel as energy source (biogenic CO_2 emissions replace fossil CO_2) or un-harvested wood sequesters carbon

Source: Scheutz *et al,* (2009)

Table 2.14: CO_2-e emission reduction for materials recycled in N Europe, Australia, and USA

Material	**Kg CO_2-e saved per tonne of material recycled – Northern Europe**	**Kg CO_2-e saved per tonne of material recycled – Australia**	**Kg CO_2-e saved per tonne of material recycled – USA**
Paper	600 - 2,500	670 – 740	838 – 937
Aluminum	10,000	17,720	4,079
Steel	2,000	400 – 440	540
Glass	500	560 – 620	88
Plastics	0 -1,000	0 – 1,180	0 – 507

Source: ISWA, (2009); RMIT, (2009); US EPA, (2006).

e/tonne paper waste (i.e. emissions) to -4,400 kg CO_2-e/tonne paper waste (i.e. savings), depending on whether recycled paper is assumed to replace virgin or recycled paper stocks, the energy assumptions, and the choice of what happens to the un-harvested wood.

The range of values for plastic (Table 2.14) reflects a number of possible factors, such as: different types of plastic polymers, direct substitution of virgin plastic versus a mixed plastic product replacing the use timber or concrete (i.e. for garden furniture and fences), assumptions regarding energy, and reprocessing techniques. Astrup *et al*, (2009) found that the substitution of virgin plastic generated greater climate benefit generated greater climatic benefit (i.e. savings of 700 – 1,500 kg CO_2-e/tonne plastics waste) than either the substitution of wood (i.e. emissions of 70 – 500 kg CO_2-e/tonne plastics waste) or production of energy (i.e. savings of 1,200 – emissions of 50 kg CO_2-e/tonne plastics waste) using plastics recycled in Europe.

A recent investigation by the UK Waste and Resources Action Programme (WRAP) of 55 LCA studies found that '*across the board, most studies show that recycling offers more environmental benefits and lower environmental impacts than other waste management options*' (WRAP, 2006). The report's main GHG-related conclusions for specific materials included:

(a) On average, virgin production of paper followed by incineration with energy recovery consumes twice as much energy as paper recycling; however, the GHG benefit of recycling paper depends largely on the system boundaries adopted by the individual LCA studies (in particular, whether the GHG 'cost' of using timber to produce paper is accounted for).

(b) Closed-loop recycling of glass results in net climate benefits compared to incineration. There is insufficient data on open-loop recycling (i.e. glass recycled into aggregate, insulation, or other secondary product) to determine the net GHG impact

(c) .Where recycled plastic replaces virgin plastic of the same kind in ratio of 1:1 (by weight), recycling of plastic was found to have a net environmental benefit compared to incineration. For every kg of plastic recycled, around 1.5 – 2.0 kg CO_2-e is saved.

(d) Production of virgin aluminum requires 10-20 times more energy than recycling aluminum. Although regional differences in energy sources cause large variations in the extent of GHG savings, there is a universal climate benefit in recycling aluminum.

(e) Production of virgin steel requires around two times as much energy as production of steel from recycled scrap. As above, regional differences in energy sources may cause variations in the extent of GHG savings; however there is a universal climate benefit in recycling steel.

China has become the major global destination for recycled materials. 50% of the UK's recovered paper and 80% of recovered plastics are exported to China. The UK's WRAP recently commissioned an investigation into the carbon impact of exporting collected recycled materials to China in order to determine whether the climate impact of overseas transport (in container ships) outweighed the benefits of recycling (WRAP, 2008). For the UK, the impact of shipping was minimal, in part due to the fact that ships would otherwise return empty to China (the majority of the shipping movement is from China to the UK – transport of recycled materials back to China represents a marginal impact). An alternative to recycling plastics that has received some interest recently is conversion of plastics to synthetic diesel. An investigation into GHG impacts of a variety of waste and energy management scenarios for London found that the climate benefits of recycling plastics from the city's MSW far outweighed conversion to diesel (Eunomia, 2008).

The role of the informal recycling sector should not be underestimated in developing nations. The World Bank estimates that around 1% of the urban population in developing countries (approximately 15 million people) earns their livelihood from waste-picking and the informal recycling sector (Medina, 2008). Because these activities are not formally organized or often sanctioned by government, their contribution to waste management and resource recovery (and the economy) is often not recognized. However, there is growing appreciation of the role of 'waste pickers' in some countries. Governments in Brazil and Colombia now support the informal sector, which has enabled the formation of waste picker organizations with greater respect and ability to negotiate direct source-collection contracts (or informal agreements) with businesses, industries, and neighbourhood associations (Medina, 2008).

A recent report on the climate impact of the informal waste sector in India estimates that activities in Delhi alone equate to savings of around 962,000 tonnes CO_2-e (Chintan, 2009). This Fig was calculated based on only paper, plastics, metals, and glass recovery, using material specific emissions factors developed for the US EPA's LCA model, WARM, in the absence of Indian LCA tools. However, the report authors note that, due to very conservative estimates of recycling rates and the much more coal-dependent energy mix in India, the values generated by WARM are likely to underestimate the contribution of the informal sector. Figure 2.7 compares the GHG savings attributed to the informal recycling sector with the estimated GHG reductions anticipated from several waste-to-energy projects and a composting plant currently registered as CDM projects for India (Chintan, 2009). The comparison is highly relevant: waste-to-energy projects generally conflict with the informal sector, limiting waste pickers' access to recyclable materials and negatively impacting their livelihood (Chintan, 2009, Global Alliance of Waste pickers/Recyclers and Allies, 2009).

The economic contribution of waste pickers should also not be overlooked. Informal recycling in Jakarta reduces the volume of waste by approximately 30%, thereby saving on collection and disposal costs, and extending the life of landfills (Medina, 2008). In major Indian cities such as Delhi and Bangalore, waste pickers prevent at least 15% of MSW going to landfill, saving the government around US$13,700 per day in waste collection and disposal costs (Sharholy, 2008). Mexican paper mills have strengthened relationships with waste picker associations in order to secure more supply of valuable waste paper.

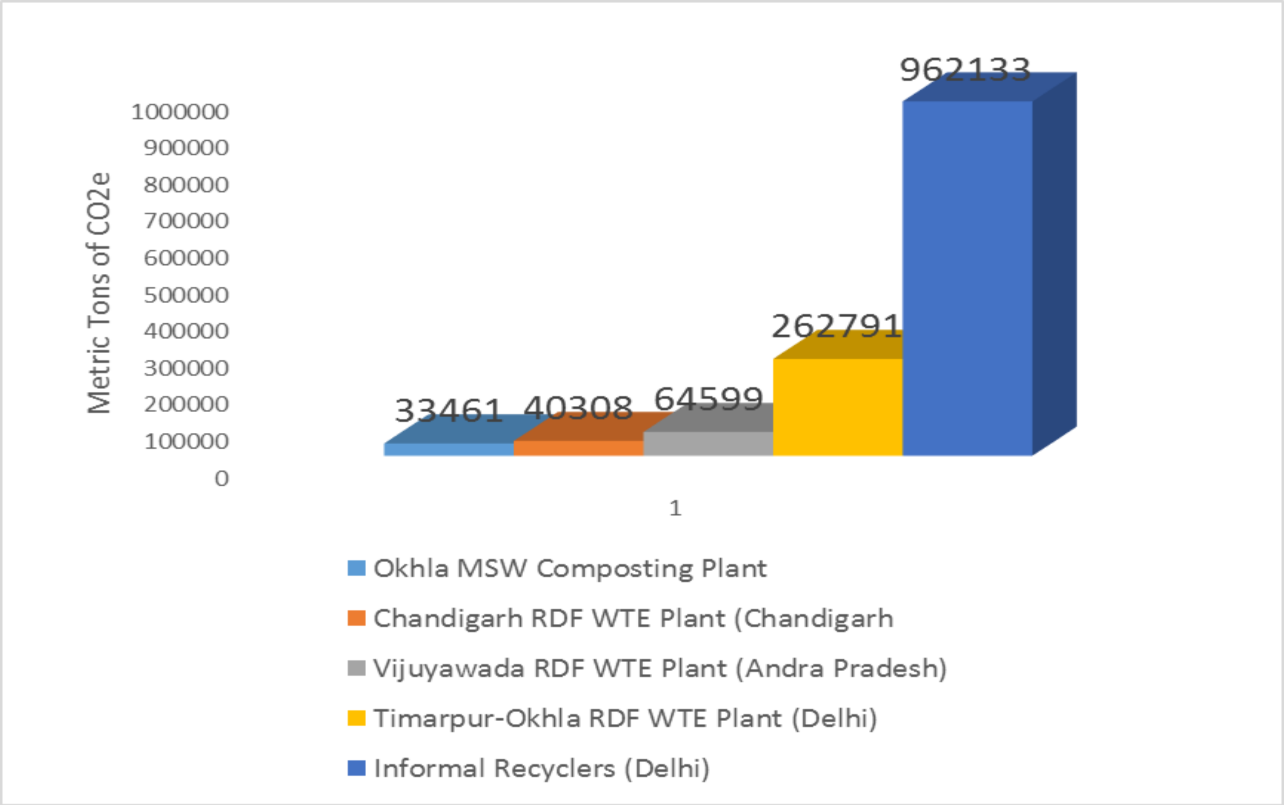


Fig 2.7: Comparison of GHG Savings attributed to Informal Sector with Estimated GHG Reduction from Waste to Energy Projects.

Source: (Chintan, 2009).

2.12.9 Waste prevention

Waste prevention is considered the most important action in the waste hierarchy; however it often receives minimal priority in terms of resource allocation and effort. Waste avoidance is critical to decoupling waste generation from economic growth. Within waste prevention there exists a raft of mechanisms that can deliver climate benefit, such as cleaner production, extended producer responsibility, sustainable consumption and production, etc. The Sustainable Consumption and Production (SCP) Branch of UNEP is involved in a number of programs targeting sustainable consumption and production, including collaborations with the International Solid Waste Association (ISWA) on waste minimization. Various mechanisms have been developed and applied to prevent waste arising, with most relying on concerted efforts to educate waste generators. Table 2.15 provides examples of several waste prevention programs.

A number of EU Directives, such as the Waste Electrical and Electronic Equipment (WEEE) Directive and the Directive on Packaging and Packaging Waste, have promoted extended producer responsibility (EPR) for specific materials in Europe. Parts of Canada and Australia also have EPR legislation in place that effectively reduces targeted waste streams, such as beverage containers, used tyres, and car batteries.

In terms of climate change impact, the benefits of waste prevention generally outweigh benefits derived from any other waste management practice: not only are net GHG emissions avoided from treatment and disposal of the waste, but there is also a noteworthy benefit in avoided GHG emissions from less raw resource extraction and manufacturing. LCA has been used to estimate the climate benefit of avoided resource use for a limited number of scenarios – it is difficult to quantify the impacts of a waste prevention measure. A US EPA study found that, generally, the net GHG emissions for a given material are lowest for source reduction and highest for landfilling (US EPA, 2006). This is especially true for prevention of paper waste where GHG savings are attributed to increases in forest carbon sequestration (i.e. less use of virgin forest materials to produce paper products equates to less deforestation).

Table 2.15: Examples of waste prevention initiatives across different waste streams

Targeted waste stream	**Initiative**	**Comments**
Commercial / Industrial waste	Cleaner Production	For example, manufacturing wastes are reduced through systems assessment and more effective use of raw materials
Municipal solid waste	Extended product life	Many products have limited lifetime for purely commercial reasons (i.e. built-in obsolescence) – increasing product durability and warranty has a direct impact on waste generation
Packaging waste	Light-weighting	Reducing the amount of material used to produce packaging (i.e. lighter plastic wrapping, lighter cardboard boxes)

Source: USEPA, (2009)

A recent report produced by the US EPA Office of Solid Waste and Emergency Response (US EPA, 2009) examines how GHG emissions could be prevented through alternative management of materials (US EPA, 2009). An estimated 42% of total US GHG emissions are due to materials management. Strategies discussed in the report include source reduction through improved product design and cleaner production, increasing product durability, and maximizing the ease of product disassembly (for recycling). A number of scenarios were modelled to estimate the potential GHG reductions, assuming no economic, institutional, or technological barriers – results of several scenarios are shown in Table 2.16 and indicate the order-of magnitude impact of various activities. The scenarios were modelled using the waste LCA tool developed by the USEPA (called WARM). The assumptions in WARM regarding LFG capture, incinerator efficiency, etc., will impact on results. The key areas for action are clear: increasing recycling, maximizing LFG capture, and reducing packaging result in significant GHG benefits.

2.13 Methods of estimating methane emissions

2.13.1 Choice of method

The *IPCC Guidelines* describe two main methods:

(A): The default IPCC methodology that is based on the theoretical gas yield (a mass balance equation).

(B): Theoretical first order kinetic methodologies, through which the *IPCC Guidelines* introduces the "First order decay model" (FOD).

The main difference between the two methods is that method A does not reflect the time variation in SW disposal and the degradation process as it assumes that all potential methane is released the year the SW is disposed. The timing of the actual emissions is reflected in method B. Only if the yearly amounts and composition of waste disposed as well as disposal practices have been nearly constant for long periods, the method A will produce fairly good estimates of the yearly emissions. Increasing amounts of waste disposed will lead to an overestimation, and decreasing amounts correspondingly to underestimation, of yearly emissions. Method B gives a

Table 2.16: Summary of selected materials management scenarios for the US

Scenario	**Estimated GHG emissions benefit (Mt CO_2-e/yr)**
Reduce packaging use by 50%	40 – 105*
Reduce packaging use by 25%	20 – 50
Increase the national MSW recycling and composting rate from current (32.5%) to 50%	75
Combust 25% of currently landfilled MSW	20 – 30
Capture 50% of currently emitted methane at US landfills for electricity generation	70

*higher benefits include GHG credit for forest sequestration

Source: US EPA, (2009)

more accurate estimate of the yearly emissions. Many countries may, however, have problems getting the necessary data and information (historical data on SW disposal, rate constant for the decay) to establish the proper basis for emission inventories with acceptable accuracy.

2.14 Carbon capture/ air extraction

Air extraction can be defined as the removal of carbon dioxide from the atmosphere. Air extraction can be viewed as a variation of flue gas scrubbing with the constraint that the source gas is at atmospheric temperature, pressure, and at ambient concentration of carbon dioxide. Air extraction technology would make the existing transportation infrastructure sustainable. It would also mitigate emissions from other smaller sources unsuitable for direct capture. As such the extraction effort would have to be able accommodate approximately 30 per cent of current US emissions or ~1.5 Gt of carbon dioxide (Energy Information Agency, 2009).

2.14.1 The rationale for air extraction

Unless painful actions are taken to reduce consumption, it is likely that world carbon consumption will grow rather than shrink. Natural processes are unlikely to adsorb all this carbon, and CO_2 levels in the air will keep rising, unless CO_2 emissions are virtually stopped. To stabilize CO_2 levels, it is necessary to not only deal with CO_2 emissions from power plants, but from all sources in an industrial economy. While it is generally agreed that the reductions demanded by the Kyoto Treaty would be far less than what would ultimately be required to stabilize CO_2 levels in the atmosphere (Houghton, 1995) it is also clear that even this goal would be too ambitious to be achieved by exclusively eliminating emissions from power plants. Since the economy and with it energy consumption have grown substantially since 1990, the reduction required in the United States is far more than the nominal seven per cent reduction which is measured relative to 1990 emissions. The economy of 2010 would most likely have to reduce carbon emissions by more than 30% relative to business-as-usual. This is equivalent to eliminating all emissions from power plants. However, in the long-term carbon reductions will have to go far below 1990 emission levels and thus it is necessary to address all carbon dioxide emissions including those from small and mobile sources. A portion of the desired reductions will be achieved by improved energy efficiency and energy savings, and another part might be accomplished by transition to non-fossil, renewable energy resources. However, here we concern ourselves with eliminating the remaining carbon dioxide emissions. Given the continuing and highly desirable worldwide economic growth, we expect this to be a large fraction of the total required emission reductions.

A source of carbon dioxide that is particularly difficult to manage is the transportation sector. A transition to electric or hydrogen fueled vehicles is in principle possible but would take a long time to accomplish. Even though it has been proposed (Seifrit, 1993) it does not appear to be economically viable to collect the carbon dioxide of a vehicle directly at the source. The mass flows would be prohibitively large. Generally, even stationary, small sources would be difficult to deal with. A unit mass of fuel results in roughly three mass units of gaseous CO_2 that would need to be temporarily stored at the source and later shipped to a disposal site. The mass of the stored material would be more than doubled once more, if one were to store the CO_2 Adsorbed onto some substrate, like CaO. Capturing CO_2 on board of an airplane is simply not possible because of the mass involved; in a car it would be prohibitively expensive; and even in a home it would not be practicable, as it would require a huge infrastructure for removal and transport of CO_2 to a disposal site.

Distributed carbon dioxide sources account for approximately half of the total emissions. While it may not be necessary to address them initially, for carbon management to be successful in the long term, they cannot be ignored. Carbon dioxide capture from the atmosphere, in principle, can deal with any source, large or small. Indeed, the appeal of biomass for sequestration and of credits for growing trees is based on the very same premise. Since photosynthesis takes the carbon it needs from the air, it can compensate for any emission, and ideally it can be done at the disposal site eliminating the need for long distance surface transportation. Thus, it is our objective to explore the feasibility of CO_2 capture from air. We would like to find out whether it is physically possible, whether it could be done at acceptable cost, and whether the scale of such an operation would be acceptable. We will show in the following that CO_2 capture is physically and economically feasible, and that the scale of operation is actually small compared to other renewable options that are considered as possible replacements for fossil energy.

2.14.2 Approach to carbon capture

Carbon dioxide capture from air is certainly possible. Plants during photosynthesis routinely accomplish this task. Chemical processes also can capture CO_2. A classic chemistry experiment is to bubble air through a calcium hydroxide solution and to remove the air's CO_2 in this fashion. Other means work as well and have been used in the past in industrial processes to generate CO_2 free air. However, in capturing CO_2 one is very much constrained by economic considerations. One can hardly spend any effort in handling the air as any cost is amplified by the dilution ratio, which is roughly one part in three thousand. It is not economically possible to perform significant amount of work on the air, which means one cannot heat or cool it, compress it or expand it. It would be possible to move the air mechanically but only at speeds that are easily achieved by natural flows as well. Thus, one is virtually forced into considering physical or chemical adsorption from natural airflow passing over some recyclable sorbent (Lackner *et al*, 1999). Once the CO_2 has been taken out of the air, the downstream processing deals with volumes and masses that are of the same order of magnitude as the CO_2 itself and is therefore not subject to the large amplification factor that results from the dilute nature of CO_2 in air. To get an appreciation for the scales, let us measure the CO_2 content of air in energy units. At 365 ppm of CO_2 in the air, a cubic meter (or 40 moles of air) contains 0.015 moles of CO_2. If this CO_2 were extracted from the air to compensate for an equivalent CO_2 emission by a gasoline engine somewhere else, we could relate the amount of CO_2 in a cubic meter of air with the heat released in the combustion of gasoline resulting in the emission of the same 0.015 moles of CO_2. This heat of combustion amounts to 10,000 J. Thus removing the CO_2 from one cubic meter of air and disposing of it opens the door for generating 10,000 J of heat from gasoline anywhere in the world. Combined, these two actions are carbon neutral. This approach to a net zero carbon economy works, because CO_2 in the air is not harmful and the natural amount in the air is large compared to the amounts human activities add on short time scales. Current annual world emissions from human activities equal 1% of the total CO_2 in the air. Since mixing times are far shorter than a year, one can use the air as a conveyer that moves CO_2 from its source to its sink. As long as the total amount in transit is small compared to the air's CO_2 content, moving CO_2 in this fashion to the sink would not unduly distort atmospheric CO_2 concentrations. Locally, mixing is very fast and therefore local CO_2 depletion or enrichment is not likely to pose a problem either. If this were not the case, emissions from power plants would cause large local deviations. In the same fashion as CO_2 enriched air mixes rapidly with ambient air to maintain constant levels of CO_2, air depleted in CO_2 will also mix rapidly and return to ambient conditions. It is, however, this mixing rate which sets the limit of how closely one could space CO_2 extraction units (Lackner *et al*, 1999; Elliot *et al*, 2001).

The carbon dioxide content of a volume of air, as measured by the heat of combustion its removal could compensate for, is far larger than the kinetic energy the same volume of air would have assuming reasonable wind velocity. At 10 m/s, which is a wind stronger than is usually assumed to prevail in windmill operations (Gipe, 1995), the kinetic energy of a cubic meter of air is 60 J, which should be compared to 10,000 J for the heat of combustion that would generate the CO_2 content of a cubic meter of air. A windmill that operates by extracting kinetic energy from natural airflow needs to be two orders of magnitude larger than a CO_2 collector that captures CO_2 to compensate for the emissions from a diesel engine that generates the same amount of electricity. Since windmills appear economically viable, this suggests that the capturing apparatus should not be too expensive to build.

One can pursue this line of reasoning a little further by looking at the same data in a slightly different fashion. Windmills are rated by energy flux per unit area. In effect the wind carries with it a flow of kinetic energy, a part of which a windmill transfers into electric energy. Thus a windmill at wind speed of 10 m/s would face an energy flux of 600 W/m^2. The equivalent CO_2 flux through the same area corresponds to 100,000 W/m^2. Thus an air "filtration" system could extract CO_2 from a stream that represents power generation of 100,000 W for every square meter of airflow. By this measure, CO_2 is far more concentrated than the kinetic energy harnessed by the windmill. By invoking a measure of power per unit area we can also compare the efficacy of our 7 approach to collecting solar energy. Peak fluxes of solar energy on the ground are around 1,000 W/m^2. Average fluxes in desert climates accounting for weather and day and night are around 200 W/m^2. Photovoltaic panels can capture maybe 25% of this flux. Under conditions of intensive agriculture, biomass growth can capture maybe 1.5% of this flux, and thus would rate at roughly 3 W/m^2 (Ranney and Cushman, 1991). Typical unmanaged forest growth would fall far short of capturing even that much carbon equivalent. The purpose of this discussion is to establish an estimate of a system's size necessary to collect CO_2 generated by an energy source of a given size. If one could maintain a flow of 3 m/s through some filter system, and collect half the CO_2 that passes through it, then the system would collect per square meter the CO_2 output from 15 kW of primary energy. This is more than the per capita primary energy consumption in the US, which is approximately10 kW. The size of a CO_2 collection system would thus have to be less than 1m2 per person. Covering the same energy demand with wind-generated electricity instead would require an area at least a hundred times larger.

Even before having defined specific filters and sorbent materials, this discussion already suggests that the cost of CO_2 collection is not prohibitively high. Thus, we need to develop a technology that would allow the capture of CO_2 from natural or man-made airflows that would enable us to recycle the sorbent and create a concentrated stream of CO_2.

2.15 Activated carbon

2.15.1 What is activated carbon?

Activated carbon is porosity (space) enclosed by carbon atoms. Activated carbon is a microcrystalline, non-graphitic form of carbon that has been processed to develop internal porosity. This porosity yield the surface area that provides ability to adsorb gases and vapors from gases and to adsorb dissolved or dispersed substances from liquid activated carbon is characterized by a vast system of pore of molecular size within the carbon particles resulting in the formation of a material with extensive surface area. However, commercial grade of activated carbons generally have a surface areas ranging from 600 to 1200 m^2/g. (Chilton *et al*, 2002)

Activated carbon is a very important material industrially, with applications in a variety of areas such as adsorbents in air and water pollution control, catalysts in the chemical and petrochemical industries, electrodes in batteries and super capacitors and also purifiers in the food and pharmaceutical industries. Further, as an environ mental pollution is increasingly becoming a serious problem the demand for activated carbon is growing (Gadkaree, 1998).

2.15.2 History of activated carbon and summary of its uses

The use of carbon extends far back into its history. Charcoal was used for drinking water filtration by ancient Hindus in India, and carbonized wood was used as a medical adsorbent and purifying agent by the Egyptians as early as 1500 B.C (Parker, and Hughes, 2008). In contrary, modern development and use has been documented more precisely. Activated carbon was first generated industrially in the first part of the twentieth century, when activated carbon from vegetable material was produced for use in sugar refining.

In the early 19th century in Europe, powdered activated carbon was first produced commercially by using wood as a raw material. In the United States, the first production of activated carbon used black ash as the source, after it was accidentally discovered that the ash was very effective in decolorizing liquids. Activated carbon has been used extensively for this purpose in many industries such as textile industry for the removal of organic dyes.

The first documented use of activated carbon in a large scale water treatment application was in 19th century in England, where it was used to remove undesirable odors and tastes from drinking water. In recent years, the use of activated carbon for the removal of priority organic pollutants has become very common. Today, hundreds of brands of activated carbon are manufactured for a large variety of purposes. Generally, activated carbon is used in metal extraction (e.g. gold), water purification (especially in home aquariums), medicine, wastewater treatment, filters in gas and filter masks, filters in compressed air and gas purification, and many other applications.

The largest market for activated carbon is currently in the municipal water purification industry, where charcoal beds have been used for the dual purpose of physical filtration and sorption. In fact, activated carbon filters are used today in drinking water treatment to remove the natural organic compounds that produce carcinogenic chlorinated by-products during chlorine disinfection of water. In wastewater treatment, activated carbon is usually used as a filter medium in tertiary treatment processes. In these applications, carbon filters are usually quite effective in removing low concentrations of organic compounds, as well as some inorganic metals.

In addition to the drinking water and wastewater treatment applications, activated carbon is also applicable in gas purification process. Filters with activated carbon are usually used in compressed air and gas purification to remove oil vapour, odor, and other hydrocarbons from compressed air and gas. The most common designs use a 1 stage or 2 stage filtration principle where activated carbon is embedded inside the filter media.

Some other common uses included corn and cane sugar refining, gas adsorption, dry cleaning recovery processes, pharmaceuticals, fat and oil removal, electroplating, catalyst support, battery electrodes, alcoholic beverage production and super capacitors.

2.15.3 Properties of activated carbon (AC)

The properties of activated carbon can be summarised as follows:

1. It is a solid, porous and black carbonaceous material
2. It has extraordinary large surface area (1200m^2/g) and pores volume that give unique adsorption properties
3. It has both chemical and physical effect on substances

2.15.4 Structure of activated carbon

Activated carbon has a disordered microstructure, which is termed amorphous carbon. X-rays studied have demonstrated that many so-called amorphous substances have crystalline characteristics, even they may not show certain features such as crystal angles and faces, usually associated with the crystalline state. The kind of carbon from which activated carbon is derived is non-graphitizing, meaning that it cannot be transformed into crystalline graphite even at temperatures of 3000ºC and above. A simple model of non-graphitizing carbon based on small graphitic crystallites joined together by cross-links, but did not explain the nature of these cross-links.

A later idea was that the cross-links might consist of domains containing sp3-bonded atoms, but this had to be discounted when neutron diffraction studies showed that non-graphitizing carbons consist entirely of sp2 atoms .A much more recent suggestion is that non-graphitizing carbon has a structure related to that of the fullerenes, in other words that it consists of curved fragments containing pentagons and other non-hexagonal rings in addition to hexagons. Such a structure would explain the micro porosity of the carbon, and many of its other properties. However, obtaining direct experimental support for this hypothesis is extraordinarily difficult. Both x-ray and neutron diffraction have been extensively applied to non-graphitizing carbons, and in some studies the diffraction data has been interpreted in terms of a structure containing non-hexagonal rings (Peter *et al*, .2008).

The IUPAC classification of pores by sizes defines the following three class of pore (IUPAC .1972):

i. Micropores, less than 2 nm (less than 20 Å)

ii. Mesopores between 2 and 50 nm, (20 to 500 Å)

iii. Macropores, 50 nm, (more than 500 Å).

According to Linares-Solano *et al,* Otowa *et al,* (1997) and Tsutomu Suzuki *et al,* (2007) (2000), there are more than 95% micropores content in the total area surface of activated carbon. The volume of micropores range from 0.15 to 0.6 cm^3/g. Conventional activated carbon were tridisperse, having all three type of pores present within their structure. Adsorbance molecules penetrate through the wider pore to micropores. Activated carbon prepared with high surface area, low volume resistivity or low ash content has been reported largely. The composition and structure of an activated carbon depends on the raw material, the activating agent and the preparation method. These parameters condition the properties of the activated carbon and hence its applications. The structure of various types of activated is shown in Figure 2.8.

2.15.5 Activated carbon adsorption.

According to Khadija Qureshi *et al,* (2008), they are most effective adsorbents in treating drinking water and industrial wastewater. The food industry is also a major consumer of activated carbon, where it is used to remove compounds that adversely affect colour, taste and odour. In the mineral industry activated carbon are used to recover gold from leached liquors. Medicinal uses and pharmaceutical industry is also another wide area for the utilization of activated carbon. In gas cleaning applications activated carbon are extensively used in air filters at industrial level as well as in general air conditioning application.

According to Gadkaree, (1998), adsorption is a process in which matter adheres to the surfaces of adsorbents (activated carbon). In the adsorption process, molecules of a contaminated are attracted to and accumulate on the surface of the activated carbon. Carbon is a commonly used adsorbent due to its very large surface area. Physical adsorption is dependent on the characteristics of the contaminant to be adsorbed, the temperature of the gas stream to be processed, and the concentration of the contaminant in the gas stream. The adsorption capacity for a particular contaminant

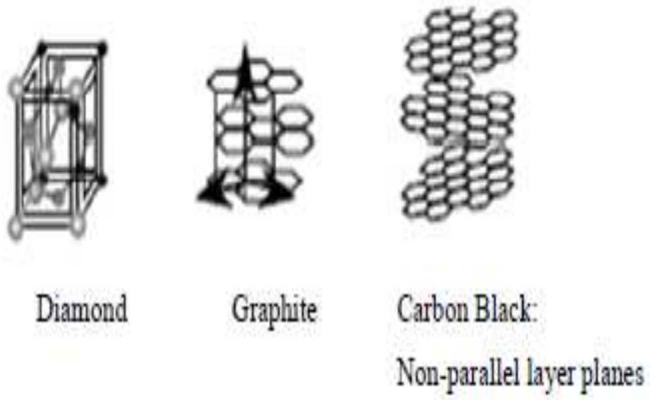


Fig 2.8: Carbon Black "Quasi-Graphitic" Microstructure compared to the two regular crystalline forms of carbon (diamond and graphite).
Source: Shafarul, (2011).

represents the amount of the contaminant that can be adsorbed on a unit weight of activated carbon consumed at the conditions present in the application.

Typical adsorption capacities for moderately adsorbed compounds range from 5 to 30 per cent of the weight of the carbon. Figure 2.9 shows the Cross section activated carbon adsorption for gases and chemicals.

2.15.6 Types of activated carbon

The types of activated carbon available in the current market are powder, granular and pellet. It is classified according to its particle sizes and shape, and each type has its specific application. The size of powder activated carbon is less than 100µm in size with an average diameter between 15 and 25 µm. Thus, they present a large internal surface with a small diffusion distance. Powdered activated carbons are mainly used in liquid phase adsorption and flue gas treatment. In wastewater treatment, the most common used of powdered activated carbon is in the secondary treatment called powdered activated carbon treatment process (Norit Americas Inc, 2001). Granulated activated carbon has a relatively larger particle size compared to powdered activated carbon and consequently, presents a smaller external surface. The size range is from 0.5 to 4.0 mm. This type of activated carbons is commonly used in water treatment facilities where the granular carbon bed to remove tastes, colors, odors and dissolved organics. In addition, granular activated carbon can also be used for gas phase application.

Meanwhile, pellet activated carbon consists of extruded and cylindrical shaped activated carbon with diameters in the range of 4-7 mm and 8-15 mm length. Pellets activated carbon is mainly used for gas phase applications because of their low pressure drop, high mechanical strength and low dust content.

2.15.7 Activated carbon production

In principle, have two main processes to produce activated carbon (AC) which is carbonization and activation. According to Savova *et al*, (2001), carbonization is a process in which material is turned into porous carbon structure through pyrolysis. In this process, most of non-carbon organic matters are decomposed. The combination of carbon atom-aromatic foliated structure is made with irregular split. Thus, the split

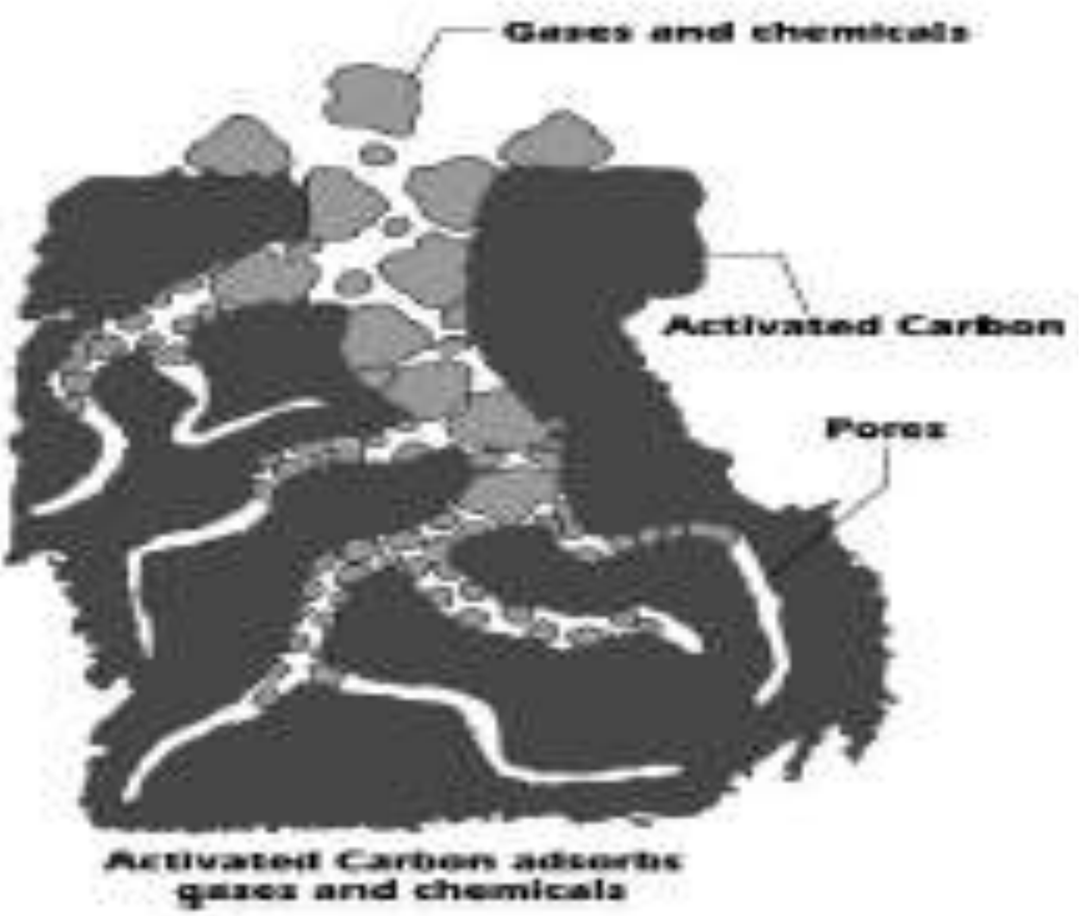


Fig 2.9: Cross Section Activated Carbon Adsorption for Gases and Chemicals. Source: (Home-Air-Purifier-Guide.Com)

will be developed into a structure with more pores during process activation. Pyrolysis is an endothermic process that offers an environmentally attractive way of reducing those residues. Unlike incineration the pyrolysis does not lead to air emission. The solid product were named char which can be activated and produced active carbon, a high value added product. Pyrolysis process included of softening of the material and release of volatile matter, then hardening and shrinkage of char. Previous study for bamboo, refer to Baksi *et al, (*2003). Carbonisation or pyrolysis is the first process in activated carbon preparation, in which bamboo is heated, decomposed and eventually converted into desired product in the absence of air. Pyrolysis process includes carbonisation (destructive/dry distillation of bamboo), charcoal processing, gasification and activated carbon processing. The pyrolysis product is bamboo charcoal and the by-product is pyroligneous acid. After that, the charcoal is activated by reaction with steam in a reactor to facilitate heat distribution and improved gas-solid contact.

From the previous research (Minkova *et al,* 2001), activation is uses physical or chemical method to removes the tar, organic wastes and other rest. Its purpose it to get more an adsorption phase of activated carbon product. However, the simple one step method for the production of activated carbon has been developed to reduce the energy expenditure during the process. This method is a feasible alternative to the traditional two-step process for the production of activated carbons by consecutive carbonization of raw material and high temperature activation (900ºC to 1000ºC) of the solid product from carbonization.

2.15.8 Production

Activated carbon is carbon produced from carbonaceous source materials such as nutshells, coconut husk, peat, wood, coir, lignite, coal, and petroleum pitch. It can be produced by one of the following processes (Minkova et al, 2001):

1. **Physical reactivation**: The source material is developed into activated carbons using hot gases. This is generally done by using one or a combination of the following processes:

- *Carbonization*: Material with carbon content is pyrolyzed at temperatures in the range 600–900 °C, in absence of oxygen (usually in inert atmosphere with gases like argon or nitrogen)
- *Activation/Oxidation*: Raw material or carbonized material is exposed to oxidizing atmospheres (air or steam) at temperatures above 250 °C, usually in the temperature range of 600–1200 °C.

2. **Chemical activation**: Prior to carbonization, the raw material is impregnated with certain chemicals. The chemical is typically an acid, strong base, or a salt (Romanos *et al*, 2012) (phosphoric acid, potassium hydroxide, sodium hydroxide, calcium chloride, and zinc chloride 25%). Then, the raw material is carbonized at lower temperatures (450–900 °C). It is believed that the carbonization / activation step proceeds simultaneously with the chemical activation. Chemical activation is preferred over physical activation owing to the lower temperatures and shorter time needed for activating material because the chemical helps to produce the pores more quickly.

Important production materials include coconut shells, palm shells, oil, husks, and sawdust, all of which have to be burnt into ashes for activated carbon making. It consists of 2 types; fine powder and granular. The fine powder is good at diffusing in water, so it is used in solution or liquid related industries. For example, it is used to bleach and adsorb odor in sugar industry, to produce cooking oil in food industry, and to purify water. The pill or flake type is used in gas-purifying industries products; such as, air purifier, poisonous gas adsorption, and cigarette butt, etc. The growth of activated carbon market depends on the growth of industries that use it, which vary greatly from air purifier industry, drinking water and tap water industry, metal-plated industry, and food industry. In addition, activated carbon can be used in a household. Its major household usage is found in products that adsorb odors; such as a refrigerator's stuffy smell, wardrobe's and closet’s smells, etc. Hence, it can be seen that activated carbon market is broad and has a potential for consistent demand in the country. Besides, it can be exported to use in the industries that need high quality activated carbon; such as, in particular kinds of air purifiers. However, the import Figs are still higher than the export.

2.15.9 Adsorption process of carbon dioxide

Adsorption is a process for removal of one or more components of a mixture with the help of a solid surface. The adsorption processes are based on significant intermolecular forces between gases (including CO_2) and the surfaces of certain solid adsorbents such as waste rubber tire derived activated carbon. Depending on the temperature, pressure and percentage of active loading, single or multiple layers of gases can be adsorbed (Meisen and Shuai, 1997).

In CO_2 capture by adsorption technology, a packed column is mainly filled by spherical adsorbent and CO_2 bearing stream is passed through the column. Carbon dioxide is attracted towards the adsorbent and adheres on the surface of adsorbent. After achieving the equilibrium, desorption to get CO_2 in pure form and regenerated adsorbent can be performed by rising the temperature since this adsorption is an exothermic process. The regenerated adsorbent can be utilized for further cycle. Solid sorbents have the potential for significant energy savings over liquid solvents, in part because they avoid the need for the large quantities of water that must be repeatedly heated and cooled to regenerate the solvent solution. However, adsorption presents lower energy requirements and avoids the shortcomings when compared to absorption (Drage *et al*, 2009). In post-combustion process, adsorption is recognized to be an attractive process for CO_2 capture from flue gases, due to its lower energy requirements (Aaron and Tsouris, 2005).

2.15.10 Activation of organic matters

A good solid sorbent material for CO_2 removal from flue gas should combine several attributes including high CO_2 adsorption capacity, high CO_2 selectivity, mild regeneration condition and sufficient cyclic stability and mechanical strength (Zhao, 2012).

Adsorption of carbon dioxide by waste rubber tire derived activated carbon was a newly established research. This type of research has not been carried by other scientists. This alternative adsorbent had been tested before for its ability for the adsorption of effluent pollutants such as phenol and mercury, remove methylene blue from aqueous solution and also in gas separation of O_2 and N_2 (Li *et al*, 2010).

Apart from waste, rubber tire derived activated carbon, many researches had also been carried out before using other materials as alternative adsorbents. Another material that had been tested for its ability to become CO_2 adsorbent is the spent coffee grounds. In this study, Spent Coffee Grounds (SCG), a residue from the soluble coffee industry, was evaluated as an adsorbent for the removal of CO_2 from flue gas. It undergoes chemical activation with CO_2, NCHA29 and NCLK3 adsorption test was measured between 0-120 kPa at 0, 25 and 50°C. The result shows that as pressure increases, adsorption capacity increases. The highest adsorption capacity occurs at lower temperature (Gonzalez *et al*, 2008).

Based on a previous study of Dreisbach *et al*. (1999) conducted adsorption equilibrium of CO_2 on Norit type activated carbons at high pressure up to 6 MPa at 298 K where they found a fairy high pure CO_2 loading up to 11.27 mmol g^{-1}. This has shown that CO_2 adsorption capacity of activated carbon increases as the temperature drops.

Furthermore, recent research carried out has proved that amine impregnated adsorbent such as MCM-41-PEI with a PEI loading of 75 wt% under atmospheric pressure at 75°C has shown the highest CO_2 adsorption capacity of 3.02 mmol g^{-1}. Increased PEI loadings resulted in higher adsorption of CO_2. The adsorption capacity at low temperature will be even larger than that high temperature if the adsorption time is sufficiently long to overcome the diffusion limitation (Xu *et al*, 2002).

There is a research conducted by Zhao (2012), using amine impregnated sorbent. He used a series of impregnated SBA-15 sorbent containing 50, 60 and 70 wt% active loading of tetraethylenepentamine (TEPA). There is an increasing trend of CO_2 adsorption capacity from 3.59-4.59 mmol g^{-1}. When the amine loading increases from 50-70 wt% (Zhao, 2012).

Besides that, the adsorption capacity increased with increasing the temperature and reached the maximum CO_2 uptake of 4.52 mmol g^{-1} at about 75°C. The low CO_2

uptake at low temperature could be a result of slow adsorption rate because the overall process is diffusion controlled. Therefore, higher temperature is beneficial to significantly accelerate the apparent adsorption rate by reducing diffusional resistance. For the temperature beyond 75°C, it inhibited the CO_2 adsorption on TEPA impregnated SBA-15 due to its exothermal nature. Therefore, this might be due to the thermodynamic limitation that makes shifting in chemical equilibrium beyond 75°C (Zhao, 2012).

On the other hand, Polyaniline-magnetite nanocapsules based nanocomposite (PANI/MNCs) is one of the solid adsorbent used to adsorb CO_2. The PANI/MNCs nanocomposite has shown a maximum adsorption capacity of 54.21 mmol g^{-1} at 14.5 bars and room temperature (28°C). According to BET theory, at high pressure, more gaseous molecules would be available per unit surface area which results in multilayer adsorption (Tamilarasan and Ramaprabhu, 2012).

Besides that, the amount of adsorbed CO_2 molecules decreases with increase in temperature with the use of PANI/MNCs nanocomposite. This may be attributed to the increase in kinetic energy of CO_2 gas molecules at higher temperatures which provides high velocity to CO_2 molecules to escape from surface active sites and pores. At low temperature, CO_2 molecules interact well with adsorbent surfaces which lead to higher multilayer formation of CO2 gas at pores of nanocomposite as well as a fraction of carbonate and bicarbonate formation (Tamilarasan and Ramaprabhu, 2012).

Activated carbons prepared from hydrothermally carbonized (HTC) waste biomass were studied with respect to the adsorption of carbon dioxide. This HTC biomass is then further activated physically or chemically. Physically Activated Carbon (PAC) was activated into activated carbons by treating the HTC biomass at an elevated temperature in a stream of CO_2 at 800°C for 0 or 2 h while Chemically Activated Carbon (CAC) were produced by first treating HTC beer waste with H_3PO_4 and by further activating this acid treated HTC biomass in a flow of N_2 at 600°C. The HTC biomass was made from four different biomass: Grass cuttings, horse manure, organic waste from beer production (beer waste) and bio-sludge from a waste water treatment plant of a paper and pulp mill. As temperature are fixed at 0°C, the adsorption capacity increases with pressure. The PAC from HTC grass cuttings also displayed an excellent cyclability for the adsorption of CO_2 (Hao *et al*, 2013).

In addition, previous research has also proved that *Eucalyptus camaldulensis* wood can be utilized as CO_2 adsorbent. *Eucalyptus camaldulensis* wood is a kind of lignocellulosic material which is obtained from a waste dump of a wood factory. It has a reasonably high content of carbon, utilized also as raw material for activated carbon. It undergoes chemical activation with $ZnCl_2$ at different impregnation ratios as well as by pyrolysis. The amount of CO_2 adsorbed onto the AC samples prepared with $ZnCl_2$ and H_3PO_4 increases as the impregnation ratio of the activating agent to biomass decreases or, in other words, the CO_2 adsorbed onto the AC increases when the BET surface area and the mesoporosity of the AC samples increases (Heidari *et al*, 2014). The CO_2 adsorption capacity increases when the temperature decreases.

Moreover, there are previous studies using mesoporous activated alumina functionalized with diethanolamine (DAAB) as the adsorbent for selective adsorption of carbon dioxide. During the adsorption process, it varied its flow rate from 90-150 mL min^{-1}. An increase in the flow rate (120-150 mL min^{-1}) led to the reduction of the residence time of the adsorbate in the column leading to poor performance of the system or reduction on the adsorption efficiency. This reflected on the adsorption capacities which were 55.94, 39.36 and 27.03 mg g^{-1} for the feed flow rates of 90, 120 and 150 mL min^{-1}, respectively (Auta and Hameed, 2014).

Furthermore, CO_2 capture was conducted at various column temperatures (35, 45 and 55°C). It was observed that lower temperature has short breakthrough time. Moreover, lower temperature of adsorption promoted intense selective interactions between impregnated basic amine group on the activated alumina (DAAB) and the acidic CO_2 gas resulting to higher adsorption capacity. In a similar manner, carbon adsorbent modified with nitrogen compound showed higher adsorption of CO_2 gas at room temperature than at elevated temperatures (Auta and Hameed, 2014).

2.15.11 *Characterization of activated carbon produced*

A. *Scanning electron microscope analysis:*

A scanning electron microscope (SEM) is a type of electron microscope that images a sample by scanning it with a high-energy beam of electrons in a raster scan pattern. The electrons interact with the atoms that make up the sample producing signals that contain information about the sample's surface topography, composition, and other properties such as electrical conductivity.

The types of signals produced by an SEM include secondary electrons, back-scattered electrons (BSE), characteristic X-rays, light (cathode luminescence), specimen current and transmitted electrons. Secondary electron detectors are common in all SEMs, but it is rare that a single machine would have detectors for all possible signals. The signals result from interactions of the electron beam with atoms at or near the surface of the sample. In the most common or standard detection mode, secondary electron imaging or SEI, the SEM can produce very high-resolution images of a sample surface, revealing details less than 1 nm in size. Due to the very narrow electron beam, SEM micrographs have a large depth of field yielding a characteristic three dimensional appearance useful for understanding the surface structure of a sample. This is exemplified by the micrograph of pollen shown to the right. A wide range of magnifications is possible, from about 10 times (about equivalent to that of a powerful hand-lens) to more than 500,000 times, about 250 times the magnification limit of the best light microscopes. Backscattered electrons (BSE) are beam electrons that are reflected from the sample by elastic scattering. BSE are often used in analytical SEM along with the spectra made from the characteristic X-rays. Because the intensity of the BSE signal is strongly related to the atomic number (Z) of the specimen, BSE images can provide information about the distribution of different elements in the sample. For the same reason, BSE imaging can image colloidal gold immuno-labels of 5 or 10 nm diameter which would otherwise be difficult or impossible to detect in secondary electron images in biological specimens. Characteristic X-rays are emitted when the electron beam removes an inner shell electron from the sample, causing a higher identify the composition and measure the abundance of elements in the sample. In a typical SEM, an electron beam is thermionically emitted from an electron gun fitted with a tungsten filament cathode. Tungsten is normally used in thermionic electron guns because it has the highest melting point and lowest vapour pressure of all metals, thereby allowing it to be heated for electron emission, and because of its low cost. Other types of electron emitters include lanthanum hexaboride (LaB_6) cathodes, which can be used in a standard tungsten filament SEM if the vacuum system is upgraded and field emission guns (FEG), which may be of the cold cathode type using tungsten single crystal emitters or the thermally-assisted Schottky type, using emitters of zirconium oxide. The electron beam, which typically has an energy ranging from 0.5 keV to 40 keV, is focused by one or two condenser lenses to a spot about 0.4 nm to 5 nm in diameter. The beam passes through pairs of scanning coils or pairs of deflector plates in the electron column, typically in the final lens, which deflect the beam in the x and y axes so that it scans in a raster fashion over a rectangular area of the sample surface. When the primary electron beam interacts with the sample, the electrons lose energy by repeated random scattering and absorption within a teardrop-shaped volume of the specimen known as the interaction volume, which extends from less than 100 nm to around 5 µm into the surface. The size of the interaction volume depends on the electron's landing energy, the atomic number of the specimen and the specimen's density. The energy exchange between the electron beam and the sample results in the reflection of high-energy electrons by elastic scattering, emission of secondary electrons by inelastic scattering and the emission of electromagnetic radiation, each of which can be detected by specialized detectors. The beam current absorbed by the specimen can also be detected and used to create images of the distribution of specimen current. Electronic amplifiers of various types are used to amplify the signals which are displayed as variations in brightness on a cathode ray tube. The raster scanning of the CRT display is synchronised with that of the beam on the specimen in the microscope, and the resulting image is therefore a distribution map of the intensity of the signal being emitted from the scanned area of the specimen. The image may be captured by photography from a high resolution cathode ray tube, but in modern machines is digitally captured and displayed on a computer monitor and saved to a computer's hard disk.

Magnification in a SEM can be controlled over a range of up to 6 orders of magnitude from about 10 to 500,000 times. Unlike optical and transmission electron microscopes, image magnification in the SEM is not a function of the power of the objective lens. SEMs may have condenser and objective lenses, but their function is to focus the beam to a spot, and not to image the specimen. Provided the electron gun can generate a beam with sufficiently small diameter, a SEM could in principle work entirely without condenser or objective lenses, although it might not be very versatile or achieve very high resolution. In a SEM, as in scanning probe microscopy, magnification results from the ratio of the dimensions of the raster on the specimen and the raster on the display device. Assuming that the display screen has a fixed size, higher magnification results from reducing the size of the raster on the specimen, and vice versa.

Magnification is therefore controlled by the current supplied to the x, y scanning coils, or the voltage supplied to the x, y deflector plates, and not by objective lens power.

B. X-Ray diffraction measurements:

X-ray scattering techniques are a family of non-destructive analytical techniques which reveal information about the crystallographic structure, chemical composition, and physical properties of materials and thin films. These techniques are based on observing the scattered intensity of an X-ray beam hitting a sample as a function of incident and scattered angle, polarization, and wavelength or energy. X-ray diffraction yields the atomic structure of materials and is based on the elastic scattering of X-rays from the electron clouds of the individual atoms in the system.

The most comprehensive description of scattering from crystals is given by the dynamical theory of diffraction. Single-crystal X-ray diffraction is a technique used to solve the complete structure of crystalline materials, ranging from simple inorganic solids to complex macromolecules, such as proteins. Powder diffraction (XRD) is a technique used to characterise the crystallographic structure, crystallite size (grain size), and preferred orientation in polycrystalline or powdered solid samples. Powder diffraction is commonly used to identify unknown substances, by comparing diffraction data against a database maintained by the International Centre for Diffraction Data. It may also be used to characterize heterogeneous solid mixtures to determine relative abundance of crystalline compounds and, when coupled with lattice refinement techniques, such as Rietveld refinement, can provide structural information on unknown materials. Powder diffraction is also a common method for determining strains in crystalline materials. An effect of the finite crystallite sizes is seen as a broadening of the peaks in an X-ray diffraction as is explained by the Scherrer Equation. Thin film diffraction and grazing incidence X-ray diffraction may be used to characterize the crystallographic structure and preferred orientation of substrate-anchored thin films. High-resolution X-ray diffraction is used to characterize thickness, crystallographic structure, and strain in thin epitaxial films. It employs parallel-beam optics. X-ray pole figure analysis enables one to analyze and determine the distribution of crystalline orientations within a crystalline thin-film sample. X-ray rocking curve analysis is used to quantify grain size and mosaic spread in crystalline materials.

X-ray diffraction spectroscopy (XRD) analyses were carried out with PANalytical X-ray, Philips Analytical. A dried sample of the produced material is grinded using an agate mortar and pestle and tested at 40kV and 40mA. The spectra were analyzed using PC-APD diffraction software.

2.16 Mathematical modelling

2.16.1 What is mathematical modelling?

Models describe our beliefs about how the world functions. In mathematical modelling, we translate those beliefs into the language of mathematics. This has many advantages

1. Mathematics is a very precise language. This helps us to formulate ideas and identify underlying assumptions.
2. Mathematics is a concise language, with well-defined rules for manipulations.
3. All the results that mathematicians have proved over hundreds of years are at our disposal.
4. Computers can be used to perform numerical calculations.

There is a large element of compromise in mathematical modelling. The majority of interacting systems in the real world are far too complicated to model in their entirety. Hence the first level of compromise is to identify the most important parts of the system. These will be included in the model, the rest will be excluded. The second level of compromise concerns the amount of mathematical manipulation which is worthwhile. Although mathematics has the potential to prove general results, these results depend critically on the form of equations used. Small changes in the structure of equations may require enormous changes in the mathematical methods. Using computers to handle the model equations may never lead to elegant results, but it is much more robust against alterations.

2.16.2 What objectives can modelling achieve?

Mathematical modelling can be used for a number of different reasons. How well any particular objective is achieved depends on both the state of knowledge about a system and how well the modelling is done. Examples of the range of objectives are:

1. Developing scientific understanding through quantitative expression of current knowledge of a system (as well as displaying what we know, this may also show up what we do not know);
2. Test the effect of changes in a system;
3. Aid decision making, including
    (i) Tactical decisions by managers;
    (ii) Strategic decisions by planners.

2.16.3 Classifications of models

When studying models, it is helpful to identify broad categories of models. Classification of individual models into these categories tells us immediately some of the essentials of their structure.

One division between models is based on the type of outcome they predict. Deterministic models ignore random variation, and so always predict the same outcome from a given starting point. On the other hand, the model may be more statistical in nature and so may predict the distribution of possible outcomes. Such models are said to be stochastic.

A second method of distinguishing between types of models is to consider the level of understanding on which the model is based. The simplest explanation is to consider the hierarchy of organizational structures within the system being modelled. For animals, one such hierarchy is as shown in Figure 2.10 while a pictorial representation of potential routes through the stages of modelling is shown in Figure 2.11

A model which uses a large amount of theoretical information generally describes what happens at one level in the hierarchy by considering processes at lower levels these are called mechanistic models, because they take account of the mechanisms through which changes occur. In empirical models, no account is taken of the mechanism by which changes to the system occur. Instead, it is merely noted that they do occur, and the model tries to account quantitatively for changes associated with different conditions.

The two divisions above, namely deterministic/stochastic and mechanistic/empirical, represent extremes of a range of model types. In between lie a whole spectrum of model types. Also, the two methods of classification are complementary. For example, a deterministic model may be either mechanistic or empirical (but not stochastic). Examples of the four broad categories of models implied by the above method of classification are shown in Table 2.17.

One further type of model, the system model, is worthy of mention. This is built from a series of sub-models, each of which describes the essence of some interacting components. The above method of classification then refers more properly to the sub-models: different types of sub-models may be used in any one system model. Much of the modelling literature refers to ’simulation models’. Why they are not included in the classification? The reason for this apparent omission is that ’simulation’ refers to the way the model calculations are done - i.e. by computer simulation. The actual model of the system is not changed by the way in which the necessary mathematics is performed, although our interpretation of the model may depend on the numerical accuracy of any approximations.

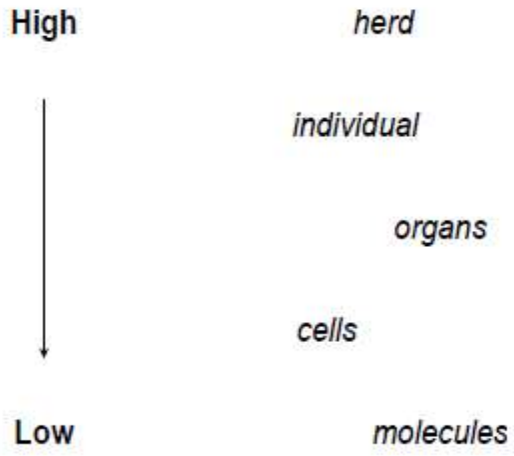


Fig 2.10: Hierarchy of organization structures
Source: Flannery and Vetterling, (1987)

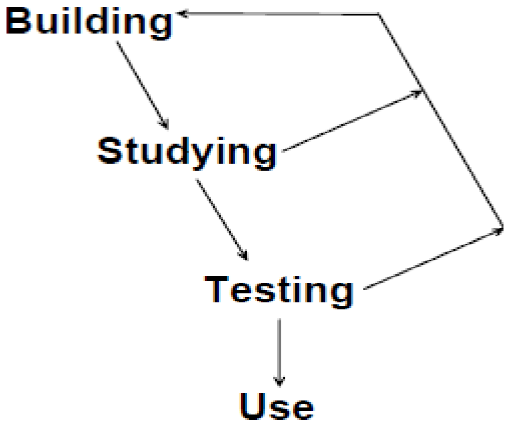


Fig 2.11: Potential routes through the stages of modelling

Source: Flannery and Vetterling (1987)

Table 2.17: Four broad categories of models

	Empirical	**Mechanistic**
Deterministic	Predicting cattle growth from a regression relationship with feed intake	Planetary motion, based on Newtonian mechanics (differential equations)
Stochastic	Analysis of variance of variety yields over sites and years	Genetics of small populations based on Mendelian Inheritance (probabilistic equations}

Source: Flannery and Vetterling, (1987)

2.15.4 Stages of modelling

It is helpful to divide up the process of modelling into four broad categories of activity, namely building, studying, testing and use. Although it might be nice to think that modelling projects progress smoothly from building through to use, this is hardly ever the case. In general, defects found at the studying and testing stages are corrected.

This process of repeated iteration is typical of modelling projects, and is one of the most useful aspects of modelling in terms of improving our understanding about how the system works by returning to the building stage. Note that if any changes are made to the model, then the studying and testing stages must be repeated.

2.16.5 Programming with MATLAB

The name MATLAB stands for MATrix LABoratory. MATLAB was written originally to provide easy access to matrix software developed by the LINPACK (linear system package) and EISPACK (Eigen system package) projects. MATLAB (Mathworks Incorporated, 2005) is a high-performance language for technical computing. It integrates computation, visualization and programming environment. Furthermore, MATLAB is a modern programming language environment: it has sophisticated data structures, contains built-in editing and debugging tools, and supports object-oriented programming. These factors make MATLAB an excellent tool for teaching and research.

MATLAB has many advantages compared to conventional computer languages (e.g., C, FORTRAN) for solving technical problems. MATLAB is an interactive system whose basic data element is an array that does not require dimensioning. The software package has been commercially available since 1984 and is now considered as a standard tool at most universities and industries worldwide. It has powerful built-in routines that enable a very wide variety of computations. It also has easy to use graphics commands that make the visualization of results immediately available. Specific applications are collected in packages referred to as toolbox. There are toolboxes for signal processing, symbolic computation, control theory, simulation, optimization, and several other fields of applied science and engineering.

2.17 Gaps in carbon capture and how it can be filled by this study

One of the applications of MATLAB is that it can be used to generate equations which is useful in predicting performance of any engineering systems. Efforts on carbon capture had been more in the energy sector and are laboratory-based. The impact of energy on the adsorption of carbon dioxide of the system has not been reported. Also not much work on modelling of the system to predict the concentration of the carbon dioxide that could be adsorbed by adsorbents had been carried out. This study therefore intends to fill the gaps by actually designing and fabricating a carbon dioxide extractor, evaluating the performance of the extractor combined with adsorbents and predicting the concentration that can be adsorbed through modelling with engineering software such as MATLAB.

CHAPTER THREE

METHODOLOGY

3.1 Study area

3.1.1 Akure

Akure is the capital of Ondo State in Nigeria. It is an indigenous African town that lies between latitude 7° 15′ 0″ N and 5° 11′42″ East of prime meridian (Wikipedia, 2010). The present population of the city according to the 2013 Census Projection is more than 387,087 people (ODMOFDRS, 2009). Akure presents a typical picture of many African cities known for having the old town area (inner core), the transitional and peripheral areas. The majority of the people are "Yorubas" while other ethnic groups constitute a smaller proportion of the population. Over seventy per cent are Christians while others are Muslims and a small proportion are adherents of traditional African religion. Most of the people are engaged in petty trading and small-scale business, while others are civil/public servants. Akure has several public, private and social amenities such as the Ondo State Specialist Hospital, banks, industries, post office, higher institutions such as the Federal University of Technology Akure (FUTA), Federal College of Agriculture, Akure, and State Agencies such as the Waste Management Board, Water Corporation and over 700 schools made up of both public and private nursery, primary and secondary schools.

3.1.2 The waste management facility (Integrated Recycling Plant and Dumping Site)

The Akure Integrated Recycling Plant was commissioned by erstwhile Nigeria's President, Chief Olusegun Obasanjo on the 14th of June, 2006 and began operations on the 1st of December, 2006. The conceptualized capacity of the plant is 25 Tons/day, 5Tons/day and 5Tons/day for Organic Fertilizer, Plastic Design and Metal Recycling respectively; the Design capacity of the plant is 5 Tons/day, 0.5Tons/day and 0 Tons/day for Organic Fertilizer, Plastic Recycling and Metal Recycling respectively; while the Actual Capacity of the plant is less than 1 Ton/day, less than

0.1 Ton/day and 0.0 Ton/day for Organic Fertilizer, Plastic Recycling and Metal Recycling respectively; the total period of production is 8 hours daily. The Recycling Plant is managed by a Project Manager who is a Research and Development Officer. The recycling plant was designed and installed by Environmental Development Foundation under the supervision of Prof. Sridhar and his team. He reports to the Director of the Planning, Research and Strategy Department of the Ondo State Waste Management Authority. The Plant consists of three Units namely; Material Recovery/Quality Control Unit, Material Processing and Production Unit and Marketing Unit. The initial size of the facility is 7 Hectares. That is, 6 Hectares for the Land Fill and 1 Hectare for the recycling Plant. Presently, the Land Fill has gone beyond the 6 Hectares. The plant started with an initial size of 80 Workers but presently, the Staff size is about 40 workers.

3.2 Study design

An exploratory study design with an intervention component was adopted. The study involved physical and chemical characterization of the solid wastes brought to the plant by wastes disposal vehicles, estimation of the carbon-emission from the dumpsite, monitoring of CO_2 levels at the dumpsite and recycling plant, the design and fabrication and modelling of the performance of a carbon-dioxide extractor to reduce the carbon-dioxide gas concentration emitted at the Waste Management Facility and the assessment of the extractability of carbon dioxide by the extractor and adsorbents. Figure 3.1 shows the location of the facility in the Akure South Local Government while Figure 3.2 is the layout of the Recycling Plant Dumping Site.

3.3 Characterization of generated solid wastes

3.3.1 *Determination of physical components*

a. *Weight determination*

Three major sources of wastes were identified. The sources were namely:

- **Roadside:** The wastes coming from this source are mainly from the office environment and are kept along the road;
- **Residential:** The wastes are mainly residential wastes. It was identified that there are 21 zones in Akure. The zone of interest for a particular month was selected by Stratified Random Sampling.

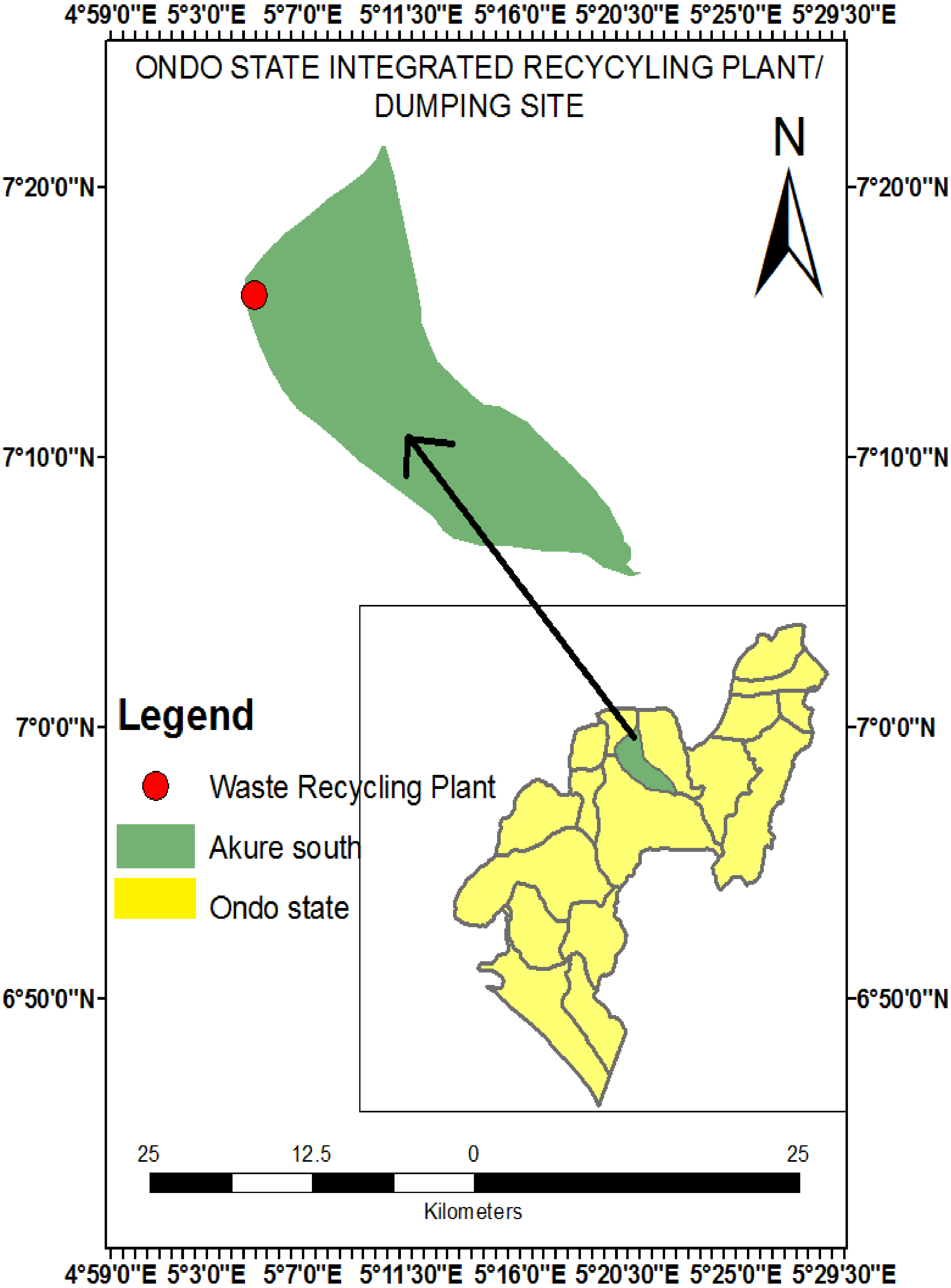


Fig 3.1: Location of Ondo State Integrated Recycling Plant on the map of Ondo State

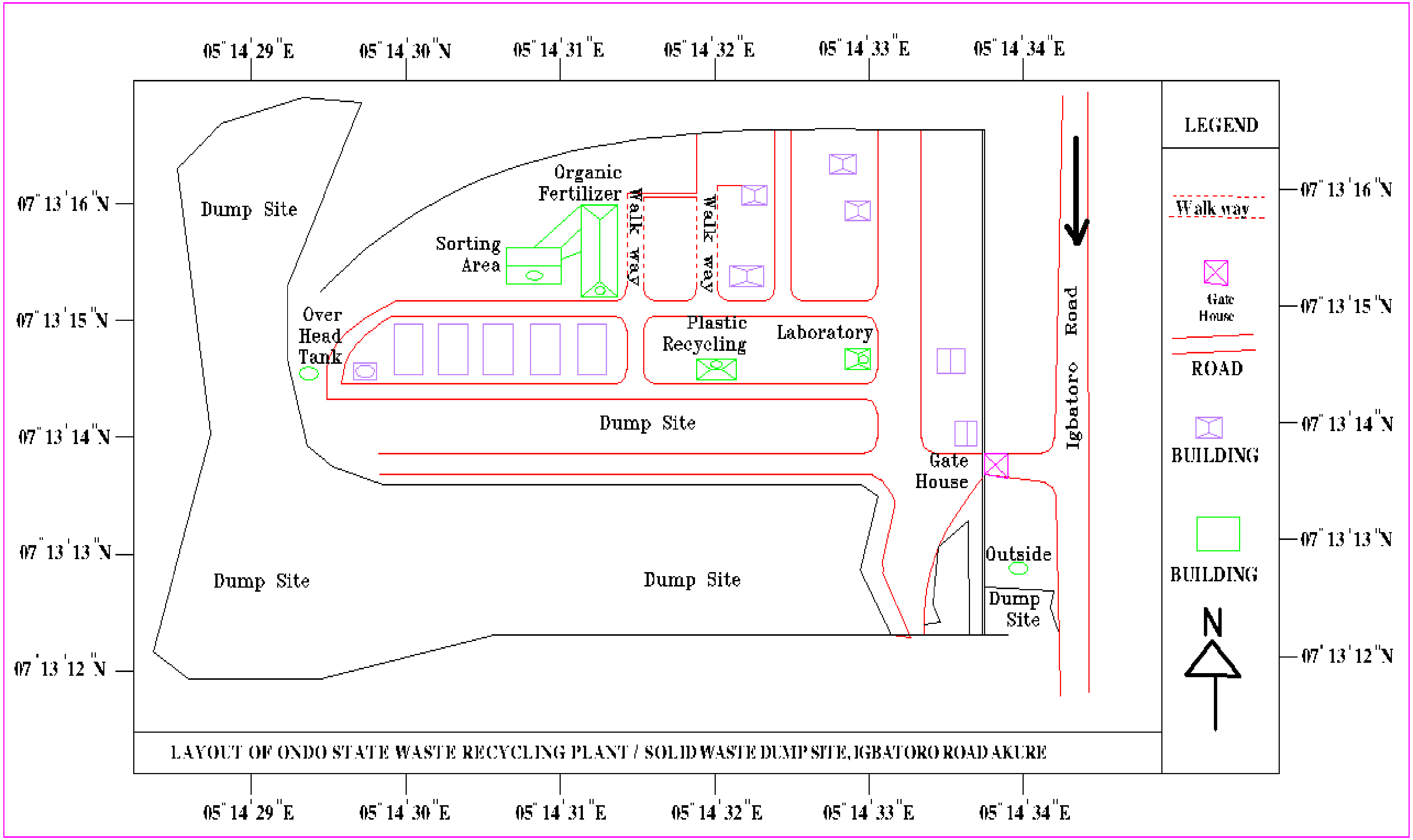


Fig 3.2: Layout of the Ondo State Integrated Recycling Plant/Dumping Site

- **Market**: The wastes that emanate mainly from the markets.

The determination of weight of the physical components was carried out for the period of a year (12 months). The segregation was done once a month by randomly picking a vehicle coming out of the Residential, the Markets and office environment (Roadside) respectively for each month. At the end of the exercise, the wastes coming from the three environments were segregated four times. The workers were encouraged to segregate the wastes centrally and the various components of the solid wastes weighed. The weights of the sorted wastes were obtained using a 20kg capacity *Camry* kitchen weighing scale. The mean weight for each location was then obtained and then multiplied by the number of vehicles for each location and month as recorded by the job card produced for this purpose. This was used to estimate the weight of wastes for each location for each month and ultimately for the year under review. Plate 3.1 shows the waste disposal vehicle with compactor majorly in use in Ondo State.

b. Density

This was obtained by taking four grab samples of paper, nylon and plastics and food wastes from each vehicle for each month. Each sample was put in a 0.5m^3container and weighed using a 20 Kg *Camry* kitchen weighing scale.

3.3.2 Chemical analysis of solid wastes

Twelve organic solid wastes samples generated for a year (that is three per quarter) were collected from the wastes brought from the three identified locations to the dumpsite. These were collected as the wastes were being segregated once a month. The physical parameters of the organic solid wastes samples measured were the moisture content, density and the pH while the chemical parameters of the organic solid wastes samples to be measured and expressed in % were nitrogen, phosphorus, potassium and carbon.

Plate 3.1: **Typical waste collection vehicle with compactor in use in Akure**

A. Food wastes sample preparation

The organic wastes material was oven dried at 65 ^{o}C for a period of 72 hours and ground to pass a 1.0 mm test sieve using a stainless steel grinder. A representative sample of approximately 25 g was retained by coning and quartering.

B. pH determination

Ten ml distilled water was added to 10 g of sample. The mixture was stirred and allowed to stand for 30 minutes; the mixture was stirred again for 2 minutes. The Dwyer Model WPH1 Water Proof pH Meter was calibrated with standard buffer 7.0 and 4.0. The pH of the waste suspension was then measured using the Electrometric pH determinations method (APHA, 1992).

C. Moisture content determination

a. Procedure

An empty moisture can was weighed W_0. About 200g of the grab sample was added to the moisture can and weighed W_1. The moisture can and sample were then dried in the oven for 24 hours, and thereafter cooled in a desiccator. The can with the dry sample was finally weighed until a constant weight was obtained W_2 (Vesilind and Reimen, 1981 in Gartner, 1991). The average value of the moisture contents was then calculated for each study area.

b. Calculation

$$\textbf{Moisture Content} = \left[\frac{\{W_1 - W_2\}}{\{W_1 - W_0\}} x\ 100\right. \text{(expressed in \%)} \qquad (3.1)$$

3.3.3 Determination of Nitrogen, Phosphorus, Potassium, and Carbon, in Organic Waste

The American Public Health Association (2008) Standard Methods for Examination of Water and Wastewater was adopted. These are as detailed below:

a. Digestion mixture preparation

About 0.42g of selenium powder and 14g lithium sulphate were added to 350 ml 30% hydrogen peroxide and mixed well. About 420 ml concentrated H_2SO_4 was slowly added while cooling in an ice bath.

b. Sample digestion

About 0.3g of oven dried (65^{O}C) ground wastes sample was measured and placed in a labelled, dry and clean digestion tube. About 4.4 ml digestion mixture was added to each tube and also to 2 reagents blanks for each batch of samples. The solution was digested for 2 hours at 360^{O}C in a furnace until the solution became colourless. The contents were then allowed to cool. About 25ml distilled water was added and mixed until no more sediment dissolved. The contents were then allowed to cool. The solution was then made up to 50ml with water and mixed well. The solution was then allowed to settle so that a clear solution could be taken from the supernatant for analysis.

A. Total Nitrogen Determination

Procedure

A Markham steam distillation apparatus was set up using NH_3 free distilled water. Steam was passed through the apparatus for 30 min. The steam bank was checked by collecting 50 ml distillate and titrating against N/70 HCl. About 5 ml of digestion mixture was transferred to the reaction chamber and 10 ml of 40% NaOH was added. The solution was steamed distilled immediately into 5 ml of 1% boric acid containing 4 drops of the mixed indicator. The distillation was continued for 2 minutes from the time the indicator turned green. The distillate was removed and titrated against N/70 HCl until when the indicator turned from green to a definite pink. The volume of standard HCl required was recorded. A blank determination was run by digesting reagent blanks in place of sample and distilled as before and titrated against N/70 HCl. The volume (ml) of N/70 HCl required for the blank was subtracted from the micro-burette reading to give a corrected volume of N/70 HCl.

Calculation

$$\%\ N\ in\ Waste\ Sample = \frac{\left[Corrected\ ml\ of \frac{N}{70}\ HCl\ x\ 0.2\right]}{Weight\ of\ Sample} \qquad (3.2)$$

B. Phosphorus determination (Vanado-molybdate Method)

Procedure

Ten ml of the wet-digested sample was pipetted into a 50 ml volumetric flask and about 0.2 ml of 0.5% Paranitrophenol indicator solution was added. Alkaline solution was made with 6 N NH_3 solutions by drop-wise addition with gentle shaking. About 1 N dilute HNO_3 was added drop-wise with shaking until the solution became colourless. About 5 ml of Ammonium Molybdate/ Ammonium Vanadate mixed reagent was then added. The solution was made to 50ml with distilled water stoppered and mixed well. The flask was kept for 30 minutes and the adsorption of the solution was measured at 400nm wavelength setting using a colorimeter. The phosphorus present in the solution was read off from a calibration curve prepared by pipetting 0, 5, 10, 15, 20 and 25 ml of the standard 10 ppm (mg/l) P solution into 50ml volumetric flasks, representing 0, 1, 2, 3, 4, and 5 ppm (mg/l) P respectively. The vanado-molybdate yellow colour was developed in the standard P solution by the addition of the p-nitrophenol indicator, NH_3 solution and HNO_3. The standards were prepared for each batch of samples.

Calculation

A graph of adsorbance was plotted against standard concentration. The solution concentrations for each unknown were determined for the two blanks. The mean blank value was subtracted from the unknowns to give a value for the corrected concentrations.

Taking a 10ml digest aliquot

For a 50 ml final solution used for colour intensity (adsorbance) measurement:

$$\%\, P\ in\ Waste\ Sample = \frac{[Concentration\ x\ 0.025]}{Weight\ of\ Sample} \tag{3.3}$$

C. Potassium determination

Procedure

Two ml of the wet digested-sample solution was pipetted into a 50 ml volumetric flask. The solution was made to mark with distilled water and mixed well. Sample solutions starting with standard and blank solutions were sprayed directly into the flame of the Genway flame photometer Model PSP7 (wavelength at 7665A, slit 0.07 mm). The amount of potassium present in the solution (c) from the calibration curve was read by plotting adsorbance readings against potassium concentrations.

Calculations

For a 2.0ml digest aliquot

$$\% \, K \text{ in Waste Sample} = \frac{[\text{Concentration } x \; 0.125]}{\text{Weight of Sample}} \qquad (3.4)$$

D. Carbon determination

Procedure

A dry empty porcelain crucible was weighed W_1. About 10g of well mixed oven dried organic waste sample of known moisture content was weighed in a dry porcelain crucible W_2. The sample was heated slowly in a furnace raising the temperatures in steps (100, 200 and 550 ^{O}C). The final temperature setting of 550 ^{O}C was maintained for 8 hours. The crucible containing a greyish white ash was removed and cooled in a desiccator and weighed W_3.

Calculations

The % Ash, % Organic matter and % Carbon were calculated as follows:

$$\% \, \text{Ash in Waste Sample} = \left[\frac{\{W_3 - W_1\}}{\{W_2 - W_1\}}\right] x \; 100 \qquad (3.5)$$

Where W_1 = Weight of the empty dry crucible

W_2 = Weight of the dry crucible containing organic waste sample

W_3 = Weight of the dry crucible containing organic waste sample following ignition

$$\% \, \text{Organic Matter in Waste Sample} = 100 - \% \, \text{Ash} \qquad (3.6)$$

$$\% \, \text{Carbon in Waste Sample} = \frac{[\% \, \text{Organic Matter in Sample}]}{1.729} \qquad (3.7)$$

Where 1.729 is the conversion factor

3.4 Estimation of methane emission potential at the dumping site

To estimate the Methane Emission Potential of the dump site the Intergovernmental Panel on Climate Change (IPCC) Default Method (DM) and First Order Decay Method (FOD) were used.

3.4.1 *The Intergovernmental Panel on Climate Change (IPCC) Default Method (DM)*

This methodology depends on estimating the Degradable Organic Carbon (DOC) content of the solid waste, and using this estimate to calculate the amount of CH_4 generated from the waste. Furthermore, this methodology assumed that all potential of CH_4 was released from waste in the year that the waste is disposed of. The DM methodology is the most widely accessible, easy to apply methodology for calculating country-specific emission of CH_4 from solid waste disposal sites. The annual CH_4 emission estimation for each region or country was calculated from Equation (1) (IPCC, 2006). The equation was employed by Bingemer and Crutzen (1987) to calculate Methane emissions. The Characterization of the Market waste by the Women is reflected in Plates 3.2a and 3.2b

The default method (IPCC, 2006) is based on the main equation 1:

EQUATION 1

$$CH_4\ Emission\ Gg\ Yr^{-1} = \left[\left\{MSW_T\ x\ MSW_F\ x\ MCF x\ DOC\ x\ DOC_F\ x\ F\ x \frac{16}{12} - R\right\}\ x\ \{1 - OX\}\right] \tag{3.8}$$

Where:

MSW_T: total MSW generated (Gg/yr)

MSW_F: fraction of MSW disposed to solid waste disposal sites

MCF: methane correction factor (fraction)

DOC: degradable organic carbon (fraction) (kg C/ kg SW)

DOC_F: fraction DOC dissimilated (IPCC default is 0.77)

F: fraction of CH4 in landfill gas (IPCC default is 0.5)

16/12: conversion of C to CH_4

R: recovered CH_4 (Gg/yr)

Plate 3.2a: Characterization of residential area waste by workers of Integrated Recycling Plant, Igbatoro Road, Akure

Plate 3.2b: Characterization of market waste by workers of Integrated Recycling Plant, Igbatoro Road, Akure

OX: oxidation factor (fraction – IPCC default is 0)

MSW_T= Total municipal solid waste (MSW) generated (Gg yr^{-1}). Total MSWT can be calculated from population (in thousand persons)_annual MSW generation rate (Gg 10^{-3} persons yr^{-1})

MSW_F= Fraction of MSW disposed of at the disposal sites. The percentage of 70% is based on field investigative studies. The remaining 30% is assumed to be lost due to recycling, waste burning at source as well as at disposal site, waste thrown into the drains and waste not reaching the landfills due to inefficient solid waste management system

MCF= Methane correction factor (fraction). The fraction depends upon the method of disposal and depth available at landfills. The IPCC document indicated the value of 0.4 for open dumps 0.5m depth and hence used for computation.

Table 3.1 reflects the Solid Waste Disposal Sites (SWDS) classification and MCF

Table 3.1 SWDS Classification and MCF: Source IPCC (2006)

Type of Site	MCF Default Values
Managed	1.0
Unmanaged-deep	(≥5m waste) 0.8
Unmanaged-shallow	(≤5m waste) 0.4
Default value-uncategorized SWDSs	0.6

DOC= Degradable organic carbon (fraction). DOC content is essential in computing methane generation. It depends on the composition of waste and varies from city to city. Equation to determine DOC values

0:4A + 0:17B + 0:15C + 0:3D

where

A= paper + textiles

B=leaves + garden trimmings

C=food wastes

D=wood

F: 0.5 is the IPCC default value

R: Rate of Recovery of Methane which is 0 for an open dump.

OX: 0 is the IPCC default value

The minimum national Figs required are:

- National MSW quantities ending up at Solid Wastes Disposal Sites (SWDSs), eventually (in lack of SW statistics) based on the number of urban inhabitants in the country multiplied with a specific national MSW disposal rate Fig, and
- National quantities of landfill gas recovered.

In most developing countries there is no gas extraction and recovery; hence the only Fig needed in the calculation is the number of inhabitants in the country, with clear focus on the urban population.

- *Determination of Degradable Organic Carbon (DOC) from the recycling plant/open dump for the wet and dry season*

The weight of the wastes components were determined as explained in Section 3.3.1. The mean weights of the Paper and Textile, Food Wastes, Leaves and Garden Trimmings and Wood for the Market, Residential and Roadside were determined for the four months. The mean weight for each location was then obtained and then multiplied by the number of vehicles for each location and month as recorded by the job card produced for this purpose. This was used to estimate the weight of wastes for each location for each month and ultimately for the year under review. The year was then classified into wet and dry seasons. The wet season was from March to September, 2013 while the dry season was from October to February, 2014. The segregation of wastes from the Market are shown in Plates 3.3a, 3.3b and 3.3c

3.4.2 Nationally Adjusted First Order Decay (FOD)-model

Several countries have made adjustments to the presented FOD-model by including supplementary information of the factors Lo and k, and are in the process of using these in their national inventories.

A model implemented in Norway in 1998 (Bartness, *et al*, 1998) is proposed as follows:

$$Q_{T,X} = K\ x\ MSW_{T(X)}\ x\ MSW_{F(x)}\ x\ MCF_{(X)}\ x\ L_{0(X)}\ x\ e^{-(T-X)}\ x\ F \qquad (3.9)$$

Where:

Plate 3.3a: Segregation of market waste into leaves and vegetables

Plate 3.3b: Segregation of market waste into cartons and paper

Plate 3.3c: Segregation of market waste into nylon and plastics

$Q_{T,x}$: the amount of methane generated in the current year from waste disposed in the year x

T: the current year (year of the emission estimate) (Gg/yr)

X: the historical year of the disposal of the relevant national MSW quantities

$Lo_{(X)}$: DOC x DOC_F for the year x (Gg CH4/Gg waste)

k: ln (2)/t½. (1/yr) which is between 0.005-0.4, the default value is 0.05 yr^{-1} is to be used as suggested under the Clean Air Act (CAA) in the U.S

t ½ : half-life period for the degradation process (yr)

MSWT(x), MSWF(x) and MCF(x) and F are the same factors as in the default method (equation 1), but estimated for the year x.

3.5 Estimation of carbon dioxide emission potential at the dumping site using the Intergovernmental Panel on Climate Change (IPCC), 2006 Guidelines

This methodology was based on the Tier 1 method of the IPCC, 2006 Guidelines. The Tier 1 method is a simple method used when CO_2 emissions from incineration/open burning are not a *key category*. Data on the amount of waste incinerated/open-burned are necessary (BREF, 2005). The calculation of the CO_2 emissions is based on an estimate of the amount of waste (wet weight) incinerated or open-burned taking into account the dry matter content, the total carbon content, the fraction of fossil carbon and the oxidation factor. The method is based on the MSW composition and for MSW, it is *good practice* to calculate the CO_2 emissions on the basis of waste types/material (such as paper, wood, plastics) in the waste incinerated or open-burned expressed:

$$CO_2 = MSW\ x \sum_j [WF_j\ x\ dm_j\ x\ CF_j\ x\ FCF_j\ x\ OF_j]\ \ x\frac{44}{12} \qquad (3.10)$$

Where

CO_2 Emissions = CO_2 emissions in inventory year, Gg/yr

MSW = total amount of municipal solid waste as wet weight incinerated or open-burned, Gg/yr

WF_j = fraction of waste type/material of component *j* in the MSW (as wet weight incinerated or open burned)

Dm_j = dry matter content in the component *j* of the MSW incinerated or open-burned, (fraction)

CF_j = fraction of carbon in the dry matter (i.e., carbon content) of component *j*

FCF_j = fraction of fossil carbon in the total carbon of component *j*

OF_j = oxidation factor, (fraction)

44/12 = conversion factor from C to CO_2

With:

$$\sum_j WF_j = 1$$

j = component of the MSW incinerated/open-burned such as paper/cardboard, textiles, food waste, wood, garden (yard) and park waste, disposable nappies, rubber and leather, plastics, metal, glass, other inert waste.

3.6 Overall emissions under present conditions

From the previous stage of characterization of the solid wastes brought to the facility, overall waste generated and recycling done by the facility was obtained. Once, this data was obtained, emissions from each material generated at the facility was estimated using the greenhouse gas emission factors developed by USEPA for Waste Reduction Model (WARM). Estimation of emissions was done in metric tons of carbon dioxide equivalent ($MtCO_2eq$). The emission factors represents the GHG emissions associated with managing one short ton of respective MSW material. The negative values in the table represent the reduction in emissions. Overall emissions from a waste component was calculated by using the equation below

$$E_x = W_{Xl} x F_{Xl} + W_{xr} x F_{Xr} \tag{3.11}$$

where,

E_x = Overall emissions from waste component X

W_{xl} = Overall weight of waste component X that is being landfilled

F_{xl} = GHG emissions factor for waste component X when landfilled

W_{xr} = Overall weight of waste component X that is being recycled

F_{xr} = GHG emissions factor for waste component X when recycled

Since no record was taken of the weight of components of waste recycled per day, therefore $\mathbf{W_{xr}}$ is assumed to be 0 for all solid wastes Components.

Also, the weight of Municipal Solid Wastes Component was converted from Kilograms to Tons.

Therefore

$$\mathbf{E_x = W_{xpaper} * F_{xpaper} + W_{xplastic} * F_{xplastic} + W_{xmetal} * F_{xmetal} + W_{xglass} * F_{xglass} + W_{xfood\ waste} * F_{xfood\ waste} + W_{xLeaves\ \&\ Hay} * F_{xLeaves\ \&\ Hay} + W_{xTyre} * F_{xTyre} + W_{xTextile} * F_{xTextile} + W_{xash} * F_{xash} + W_{xwood} * F_{xwood}}$$

3.7 Municipal Solid Waste (MSW) management and green house gases mitigation in the solid waste disposal facility for Akure.

The scenario for solid waste management practices and greenhouse gases mitigation was estimated using the greenhouse gas conversion and correction factors developed by U.S EPA for Waste Reduction Model (WARM). Estimation of emissions was done in metric tons of carbon dioxide equivalent ($MtCO_2eq$) Overall emissions reduction from a Municipal Solid Waste Management Practice was calculated by using the equation below. The Conversion and Correction Factors are obtained from USEPA, 2002 and IPCC, 2006

$$E_X = \sum W_{X_r}\, x\, Cv_{Xl}\, x\, Cr_{xl} \qquad (3.12)$$

where,

Ex = Overall emissions from waste management practice

Wx_r = Overall weight of waste component X that is being recycled

Cvx_l = Conversion factor of waste management practice

Crx_l = Correction factor of waste management practice

3.8 Monitoring of the carbon dioxide level at the study area

3.8.1 Calibration of the carbon dioxide meter

The calibration procedure was obtained from the operation manual of the P-Sense Plus CO_2 Meter AZ-7755.

I. Carbon dioxide calibration

The meter was placed in the calibration site which is fresh outdoor air that is well ventilated and in sunny weather. The meter was turned on and held down simultaneously, 400 was entered as CO_2 calibration mode. 400ppm and "CAL" were allowed to blink on the LCD for a period of about 5 minutes until the blinking stopped signaling the completion of the calibration after which the meter automatically goes back to normal mode.

II. Relative humidity calibration

The meter defaults to calibrate the humidity with 33% and 75% salt solution, while the ambient condition is recommended to be at 25^{o} C

a. Calibration with 33% salt solution

The sensor probe was plugged into 33% salt solution bottle. It was held down and under normal mode and 33% calibration was entered. "CAL" and calibrating value (32.7% if at 25^{o}C) was blinking on the LCD. This was allowed for about 60 minutes when "CAL" and humidity stopped blinking. This indicated that calibration was completed and meter returns to normal mode.

b. Calibration with 75% salt solution

After 33% calibration, the sensor probe was plugged into 75% salt bottle, then the Min/Max/AV button was pressed to enter 75% calibration. "CAL" and calibrating value (75.2% if at 25 C) was blinking on the LCD with current temperature at the left. This was allowed for about 60 minutes when "CAL" and humidity stopped blinking. This indicated that calibration was completed and meter returns to normal mode.

3.8.2 Measurement of Carbon Dioxide Levels at the waste management facility

At the recycling plant and dump site, measurements were taken at seven sampling points namely; Gate house, Roadside, Laboratory, Plastics Recycling unit, Organic Recycling Unit, Sorting Bay, Overhead tank and Composting unit. The meter was taken to a sampling point and placed about 80 cm from the ground. The meter was then switched on for 60 seconds after which the readings of the Carbon dioxide concentration in ppm which were displayed on the screen were recorded. The procedure was repeated thrice for each sampling point. The CO_2 monitoring was done every day for a week at 9.00a.m, 12.00 noon and 2.00 p.m daily. The monitoring was carried out twice; during the wet and dry season that is in May and November as reflected in Plates 3.4 and 3.5. The Temperature and Relative Humidity readings were also taken using the -Sense Plus CO_2 Meter AZ-7755 shown in Figure 3.3.

3.9 Design of carbon dioxide extractor

This section presents the review of material selection and detailed analysis of design of component parts of carbon dioxide extractor machine. Figure 3.4 shows the design diagram of the carbon dioxide extractor, while Figure 3.5 shows the hidden details of the carbon dioxide extractor with Plate 3.6 showing the fabrication of the extractor while in progress.

3.9.1 Material selection for machine design

For better and efficient utilization of engineering material for machine design, it is vital for a designer to be familiar with different types of engineering materials and their available properties. Most engineering properties that are available for engineering design are mechanical, physical, electrical, thermal, surface properties, etc. The important factors considered for the selection of these properties are: availability of material, fitness of materials for use and cost of materials. Knowledge of these properties allows the designer to determine the size, shape, durability, and life span of the design taken into consideration and method of fabricating structure and machine element.

I. Selecting materials for individual component parts of the extractor

The selection for individual component parts of this project are based upon considerations of the properties required, these include; Mechanical, Electrical, Thermal and Surface properties.

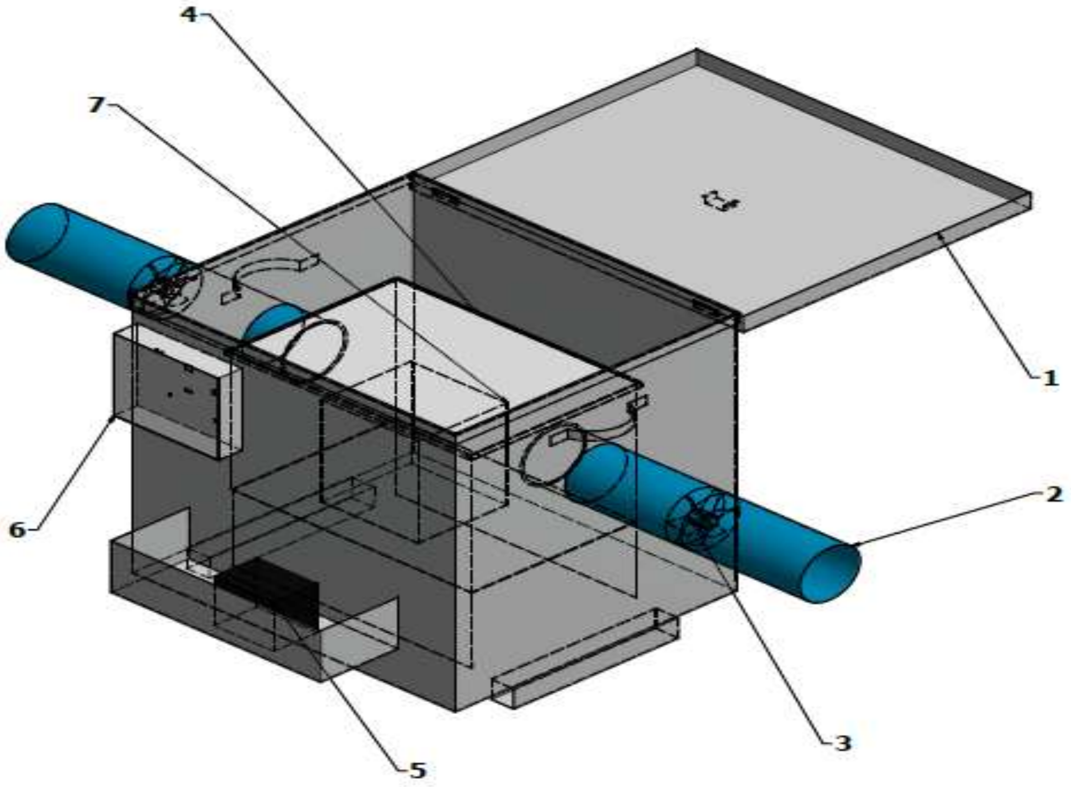
i. Mechanical properties

These are those that indicate how the material is expected to behave when subjected to various loads or combination of loads. These mechanical properties are determined

Plate 3.4: Spontaneous burning of solid wastes at the Solid Waste Management Facility dumping site at Akure

Plate 3.5: Measurement of environmental CO_2 at the dumping site at at the Solid Waste Management Facility dumping site at Akure

Fig 3.3: P-Sense Plus CO_2 Meter AZ-7755



PART LIST

S/N	PART	QTY
1	CASE	1
2	4 INCH PIPE	2
3	FAN	2
4	BUCKET	1
5	BATTERY	2
6	ELECTRICAL PANEL	1
7	RESIN	1

Fig 3.4: Design diagram of the carbon dioxide extractor

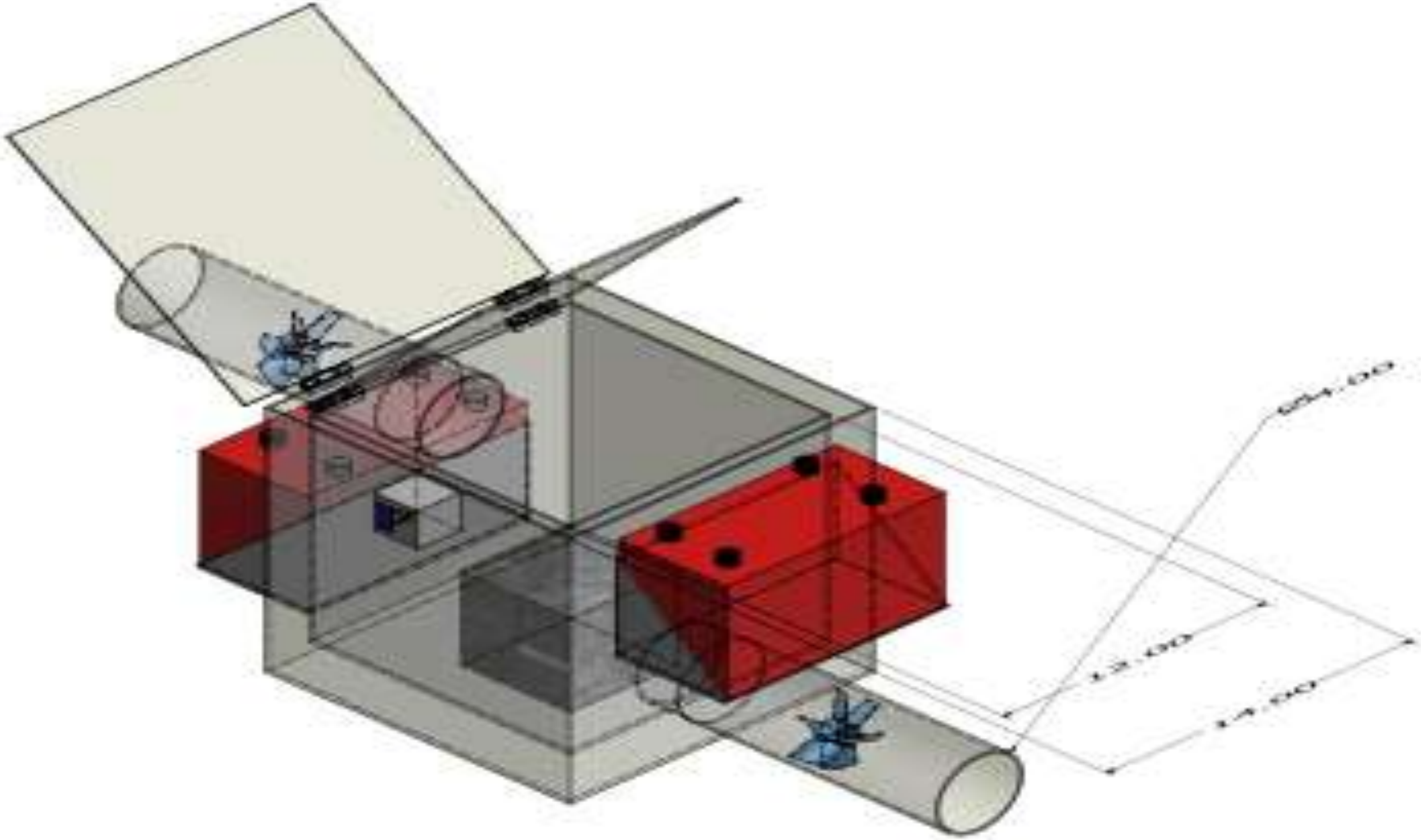


Fig 3.5: Diagram of carbon dioxide extractor showing hidden details and dimensions

Plate 3.6: Fabrication of extractor in progress

by standardized test method e.g those outlined by American Society of Testing Materials (ASTM) (Shigley and Mischke, 1989).

Examples of mechanical properties are

- **Hardness**: the ability of material to withstand scratching, wear and abrasion, indentation by harder bodies.
- **Toughness**: this is the amount of energy a material can adsorb before its fracture.
- **Fatique strength**: this is the maximum stress for which a fatique will not occur within a particular number of cycles such as 500, 000, 000. (Askeland, 1994).
- **Ductility**: this is the ability of a material to be permanently deformed without breaking when subjected to the applied force.

  Strength: this is the ability of material to resist the application of applied force without pupture

ii. Electrical properties

These are the properties displayed when the material is used in electrical circuit or electrical components e.g resistivity (resistance of the material to the flow of electric current), conductivity (ability of materials to conduct electricity), and resistance to electrical breakdown.

iii. Thermal properties

These are the properties displayed when there is heat input to material, e.g thermal resistance (ability of a material to resist heat), expansivity (ability of a material to change in volume in response to change in temperature) and heat capacity (ability of material to heat up and cool down and how well it conduct heat).

iv. Surface properties

These include abrasion and wear, corrosion and solvent resistance.

Table 3.2 contains each individual component parts of the Carbon (IV) Oxide extraction machine functions; machine selected and reasons for the selection of the materials.

Table 3.2: Material selection and reasons for selection of the material for individual components

S/No	Components	Functions	Materials selected	Reasons for selection
1	**Housing**	❖ To protect the user from moving parts ❖ To house plastic casing for the adsorption of CO_2 ❖ To enhance the aesthetic presentation of the machine	Galvanized iron	❖ Excellent corrosion resistance ❖ Light in weight
2	Adsorbent Casing	❖ To house the adsorbent ❖ To protect the moving blade shaft ❖ To ensure free movement of fan blade shaft at desired speed ❖ To contain the adsorbent	Plastic	❖ Non reactive with the adsorbent ❖ Relatively inexpensive
3	Baking pan	❖ To prepare the activated carbon at a specific temperature	Aluminum	❖ High thermal conductivity ❖ Ability to withstand high temperatures ❖ Non reative at high temperature
4	Pipe	❖ To allow the passage of air into and out of the machine ❖ To house the blade shaft that extracts air in and out of the machine	PVC pipe	❖ Low wear and corrossion resistance ❖ Low cost
5	Control system	❖ To allow for resilience timing of 10 minutes in the adsorbent	Bought-out	❖ The machine needs to be managed or regulated by a device ❖ To give room for a considerable reaction between the adsorbent and air taken
6	Directional fan	❖ For extracting or moving air through the duct to the casing from the environment and out of the machine to the environment	Bought-out	❖ Controlled air is need for optional operation of machine
7	Adsorbent	❖ To adsorb CO_2 from the air taken in by the directional fan	Saw dust soaked with (KOH, NaOH and $Ca(OH)_2$)	❖ Pyrolyzed sawdust+(KOH, NaOH and $Ca(OH)_2$) is a very good CO_2 adsorbent ❖ Sawdust is readily available ❖ Low cost of KOH, NaOH and $Ca(OH)_2$
8	Grille (filter)	❖ To sieve dirts from entering through the pipe to the adsorbent which could cause blockage of the pore space	Cotton	❖ Relatively inexpensive ❖ A very good dirt filter

3.9.2. Design calculation

In design analysis of Carbon dioxide extractor machine for good performance, the following component parts are designed for:

- Air flow and pipe design
- Housing design
- Baking pan design
- Casing design
- Fan design
- Production of activated carbon

A. Design limit

This project was required to provide a means of extracting carbon dioxide generated from the environment such as open dump site and places of high fossil fuel consumption by taking in air, extracting the carbon dioxide and releasing a carbon dioxide free air. The machine is also expected to operate at resilience time of ten minutes.

3.10 Evaluation of the performance of the carbon dioxide extractor

3.10.1 *Production of activated carbon*

The standard method used for the production of activated carbon was chemical activation. The raw material which was sawdust was first impregnated through soaking with potassium hydroxide, sodium hydroxide or calcium hydroxide respectively. This was followed by carbonization at a temperature of 500^{o}C for 5 hours. The procedure is as expressed below:

I. Preparation of sawdust

The sawdust was collected free of cost from the Ogendengbe Sawmill at the Idashen Area of Owo, Ondo State. Sawdust samples were sieved (pore size of 0.25 mm), washed several times to remove dust and first sun- dried for 24 hours as presented in Plate 3.7 . The sun-dried saw dust was later dried at 110^{0}C for 24hours in a drying oven at the Laboratory of the Ondo State Water Corporation, Alagabaka, Akure as presented in Plate 3.8

Plate 3.7: Sun drying of sawdust

Plate 3.8: Drying of sawdust in an Oven at 110^{o}C for 24 hours

II. *Production of activated carbon with potassium hydroxide (K OH)*

150 g of sawdust was well mixed with 150 g of KOH pellets which was thoroughly soaked and mixed with 150ml of distilled water. The sample was then left for 5 minutes until it became stable. The stable sample was then transferred to the Techmel and Techmel Furnace at 500°C for 5 hours.

III. *Production of activated carbon with sodium hydroxide (Na OH)*

150 g of sawdust was well mixed with 150 g of KOH pellets which was thoroughly soaked and mixed with 150ml of distilled water. The sample was then left for 5 minutes until it became stable. The stable sample was then transferred to the Techmel &Techmel Furnace at 500°C for 5 hours.

IV. *Production of activated carbon with calcium hydroxide $Ca(OH)_2$*

150 g of sawdust was well mixed with 150 g of Ca $(OH)_2$ pellets which was thoroughly soaked and mixed with 150ml of distilled water. The sample was then left for 5 minutes until it became stable. The stable sample was then transferred to the Techmel &Techmel Furnace at 500°C for 5 hours. The preparation of the activated carbon and the Techmel &Techmel Furnace are reflected in Plates 3.9 and 3.10 while the produced activated carbon of sawdust and KOH, sawdust and NaOH and sawdust and $Ca(OH)_2$ are shown in Plates 3.11, 3.12 and 3.13 respectively.

V. Characterization of Activated Carbon

The particle properties of the activated carbon samples were investigated using a Scanning Electron Microscope (SEM), Make: Phenom proX SEM, Model No: 800-07334 operated at 25kV at the Mechanical Engineering Department at the Covenant University, Ota. The SEM is shown in Plate 3.14

3.10.2 Monitoring of carbon dioxide adsorbed by extractor and different activated carbons.

Five Wooden frames made up of Tie rods of sizes 0.5, 0.75, 1.00, 1.25, and 1.50 m^3 respectively were constructed as shown in Plate 3.15. A thick Nylon Sheet was then used to cover the wooden frames. This is to prevent the gas fumes from escaping to the atmosphere.

Plate 3.9: Preparation of sawdust for carbon capture with KOH

Plate 3.10: Furnace in operation at 500°C for heating the sawdust and KOH

Plate 3.11: Activated carbon produced from sawdust with KOH

Plate 3.12: Activated carbon produced from from sawdust with NaOH

Plate 3.13: Activated carbon produced from sawdust with $Ca(OH)_2$

Plate 3.14: Scanning Electron Microscope (SEM), Make: Phenom proX SEM, Eindhoven in the Netherlands, Model No: 800-07334)

Plate 3.15: Naked frames of chambers from 0.50 to 1.50 m^3

The adsorbent made up of sawdust and KOH was placed in the plastic container in the Carbon Dioxide Extractor. The extractor was then placed in between two of the wooden frames of sizes 0.5 and 0.75 m^3, (inlet and outlet) which were adequately covered with a black thick nylon as reflected in Plate 3.16. Five (5) kg of solid wastes was kept in a medium sized pot as shown in Plate 3.17 was set ablaze and allowed to burn for 5 minutes to release some emissions. The pot was then placed in the inlet wooden frame. The baseline concentration of the carbon dioxide was then measured. The extractor was then switched on and the inlet fan operated for 10 minutes. The post concentration of the carbon dioxide at the inlet chamber was then measured. There was another interval of another 10 minutes, before the expiration of the interval, the pre concentration of the carbon dioxide at the outlet chamber was then measured. After the expiration of the 10 minutes interval, the outlet fan of the extractor picked up and operated for another 10 minutes and the post concentration of the carbon dioxide was then measured. This was repeated for 0.75 and 0.75 m^3, 1.0 and 0.75 m^3, 1.25 and 0.75 m^3 and 1.50 and 0.75 m^3; (inlet and outlet) respectively. The measuring of the pre-concentration of the carbon dioxide is shown in Plate 3.18. The exercise was then repeated for the other treatment of adsorbent of (Sawdust and Na OH) and (Sawdust and Ca $(OH)_2$) by replacing the adsorbents in the plastic container of the carbon dioxide extractor respectively.

3.10.3 Evaluation/ prediction of the performance of the extractor (activated carbon)

A. Modelling and prediction of the performance of extractor combined with activated carbon

To predict the performance of the activated carbon in terms of the carbon dioxide adsorbed by each of the activated carbon (Sawdust + Alkaline), the following was used to generate the concentration of CO_2 in the system:

1. Conc. of CO_2 inlet in ppm = (post – pre) concentration of CO_2 at inlet
2. Conc. of CO_2 at outlet in ppm = (post – pre) concentration of CO_2 at outlet
3. Conc. of CO_2 Adsorbed in ppm = Conc. of Co_2 inlet in ppm - Conc. of CO_2 at outlet in ppm

Plate 3.16: Carbon dioxide extractor placed between the covered inlet and outlet chambers

Plate 3.17: Solid wastes burnt in medium size pot as source of emissions

Plate 3.18: Measurement of baseline carbon dioxide

B. Assessment of the effectiveness of the extractor combined with activated carbon

I. Calculation of potential carbon dioxide

Five samples of 200g of solid waste were collected and characterized. The samples were then equally divided into two groups of five samples of 100g each. Five samples of 100g were then burnt for five minutes and the other five samples left unburnt, after which both groups were taken to the Agronomy Department of Institute of Agricultural Research and Training, Ibadan, Oyo State. Ultimate analysis were conducted on the burnt and unburnt waste to obtain the % carbon dioxide. The difference of the % Carbon dioxide of the unburnt and burnt wastes for the five samples for each activated carbon/adsorbents were found and was calculated as the mean potential carbon dioxide. The percentage was then converted to parts per million (ppm).

II. Calculation of adsorbed carbon dioxide

The Adsorbed carbon dioxide was calculated by finding the mean difference between the concentration of carbon dioxide at the inlet chambers in ppm and the concentration of carbon dioxide at outlet chambers in ppm for each treatment of the activated carbon for the five sizes of the inlet chambers.

III. Determination of effectiveness of extractor combined with activated carbon

The effectiveness was then determined by comparing the mean adsorbed carbon dioxide for each activated carbon with the mean potential carbon dioxide.

3.11 Proximate analysis of biomass (ASTM D3174-76)

3.11.1 Determination of moisture and dry Matter

Two grams of sample was weighed into a previously weighed crucible and placed in a Gallenkamp drying oven at 105°C. The change in mass is taken at every 6hours till a constant mass is reached. % moisture was calculated using the formula:

$$\%Moisture = \frac{W_i - W_f}{W_i} \ x\ 100 \qquad (3.13)$$

Where W_i = initial mass of the sample

W_f = final constant mass of the sample

$$\%\ Dry\ Matter = 100 - \%\ Moisture \qquad (3.14)$$

3.11.2 *Determination of volatile matter*

Two grams of sample was weighed into a closed crucible and heated in a gallenkamp muffle furnace set at 600°C for six minutes followed by heating for another 6 minutes at a temperature of 900°C

The amount of volatile present is equal to loss in weight which is calculated using the formula:

$$\%\ Volatile\ matter = \frac{\{W_i - W_f\}}{W_i}\ x\ 100 \qquad (3.15)$$

W_i = Initial mass of the sample

$W_{f\,=}$ final constant mass of the sample

3.11.3 *ASTMD3174-76(American Standard Testing Method)*

Determination of Ash

Two grams of sample was weighed into a previously weighed crucible and placed in a muffle furnace set at 900^{0}C for 6hrs till a white greyish matter is obtained. The amount of residual white greyish matter is obtained by the formula.

$$\%\ Ash = \frac{\{\,M_a - M_o\,\}}{M_s} \qquad (3.16)$$

Where Ma = mass of crucible plus Ash

Mo= mass of empty crucible

Ms= mass of sample

3.11.4 *Determination of Fixed Carbon*

The amount of fixed carbon is calculated using the formula:

$$\%\ Fixed\ Carbon = 100 - \{\,\%\ Moisture + \%\ Ash + \%\ Volatile\ Matter\} \qquad (3.17)$$

3.12 Ultimate analysis of biomass (ASTM 3174 – 76)

3.12.1 Determination of Carbon, Hydrogen, Oxygen

A. Determination of Carbon, Hydrogen and Oxygen

Two grams of sample was weighed into platinum crucible and placed in a Liebig – Pregl chamber containing magnesium percolate and sodium hydroxide. The sample was burnt off to produce carbon oxide hydroxide and water. The CO_2 was adsorbed by sodium hydroxide while water was adsorbed by magnesium percolate. The amount of water and carbon dioxide were calculated by difference.

$$\%C = \frac{\{a \; x \; 0.2727\}}{Weight\ of\ Sample} \; x \; 100 \qquad (3.18)$$

$$\%H = \frac{\{a \; x \; 0.1117\}}{Weight\ of\ Sample} \; x \; 100 \qquad (3.19)$$

Where: a = quantity of CO_2

b = quantity of H_2O

B. Energy determination (AOAC Official Method 2003.09)

Apparatus: Gallenkamp Ballistic Bomb Calorimeter.

Reagents: Benzoic Acid.

Determination

Each sample of 0.25 g depending on bulkiness was weighed into the steel capsule. A 10cm cotton thread was attached to the thermocouple to touch the capsule. The Bomb as reflected in Plate 3.19 was closed and charged in with oxygen up to 30 atm. The Bomb was fixed up by depression the ignite switch to burn the sample in an excess of oxygen. The maximum temperature rise in the bomb was measured with the thermocouple and galvanometer system. The rise in temperature was compared with that obtained for 0.25gm of Benzoic value of each sample was determined by the following stepwise calculations:

Calculations:

Mass of Benzoic Acid = W_1 (grams)

Calorific value of 1gm Benzoic Acid = 6.32 Kcal/g

Plate 3.19: Gross energy determination using Gallenkamp Ballistic Bomb Calorimeter

Heat released from Benzoic Acid = 6.32 x W_1 Kcal

Galvanometer deflection without sample = T_1

Galvanometer deflection of Benzoic Acid = $T_2 - T_1$

$$\textit{Calibration Constant} = \frac{\{6.32\ x\ W_1\}}{\{T_2 - T_1\}} = y \qquad (3.22)$$

The standardizing is repeated five times and average value calculated for y.

Mass of sample = 0.25gm

Galvanometer deflection with sample = T_3

Galvanometer deflection of sample = $T_3 - T_1$

$$\textit{Heat Released from Sample} = \{T_3 - T_1\}y\ KCal \qquad (3.23)$$

$$\textit{Calorific Value of Sample} = \frac{\{T_3 - T_1\}}{0.25}\ KCal/g \qquad (3.24)$$

3.13 Data analysis

Data analysis was carried out using descriptive Statistics and ANOVA at 5% level of significance.

CHAPTER FOUR

RESULTS AND DISCUSSION

This Chapter presents the description of the characterization of the waste brought to the Open dump from the various locations, the estimation of the methane emissions, the environmental carbon dioxide gas levels emitted at the waste management facility at the sampling points at the recycling plant and dumping site along Igbatoro road, Akure. This was shown by the results of the physico-chemical assessment of the generated wastes from the market, residential and roadside for one year and the measurements of carbon dioxide readings of the sampling points in the wet and dry seasons. The performance of the carbon dioxide extractor with the various treatments of chemically activated carbon were also evaluated.

4.1 Characterization of generated wastes

4.1.1 Physical assessment of components of solid wastes

The result of the survey showed that the major wastes brought from the market during the four months included paper/carton, nylon, food wastes, leaves and garden trimmings, plastic, textiles, wood, metal, can/tins, sand, ash and bottles, tyre, battery, wire, bones and POP. The Average percentage composition by weight of the physical components brought from the market, roadside and residential is illustrated by Table 4.1. The most generated at the market as reported is the food wastes, 31.0% followed by nylon, paper, and sand at 30.0, 17.0 and 11.0% respectively. For composition by weight of the wastes brought from the roadside, the most generated is sand 30.0% followed by nylon, paper and food wastes at 23.0, 17.9 and 17.6% respectively. The average composition by weight of the wastes brought from the residential areas revealed that the most generated is the Nylon 27.1% followed by food wastes, sand and paper at 25.4, 17.4 and 17.3% respectively.

Figure 4.1 shows the mean monthly weight of wastes as brought from the three

Table 4.1: Percentage of average characterized recyclable solid wastes components at various locations

Parameter	Market %	Roadside %	Residential %	Total %
Paper	15.7	17.9	17.3	17.3
Nylon	28.5	22.6	27.1	26.6
Food Wastes	30.1	17.6	25.4	25.0
Leaves & Garden Trimmings	3.5	1.9	2.8	2.8
Plastics	1.7	1.5	1.6	1.6
Textiles	3.4	1.8	5.4	3.6
Wood	0.9	0.8	0.9	0.9
Metals	0.2	0.0	0.1	0.1
Cans/Tins	0.0	0.6	0.3	0.3
Sand	10.2	30.1	17.4	18.9
Ash	2.8	2.8	0.8	1.9
Bottles	2.1	1.5	0.5	0.8
Tyre	0.0	0.0	0.4	0.1
Battery	0.0	0.0	0.0	0.0
Wire	0.1	0.1	0.0	0.0
Bones	0.5	0.5	0.0	0.1
POP	0.3	0.3	0.0	0.1
Total	100.0	`100.0	100.0	100.0

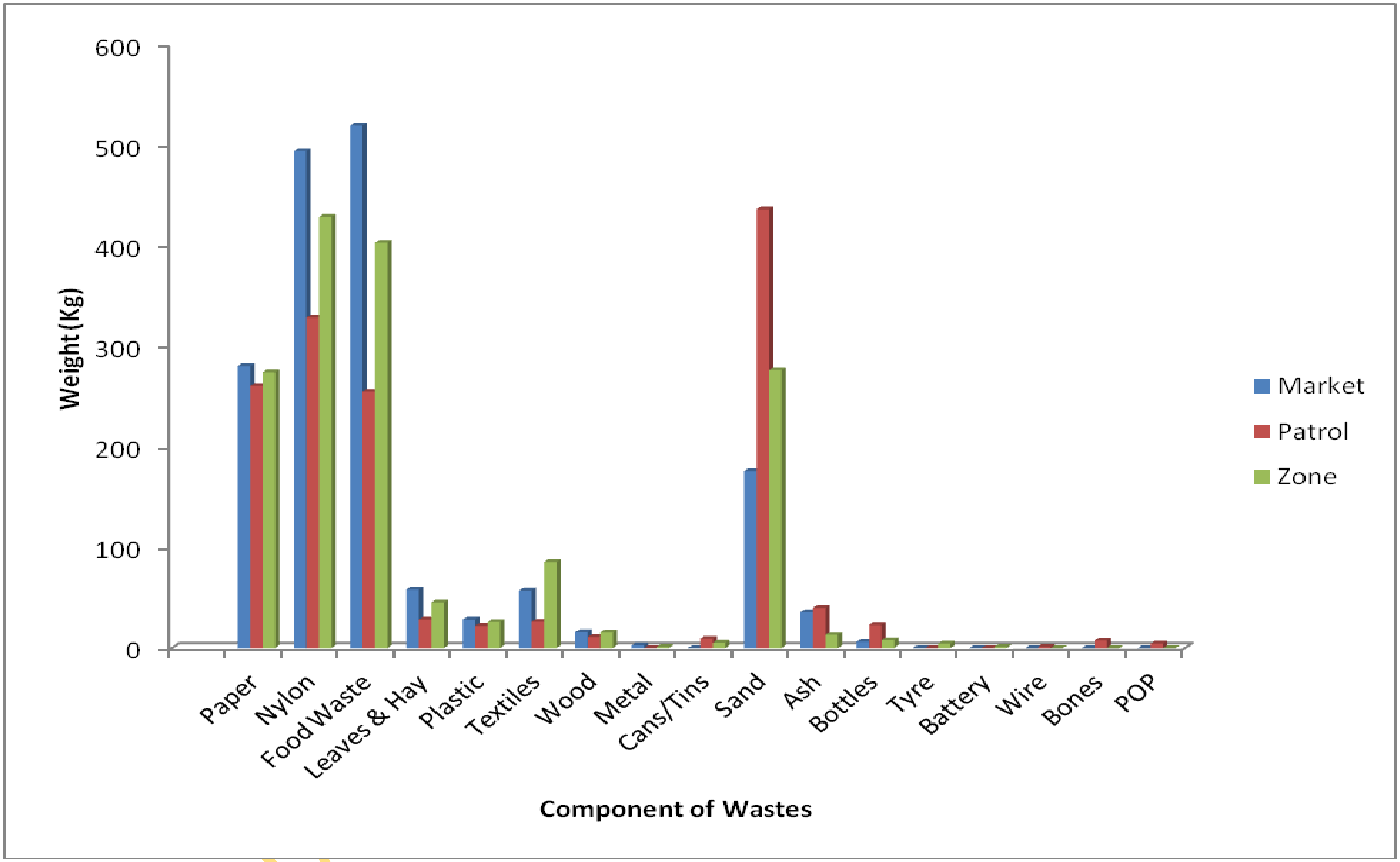


Fig 4.1: Mean monthly weight of solid waste components as characterized from collection trucks from the three locations

locations by waste disposal vehicles which were randomly selected and characterized in kilograms. From the wastes brought from the market, food wastes was the most generated component of solid wastes with a value of 520 kg; this was followed by nylon, paper and sand with 494, 280 and 176 kg respectively. From the roadside, sand as the most generated with 436 kg followed by nylon, paper and food wastes with 328, 260 and 255 kg. From the residential areas, nylon was the most generated with 429 kg followed by food wastes, sand and paper with 403, 276 and 274 kg respectively.

From the above, it was revealed that paper, plastics, food waste and garden trimmings were the major components of the solid waste generated in the three locations. Percentage composition of the total waste generated at the three locations combined revealed that food waste was the most generated followed by nylon, paper, sand, textiles and garden trimmings in that order. The percentage composition of the waste components was different from the observation of Kundell, (1996) composition of municipal solid waste as: paper and paperboard, yard waste, plastic, metals, wood, glass, food waste and miscellaneous in-organics. This also disagrees with a previous research work by Hoornweg *et al*, (1999) where they found that wastes streams are over 50% organic materials in developing countries. The reason for the difference might be as a result of the practice of feeding domestic animals with the food wastes, which will not allow the organic wastes to get to the open dump. It could also be observed that the percentage components of wastes that actually arrive at the dumping site were very much lower than the findings of Adewumi et al, (2005) and Adewumi and Babatola (2009). This definitely connotes that there are a lot of recycling activities going on in Akure Township.

The waste generated depended to a large extent on the nature of activities in place, this was revealed by the results of the survey of the different locations. Food wastes was the most generated component of solid wastes at the market, at the Residential/Residential; while at the roadside; sand was the most generated. This shows that there is a significant difference in the percentage composition of the waste generated across the locations which is in agreement with Khan and Ahsan, (2003) who stated that the composition of wastes from commercial areas depends upon the nature of activities.

Generally, the amount of the biodegradable components and organic materials at all locations were below 60% which disagrees with the findings of Fakere et-al (2012) that most of the solid wastes in Akure are putrescibles. This might be as a result of the fact that the residents who patronize the Waste Management Agency are high income earners. According to Ogwueleka (2009), high-income earners consume more of packaged products that give rise to a higher percentage of non-biodegradables (inorganic materials) like metals, plastics, glass /ceramics. This also is in disagreement with Dhussa and Varsney (2000), who stated that developing countries generally have high food and yard wastes as compared to developed countries with a large fraction of paper and plastic contents that can be recycled. The low volume of the garden trimmings generated at the three locations was as a result of the fact that Akure is getting more urbanized. Overall, the volume of waste generated is enormous and the composition makes recycling and composting to be viable waste management options in the town. This is as evidenced in the establishment of a recycling Plant which presently is under-utilized making open burning the major method of waste management.

4.1.2 Comparison of the physico-chemical components of solid waste generated in the three locations

Table 4.2 shows that the weight of the solid waste generated daily varied significantly at the three locations except paper which was uniformly generated at the three locations. From the wastes brought from the market; food wastes, nylon, paper and sand were highly generated daily with mean daily values of 519.5±49.2 kg for food wastes, 493.8±46.8 kg for nylon, 280.3±26.5 kg for paper and 175.6±17.0 kg for sand. From the wastes brought from the roadside; sand, nylon, paper and food wastes were highly generated daily with mean daily values of 436.0±39.7 kg for sand, 328.3±29.9 kg for nylon, 260.3±23.7 kg for paper and 254.9±23.3 kg for food wastes. From the wastes brought from the residential areas; nylon, food wastes, sand and paper were highly generated daily with mean daily values of 436.0±65.3 kg for nylon, 402.8±57.1 kg for food wastes, 276.0±39.1 kg for sand and 274.0±39.1 kg for paper.

Table 4.2: Comparison of various components by weight of solid wastes generated from the study sites

Component	Location	Mean (Kg)	SD	P- Value (<0.05)
Paper	Market	280.3	26.5	0.65
	Roadside	260.3	23.7	
	Residential	274.0	39.1	
Nylon	Market	493.8	46.8	0.00
	Roadside	328.3	29.9	
	Residential	436.00	65.3	
Food Wastes	Market	519.5	49.2	0.00
	Roadside	254.8	23.3	
	Residential	402.8	57.1	
Leaves & Garden Trimmings	Market	57.8	5.4	0.00
	Roadside	28.3	2.9	
	Residential	45.0	6.5	
Plastic	Market	28.0	2.9	0.03
	Roadside	21.5	2.1	
	Residential	25.8	3.5	
Textiles	Market	56.8	5.4	0.00
	Roadside	26.0	2.5	
	Residential	85.3	12.0	
Wood	Market	15.8	1.1	0.05
	Roadside	10.6	1.5	
	Residential	15.5	4.4	
Metals	Market	2.6	0.7	0.00
	Roadside	0.0	0.0	
	Residential	1.1	0.3	
Cans/Tins	Market	0.0	0.0	0.00
	Roadside	9.0	0.8	
	Residential	4.9	0.9	
Sand	Market	175.6	17.0	0.00
	Roadside	436.0	39.7	
	Residential	276.0	39.1	
Ash	Market	35.0	2.9	0.00
	Roadside	39.5	3.7	
	Residential	12.8	1.7	

Table 4.2 continued: Comparison of various components by weight of solid wastes generated from the study sites

Component	Location	Mean (Kg)	SD	P- Value (<0.05)
Bottles	Market	6.0	0.7	
	Roadside	22.5	2.2	0.00
	Residential	7.5	1.3	
Tyre	Market	0.0	0.0	
	Roadside	0.0	0.0	0.00
	Residential	4.0	0.4	
Battery	Market	0.0	0.0	
	Roadside	0.0	0.0	0.00
	Residential	1.1	0.3	
Wire	Market	0.0	0.0	
	Roadside	1.0	0.1	0.00
	Residential	0.0	0.0	
Bones	Market	0.0	0.0	
	Roadside	7.1	0.7	0.00
	Residential	0.0	0.0	
POP	Market	0.0	0.0	
	Roadside	4.0	2.1	0.00
	Residential	0.0	0.7	

4.1.3 Physico-chemical conditions for efficient composting of food waste

Table 4.3 shows that the mean monthly value of the characteristics of all the physico-chemical components of the food wastes generated in three months at the three locations. The concentrations did not vary at the three locations except the values of density which were 229.3+13.8, 247.1+5.9 and 248.5+4.9 kg/m^3 from market, roadside and residential areas respectively. The situation was not the same for the physico-chemical parameters needed for efficient composting as they varied at the three locations as presented in Table 4.4. The C: N ratio at roadside, residential and market were 15.1:1, 25.5:1 and 20.1:1 respectively. The Moisture Content for roadside, residential and market were, 44.1+0.9, 41.3+1.0 and 42.5+0.6% respectively. The pH values for roadside, residential and market were 4.8+0.5, 5.1+1.0 and 4.9+0.6 respectively. There was significant difference in the values of the C: N ratio for the roadside wastes (15.1:1), residential/ zone wastes (25.5:1) and market wastes (20.1:1) respectively. The values except that of the residential/ zone wastes were below the acceptable standards according to the guideline limits given by Haug et al, (1994). The low value associated with roadside wastes could be as a result of the fact that since it is an office environment, the volume of food wastes is low because most people take their wastes back home which is a good source of food waste. There is a high mean value of nitrogen but the source of organic carbon from other food sources is low, therefore there is need for increase in the food sources with high carbon content at the Roadside environment. For Moisture Content; the values were all below the acceptable standards this might be associated with the fact that since the wastes are not collected immediately, the moisture content would have reduced. There is therefore need to increase the moisture content to the optimum value of 55% by adding water to the biodegradable waste. There was no significant difference also for the pH obtained at the three locations. The values were all below the acceptable standards. The pH would affect the rate of biological conversion during composting; there is therefore the need to increase the pH of the biodegradable waste at the three locations in order to have a good source of compost from the three locations. Therefore, although the biodegradable waste generated in these areas can be

Table 4.3: Comparison of physico-chemical characteristics of organic wastes from the three locations

Parameter	Location	Mean	SD	P- Value (<0.05)
Nitrogen (%)	Market	3.4	0.7	
	Roadside	2.1	0.8	0.15
	Residential	2.7	0.6	
Phosphorus (%)	Market	0.08	0.04	
	Roadside	0.13	0.14	0.58
	Residential	0.05	0.03	
Carbon (%)	Market	53.09	1.5	
	Roadside	53.08	1.8	0.99
	Residential	53.24	1.4	
pH	Market	4.8	0.5	
	Roadside	5.1	1.0	0.88
	Residential	4.9	0.6	
Moisture Content (%)	Market	64.1	0.9	
	Roadside	71.7	5.9	0.50
	Residential	72.5	1.6	
Density (kg/m^3)	Market	229.3	13.8	
	Roadside	247.1	5.9	0.00
	Residential	248.5	4.9	

Table 4.4: A comparison of physico-chemical conditions required for composting of biodegradable wastes

Parameter	Roadside	Residential	Market	Standard	Reference
C:N Ratio	15.1:1	25.5 : 1	20.1:1	25:1 - 30:1	(Haug et al, 1994)
Moisture Content (%)	64.1±0.9	71.73±5.9	72.5±1.6	50.0 – 60.0	(Haug et al, 1994)
pH	4.77±0.5	5.1±1.0	4.9±0.6	6.5 – 8.0	(Haug et al, 1994)

/

a source of compost in the solid wastes facility, there is need for pretreatment of the biodegradable waste.

4.2 Estimation of the carbon emissions potential

4.2.1 Waste collection trucks coming to the waste management facility

The number of trucks coming to the Waste Facility from the three locations is reflected in Figure 4.2. The highest number of trucks that came to the Facility was 837 in the month of August with 50, 250 and 572 for market, roadside and residential respectively. While the lowest number of trucks were 704 in the month of march with 31, 256 and 417 for market, roadside and residential respectively.

4.2.2 Comparison of Degradable Organic Carbon components per season for a year

Figure 4.3 reflects the components of the degradable organic carbon generated in the facility per season for a year in kilograms for the three locations. The total weights generated for paper and textile, food waste, leaves and garden trimmings and wood were 21,685,236, 23,384,682, 2,607,321 and 901,430kg; 15,880,890, 17,173,596, 1,914,879 and 661,099kg for the wet season and dry season respectively.

4.2.3 Estimation of methane emission from the waste facility

A. Estimation of methane emission using IPCC default method and National FOD method

In most developing countries, the dominant disposal method is open dumping compared to the extensive use of sanitary landfills in the western countries. This is due to lack of finances of the government, rapid population growth, and increasing urbanization (Visvanathan, 2006; Barton *et al*, 2008). The situation is not different in Nigeria as evidenced in the waste disposal method of open dumping in the study area.

The amount of methane emitted from a certain site is dependent on several factors including non-chemical properties e.g. size of population whose solid waste is disposed of, quantity and type of waste as well as chemical parameters such as composition and fraction of degradable organic carbon of waste, moisture, pH-value, temperature at the site (Gyalpo, 2008).

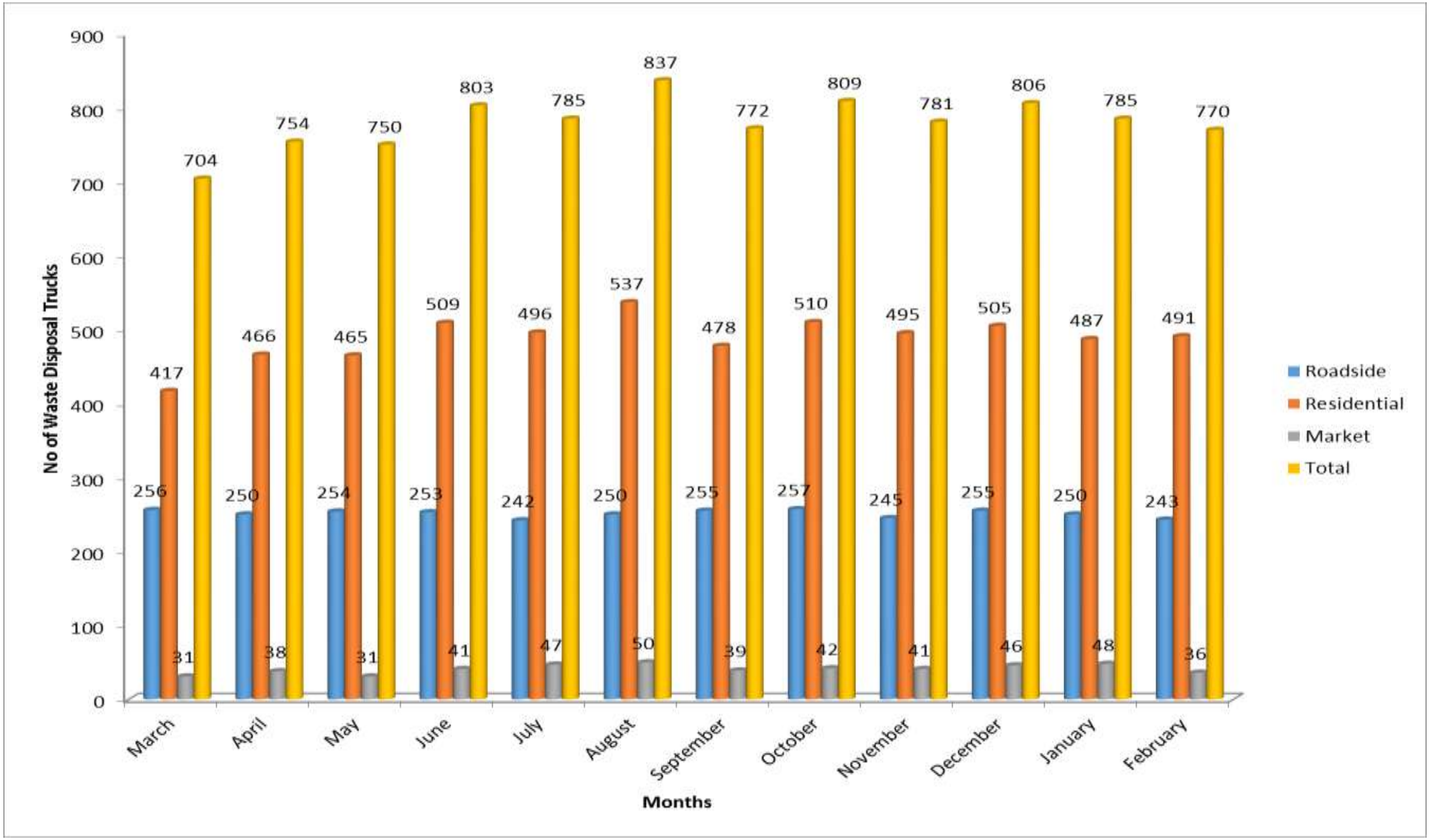


Fig 4.2: Number of waste collection trucks coming to waste facility by location for a year

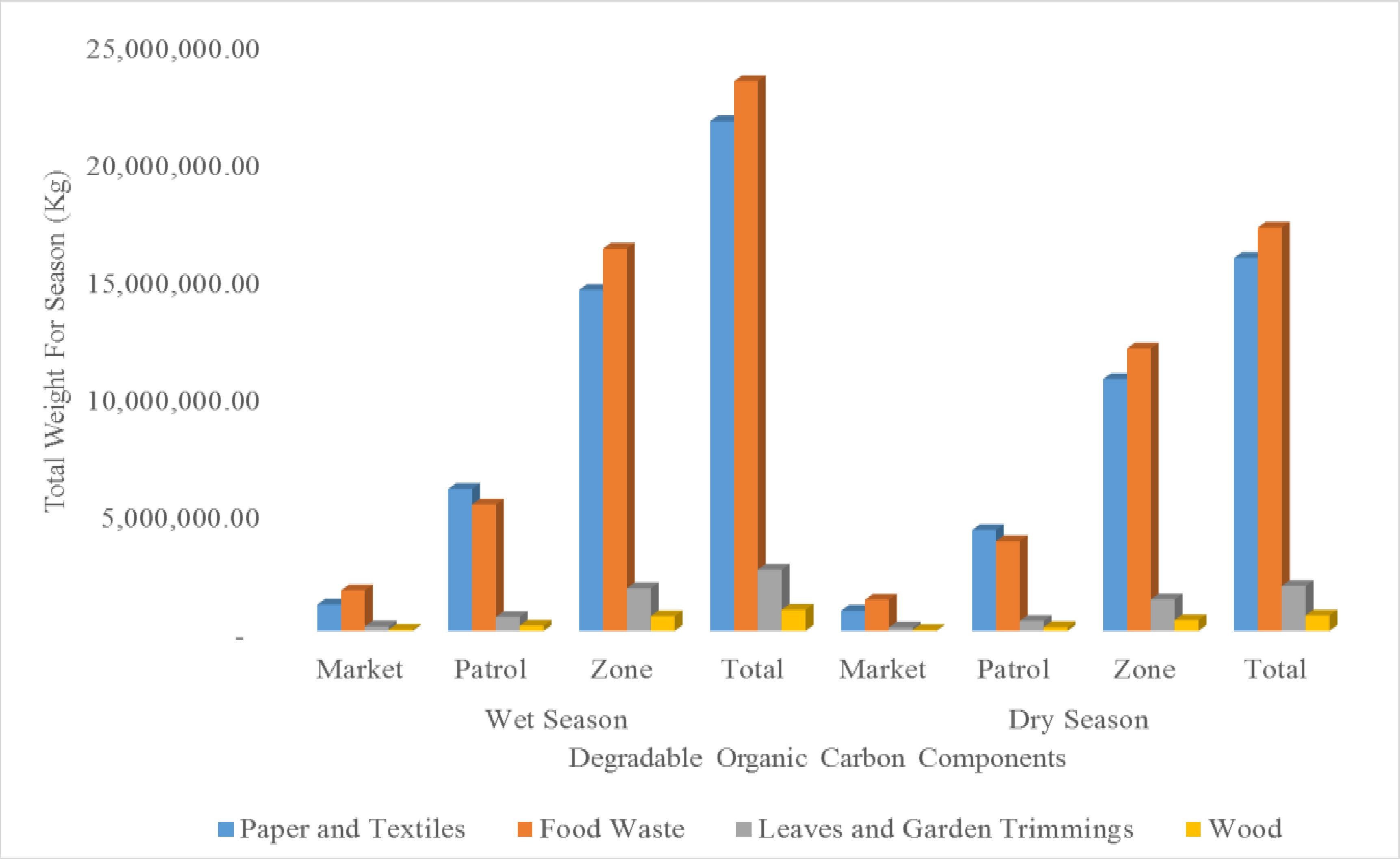


Fig 4.3: Total Degradable Organic Carbon components generated at the waste facility per seasons for a year

Various studies have been carried out to quantify methane emission from open dumps, especially in India and Thailand, but scanty information exist in Nigeria on the subject matter. The methane emission from the study area as shown by Tables 4.5 and 4.6 revealed that the calculation by the default method was 80.8 and 42.3 Gg/yr in the wet and dry seasons respectively, whereas using the National First Order Decay (FOD) method, the methane emission was 2.9 and 1.5 Gg/yr in the wet and dry seasons respectively, which reflects a seasonal variation in the estimated methane emissions.

As reflected in the results the estimations by the empirical methods were not different. This was in agreement with Kumar *et al* (2004) who argued that the values of the default method were higher due to the assumption that all potential methane is emitted in the same year in which the solid wastes were disposed of. Therefore, the values estimated by the FOD method are more realistic. This method Kumar *et al* (2004) proposed assumes that the decomposition of organic matter takes place in two phases.

Large differences of methane estimations from open dumps from developing countries are found in the literature. The estimations have to be handled with care as lot of uncertainties exist because regarding open dumps, there are several factors which have to be considered such as the specific micro which hinders or enhances the anaerobic decomposition of organic waste. Furthermore, climatic conditions, age, and gas migration lead to wide variation of measurement results. Thus uncertainties are associated with the degree of factors affecting the methane emission estimation (Doorn *et al*, 2000)

4.3 Estimation of carbon dioxide emission potential at the dumping site using the Intergovernmental Panel on Climate Change (IPCC), 2006 guidelines

The carbon-dioxide emission potential estimated from the study area was 1.2 Gg/yr as shown by Table 4.7. The value was not in agreement with that of Nabegu, (2011) who estimated 33.2 Gg/yr. This might have been as a result of the fact that the study was carried out for about five months which is March to July. In general, the total generation of CO_2 based on the current data for Nigeria is low when compared to emissions from the United States and other developed economies. However, Nigeria’s gross emissions may approach those of these countries if its population continues to grow at the current rate of 3.5% per annum since per capita emissions is also likely to increase and nothing

Table 4.5: Estimation of seasonal variation of methane emission from the solid waste facility using default IPCC methodology

Season	Methane Emissions (Gg/Yr)	MSW_T	MSW_F	MCF	DOC	DOC_F	F	16/12-R	1- OX
Wet Season	80.8	43,903	0.7	0.4	0.0128	0.77	0.5	1.333	1
Dry Season	42.3	30,979	0.7	0.4	0.0095	0.77	0.5	1.333	1

- **Methane emissions** $(\mathrm{Gg\ Yr^{-1}}) = \left\{ \mathrm{MSW_T \ x\ MSW_F\ x\ MCF\ x\ DOC\ x\ DOC_F\ x\ F\ x} \frac{16}{12} - \mathrm{R} \right\} \mathrm{x} \{ 1 - \mathrm{O_x} \}$
- **MSW_T** = 387,087 X 0.53Kg/Person/Day X 214/1000 (Wet Season)
- **MSW_T** = 387,087 X 0.53Kg/Person/Day X 151/1000 (Dry Season)
    - **Approximate Population of Akure** = 387,087
    - **Wastes Generation Rate for Akure** = 0.53Kg/Person/Day (Data from Ondo State Waste Management Agency)
- **DOC=** (0.4(37,566,126.00)+0.17(40,558,278.00)+0.15(4,522,200.00)+0.3(1,562,528.40))X 10^{-9}

Table 4.6: Estimation of seasonal variation of methane emission from the solid waste facility using the Nationally Adjusted FOD-model

Season	Methane Emissions (Gg/Yr)	K	MSW_T	MSW_F	MCF	DOC	DOC_F	F	$e^{-0.05(2013-2012)}$
Wet Season	2.9	0.05	43,903	0.7	0.4	0.0128	0.77	0.5	0.9512
Dry Season	1.5	0.05	30,979	0.7	0.4	0.0095	0.77	0.5	0.9512

- **Methane emissions** $(Gg\ Yr^{-1}) = K \times MSW_{T(2013)} \times MSW_{F(2013)} \times MCF_{(2013)} \times DOC_{(2013)} \times DOC_{F(2013)} \times F \times e^{-K(2013-2012)}$
- **MSW_T** = 387,087 X 0.53Kg/Person/Day X 214/1000 (Wet Season)
- **MSW_T** = 387,087 X 0.53Kg/Person/Day X 151/1000 (Dry Season)
    - **Approximate Population of Akure** = 387,087
    - **Wastes Generation Rate for Akure** = 0.53Kg/Person/Day (Data from Ondo State Waste Management Agency)

DOC= $(0.4(37{,}566{,}126.00)+0.17(40{,}558{,}278.00)+0.15(4{,}522{,}200.00)+0.3(1{,}562{,}528.40)) \times 10^{-9}$

Table 4.7: Estimation of carbon dioxide emissions from the solid waste facility using default IPCC methodology

Carbon-dioxide Emissions (Gg/Yr)	**Component of Waste**	**MSW (Gg)**	**WF_j**	**dm_j**	**CF_j**	**FCF_j**	**OF_j**	**(WF_j * dm_j * CFj *FCFj *OF_j)**	**44/ 12**
	Paper	30.30	0.1747	0.90	0.44	0.01	0.58	0.000401238	
	Nylon + Plastic + Battery	47.70	0.2750	1.00	0.00	0.00	0.58	0.000000000	
	Biodegradable Waste	40.56	0.2338	0.40	0.38	0.00	0.58	0.000000000	
	Garden Trimmings	4.52	0.0261	0.40	0.49	0.00	0.58	0.000000000	
	Textiles	7.26	0.0419	0.80	0.30	0.20	0.58	0.001165772	
	Wood	1.56	0.0090	0.85	0.50	0.00	0.58	0.000000000	
	Metal + Cans/Tins/Wire	0.79	0.0046	1.00	0.00	0.00	0.58	0.000000000	
	Sand	36.18	0.2086	0.90	0.00	0.00	0.58	0.000000000	
	Ash	2.53	0.0146	0.90	0.00	0.00	0.58	0.000000000	
	Bottles	1.37	0.0079	1.00	0.00	0.00	0.58	0.000000000	
	Rubber/Tyre	0.28	0.0016	0.84	0.47	0.67	0.58	0.000250165	
	Bones	0.26	0.0015	0.90	0.00	0.00	0.58	0.000000000	
	POP	0.15	0.0008	0.90	0.00	0.00	0.58	0.000000000	
1.2		**173.46**	**1.0000**					**0.001817176**	**3.6667**

is done with respect to mitigating the emissions emanating from the solid wastes sector.

4.4 Overall emissions under present conditions

Table 4.8 shows the total quantity of wastes generated in the Facility in Tons. The total weight generated for a year was 44,708, 33,403, 52,576, 4985 and 8007 Tons for biodegradable waste, paper, plastics, leaves and garden trimmings and textiles respectively. The weight of Municipal Solid Wastes Component was converted from Kilograms to Tons to be utilized in the USEPA for Waste Reduction Model (WARM), (USEPA, 2009).

Therefore

$$\mathbf{Ex} = 33402.93 * 1.52 + 52575.71 * 0.04 + 875.96 * 0.04 + 1513.39 * 0.04 + 44707.85 * 1.54 + 4984.87 * (-0.16) + 311.78 * 0.04 + 8006.64 * 0.04 + 2787.20 * 0.04 + 1722.39 * (-0.83)$$

$$\mathbf{Ex} = 50772.45 + 2103.03 + 35.04 + 60.53 + 68850.09 - 797.57 + 12.47 + 320.27 + 111.49 - 1429.58$$

$$\mathbf{Ex} = 119{,}938\ \mathrm{MtCO_2eq}$$

4.5 Municipal Solid Waste (MSW) Management and Green House Gases Mitigation in the Solid Waste Disposal Facility for Akure.

Table 4.9 shows the summary of the scenario development for waste disposal practices and GHG mitigation. It summarizes the total of Greenhouse emissions that could have been prevented if the under listed Municipal Solid Waste Management Practices were adopted.

4.5.1 Composting

It is assumed that the biodegradable organic content from the MSW is completely stabilized by the aerobic windrow method and used as manure. Biological conversion factor for composting is assumed as 0.084 for GHG emission calculation. It was estimated that around 3,755 Mt CO$_2$ will be emanated from the complete biological conversion of organic components from the MSW under aerobic conditions. But generally, composting processes will be extended between 30 and 45 days until the achievement of C/N ratio of less than 20, since the complete biological

Table 4.8: Total waste composition from the three locations for a year in Tonnes

Waste Component	**Distribution %**	**Total Quantity Tonnes/Year**
Biodegradable Waste	23.4	44708
Paper	17.5	33403
Plastic	27.5	52576
Leaves & Hay	2.6	4985
Textiles	4.2	8007
Wood	0.9	1722
Metal	0.5	876
Bottles	0.8	1513
Rubber	0.2	312
Inert	22.5	43106
Total	**100.0**	**191208**

Table 4.9: Scenario development for waste disposal practices and GHG mitigation

Waste Management Option	Waste Quantity (Kg)	Conversion Factor*	Correction factor	GHG Emissions ($MtCO_2$)
Aerobic Composting (AC)	44708	0.084	50% (0.5)	1878
Anaerobic Digestion (AD)	Organic = (Biodegradable Wastes)	0.029	70% (0.7)	908
Waste Recycling				
Paper	33403	0.6	100% (1.0)	20042
Nylon + Plastic + Battery	52576	0.3		15773
Glass/Bottles	1513	4.0		6054
Metal + Cans/Tins/Wire	876	0.08		70
AC + Waste Recycling	**131,563 (Organic + Recyclables)**	-		**43816**
AD + Waste Recycling		-		**42846**

Note: * The conversion factor from USEPA, 2006 and IPCC, 2006 conversion of carbon content will take a long time. Hence the correction factor of 0.5 is applied in the GHG emission calculation assuming that only 50% of organic content is processed/converted under composting technology in the field. Finally, around 1,878 Mt CO_2 was estimated to be released from the composting process and the remaining carbon will be applied to the 'Carbon Sink Soil'.

Since the CO_2 from the biodegradable organic is considered as biogenic, the emission of 1,878 Mt CO_2 will not be considered as mitigation of GHG. But the composting of biodegradable organics will avoid the uncontrolled dumping of wastes in open dumps, which is considered to be the major setback for developing countries like Nigeria and continuous source of methane emissions.

4.5.2 Anaerobic digestion

Anaerobic treatment of organic fraction is considered for mitigating GHG emissions from the MSW. The organic conversion factor of 0.029 along with the correction factor of 0.7 (70% of organic fraction converted into biogas) is considered to calculate equivalent CO_2 emission. It is estimated that 908 MtCO_2 will be released at the end of anaerobic degradation and the digestate can be applied to the 'Carbon Sink Soil' with proper pre-treatment. The methane from the anaerobic digester which has around 21 times the Global Warming Potential (GWP) than the produced $CO_{2,}$ can be used as fuel for energy production that will in turn reduce the consumption of fossil fuels. The digestate from the anaerobic reactor can be applied to the 'Carbon sink Soils' as manure after proper treatment.

4.5.3 Recycling

In recycling, it is considered that the valuable materials from the waste streams were source segregated and 100% recycled to reduce the raw material consumption. The conversion factors considered for paper, plastics, glass and metal were 0.6, 0.3, 4.0 and 0.08 respectively. Cumulative of 41,938 MtCO_2 can be reduced by recycling of materials by 100% from the waste stream. Recycling of waste further reduces GHG emissions through lower energy demand for production (avoided fossil fuels) and by substitution of recycled feed stocks for virgin materials.

4.5.4 Total GHG emission reduction from the waste management practices.

As presented in Table 4.9, the Aerobic Composting for Organic waste and recycling of valuables together will reduce the emission of **43,816 MtCO$_2$eq** as compared to **119,938 MtCO$_2$eq** earlier calculated. On the other hand, anaerobic digestion for organic waste along with proper recycling strategy will reduce the emission of **42,846 MtCO$_2$eq** into the atmosphere compared to **119,938 MtCO$_2$eq** earlier calculated.

4.6 Variations in wastes generation across seasons

Table 4.10 shows the variations in total wastes generation between the months of March to September, 2013 which represented the wet season and the months of October, 2013 to February 2014 which represented the dry season at the solid wastes management facility. From the wastes brought from all locations, nylon and plastic was the most generated component of solid wastes with 9,159,995.0 ± 8,453,005.4 and 6,777,621.3 ± 6,313,977.0 kg in the wet and dry seasons with no significant difference; this was followed by food waste, paper and textiles with 7,794,894.0 ± 7,569,909.7 and 5,724,532.0 ± 5,596,562.0 kg; 5,834,005.0 ± 5,079,633.8 and 4,266,871.0 ± 3,745,337.8 kg and 1,785,388.8 ± 1,394,407.0 and 1,320,720.2 ± 1,026,759.0 kg in the wet and dry seasons respectively and all with no significant difference.

From the above, it was revealed that more wastes were brought to the facility during the wet season than the dry season although with no significant difference, although this does not translate to increase in the emission of carbon dioxide. This can be adduced to the fact that during the wet season, there is high humidity as indicated in Table 4.11 which does not encourage burning thus preventing emission of carbon dioxide, while the temperature is higher in the dry season thus encouraging burning which leaves to higher emissions as shown in Table 4.12. It could also be observed that the standard deviation of the distribution of wastes generated were very high because the wastes were not evenly generated from the three locations.

Table 4.10: Variations in waste generation across seasons

Component	Wet Season		Dry Season		P- Value (<0.05)
	Weight (kg)	**SD**	**Weight (kg)**	**SD**	
Paper	5,834,005.0	5,079633.8	4,266,871.0	3,745,337.8	0.69
Nylon & Plastics	9,159,995.0	8,453,005.4	6,777,621.3	6,313,977.0	0.67
Food Waste	7,794,894.0	7,569,909.7	5,724,532.0	5,596,562.0	0.72
Leaves and Hay	869,107.0	846,914.9	638,293.0	626,156.8	0.72
Textiles	1,785,388.8	1,394,407.0	1,320,720.2	1,026,759.0	0.79
Wood	300,476.5	293,405.3	220,366.3	216,941.7	0.72
Metal	22,426.3	17,026.4	16,518.5	12,664.8	0.80
Can and Tins	129,212.0	111,946.9	93,641.0	81,254.9	0.68
Bottles	265,680.6	229,485.2	191,959.4	163,136.1	0.67
Tyre	93,920.1	54,224.8	69,380.4	40,056.8	0.84
Battery	24,500.9	14,145.6	18,099.2	10,449.6	0.84
Wire	12,498.5	7,216.0	8,876.8	5,125.0	0.83
POP	28,336.0	23,836.0	25,120.0	20,125.0	0.83

*The period of wet season was from March to September, 2013 while that of Dry season was from October 2013 to February, 2014

4.7 Survey of temperature, relative humidity and carbon dioxide environmental levels from the waste management facility across seasonal variations

4.7.1 Variations in the relative humidity across seasons

Table 4.11 reflects the variations in the relative humidity in the seven locations across seasons. It showed that in the morning, there was variation of the relative humidity only at the overhead tank which were 84.9 ± 9.7 and 81.8 ± 7.8% for the wet and dry seasons respectively. At noon, there was variation at the overhead tank and gate house, which were 74.9 ± 12.6 and 52.9 ± 8.9%; 66.9 ±15.6 and 53.7 ± 5.4% for the wet and dry seasons respectively. At the afternoon, the relative humidity varied in all locations except the laboratory which were 66.5 ± 9.7 and 65.7±8.48% for the wet and dry seasons respectively.

4.7.2 Variations in the air temperature in the seven locations across seasons

Table 4.12 reflects the variations in the air temperature in the seven locations across seasons. It showed that in the morning, there was no variation of the air temperature in all locations for the wet and dry seasons respectively. At noon, there was only variation of the air temperature at the overhead tank which were 31.3 ± 5.1 and 35.4 ± 1.9 °C for the wet and dry seasons respectively. At the afternoon, the air temperature varied in the plastic recycling, overhead tank and sorting area with which were 30.7 ± 2.7 and 33.0 ± 1.7°C, 32.0 ± 3.4 and 36.0 ± 2.2°C and 32.7 ± 2.7 and 36.5 ± 2.1°C for the wet and dry seasons respectively.

4.7.3 Diurnal and seasonal variations in environmental carbon dioxide levels within the vicinity of the solid wastes management facility

Table 4.13 reflects the variations in the carbon dioxide levels in the seven locations across seasons. It showed that in the morning, there were no variations of the carbon dioxide levels in the laboratory, sorting area and gate house with values of 506.9 ± 71.1 and 537.0 ± 91.8 ppm; 450.6 ± 28.4 and 456.0 ± 10.8 ppm; 442.6 ± 19.4 and 448.0 ± 10.4 ppm, for the wet and dry seasons respectively. At noon, there were no variations of the carbon dioxide levels in the plastic recycling, overhead tank and gate house with values of 415.0 ± 15.9 and 458.5 ± 44.1 ppm; 427.3 ± 20.5 and 443.5 ± 10.4 ppm; 425.6 ± 14.3 and 438.0 ± 7.1 ppm for the wet and dry seasons respectively.

Table 4.11: Variations in relative humidity in various locations across seasons

Parameter (%)	Location	Wet Season		Dry Season		P – Value (<0.05)
		Mean	SD	Mean	SD	
Relative Humidity Morning	Laboratory	76.8	6.3	83.6	6.1	0.09
	Organic Fertilizer	84.1	6.8	86.9	7.3	0.29
	Plastic Recycling	81.9	5.7	86.0	9.6	0.24
	Over Head Tank	84.9	9.7	81.8	7.8	0.05
	Sorting Area	83.4	6.3	82.9	9.5	0.84
	Gate House	81.0	8.5	75.9	14.0	0.23
	Outside	78.6	10.4	77.1	12.6	0.47
Relative Humidity Noon	Laboratory	68.6	3.7	74.5	7.2	0.14
	Organic Fertilizer	71.0	12.6	65.8	7.3	0.18
	Plastic Recycling	68.4	12.9	60.6	5.5	0.17
	Over Head Tank	74.9	12.6	52.9	8.9	0.00
	Sorting Area	66.5	17.1	57.9	9.4	0.21
	Gate House	66.9	15.9	53.7	5.4	0.03
	Outside	68.0	15.4	54.2	8.2	0.01
Relative Humidity Afternoon	Laboratory	66.5	9.7	65.7	8.4	0.88
	Organic Fertilizer	67.2	13.4	55.8	3.1	0.04
	Plastic Recycling	65.8	12.1	53.8	3.4	0.04
	Over Head Tank	67.8	14.9	46.1	3.6	0.00
	Sorting Area	64.4	14.2	45.7	3.7	0.02
	Gate House	64.0	12.0	46.5	6.7	0.00
	Outside	61.7	11.3	49.9	6.8	0.05

Table 4.12: Variations in air temperature in various locations across seasons

Parameter (^{o}C)	Location	Wet Season		Dry Season		P – Value
		Mean	SD	Mean	SD	(<0.05)
Air Temperature Morning	Laboratory	28.4	1.6	28.0	1.1	0.56
	Organic Fertilizer	26.8	1.5	27.0	1.7	0.79
	Plastic Recycling	27.1	1.4	26.8	1.9	0.77
	Over Head Tank	28.4	2.3	28.0	1.9	0.40
	Sorting Area	28.1	2.5	28.6	1.5	0.67
	Gate House	28.6	2.8	29.6	2.7	0.46
	Outside	28.6	2.8	29.0	2.5	0.62
Air Temperature Noon	Laboratory	30.7	1.8	30.3	1.7	0.76
	Organic Fertilizer	29.6	2.9	31.0	0.7	0.23
	Plastic Recycling	30.0	2.5	31.5	1.5	0.17
	Over Head Tank	31.3	5.1	35.4	1.9	0.05
	Sorting Area	32.1	4.2	34.4	2.0	0.22
	Gate House	33.2	5.3	35.6	2.2	0.39
	Outside	31.9	4.2	34.9	2.8	0.12
Air Temperature Afternoon	Laboratory	31.3	2.8	30.3	1.6	0.56
	Organic Fertilizer	30.3	2.9	31.8	1.1	0.13
	Plastic Recycling	30.7	2.7	33.0	1.8	0.04
	Over Head Tank	32.0	3.4	36.0	2.2	0.03
	Sorting Area	32.4	2.7	36.5	2.1	0.01
	Gate House	33.5	3.1	36.0	1.8	0.15
	Outside	33.4	3.1	36.2	2.2	0.02

Table 4.13: Variations in carbon dioxide levels in various locations across seasons

Parameter (ppm)	Location	Wet Season		Dry Season		P – Value (<0.05)	Air Quality Regulatory Limits (ppm)
		Mean	SD	Mean	SD		
Carbon Dioxide Morning	Laboratory	506.9	71.1	537.0	91.8	0.48	400
	Organic Fertilizer	424.0	11.7	467.0	34.9	0.01	
	Plastic Recycling	428.2	13.6	446.0	8.5	0.01	
	Over Head Tank	433.3	17.4	456.0	13.3	0.00	
	Sorting Area	450.6	28.4	456.0	10.8	0.63	
	Gate House	442.6	19.4	448.0	10.4	0.51	
	Outside	431.6	22.1	466.0	11.3	0.02	
Carbon Dioxide Noon	Laboratory	441.3	18.6	541.7	92.2	0.05	400
	Organic Fertilizer	412.7	11.1	452.7	23.7	0/01	
	Plastic Recycling	415.0	15.9	458.5	44.1	0.08	
	Over Head Tank	427.3	20.5	443.5	10.4	0.08	
	Sorting Area	414.0	14.0	456.5	12.7	0.00	
	Gate House	425.6	14.3	438.0	7.1	0.12	
	Outside	417.4	9.0	461.0	14.2	0.00	
Carbon Dioxide Afternoon	Laboratory	441.7	35.8	630.0	124.5	0.01	400
	Organic Fertilizer	418.7	17.2	467.0	51.0	0.05	
	Plastic Recycling	412.3	18.9	510.0	70.0	0.02	
	Over Head Tank	428.7	33.9	444.0	20.0	0.04	
	Sorting Area	421.7	11.9	455.0	16.1	0.02	
	Gate House	434.3	45.3	438.0	7.2	0.79	
	Outside	407.3	11.3	461.0	17.4	0.00	

At the afternoon there was no variation of the carbon dioxide levels only at the gate house with values of 434.3 ± 45.3 and 438.0 ± 7.2 ppm for the wet and dry seasons respectively.

These reflect the variations in the carbon dioxide levels at the waste facility in Akure. The levels of CO_2 ranged between 407.3 and 506.9 ppm and in the wet season and 430.0 and 630.0 ppm in the dry season which shows that CO_2 concentration present in the atmosphere were above the regulatory limit of 400.0 ppm (FEPA, 1995). The atmospheric CO_2 data showed clear seasonal and diurnal variations. During the diurnal variation, the maximum CO_2 concentrations occurred in the morning during the wet season while it is otherwise during the dry Season. In the dry season, diurnal variation was caused by the fact that most of the burning was done during this period and it was usually more effective in the afternoons because of the dryness of the dump waste and increase in temperature which makes it more conducive for burning, thereby leading to the increase of the CO_2 concentration. This is contradictory to the results obtained from a study by Yashuhiro *et-al* (2007). This has great implications on the climate patterns as it has been established that approximately 45% of gas emitted from landfills is carbon dioxide and in terms of climate change it has global warming potential (GWP) of 1 (Gribben, 1986) .

4.8 Design of carbon dioxide extractor

4.8.1 Air flow and pipe design

In this context, the pipe size d, the flow rate Q, the air mean velocity V, and the pressure loss ΔP would be determined. In the determination of these, the following parameters would be utilized:

- Kinematic viscosity of air = 15.68×10^{-6} $kgm^{-1}s^{-1}$
- Air density (ρ) = 1.2 kg m^3
- Absolute viscosity of air = 1.983×10^{-5} kgm^{-1} s^{-1}
- Absolute pipe roughness of pvc (ks) = 0.0015mm
- Specific gravity of air (Sg) = 1.02
- Diameter of pipe = 0.1016meters (4 inches)

- Length of pipe = 0.30 meters (11.8 inches)

I. Determination of pipe diameter (d)

The determination of the pipe required to transport a given amount of fluid is the first step in designing a piping system. The relationship is given as follows:

$$d = \frac{0.73\sqrt{Q/Sg}}{\rho 0.33} \qquad (4.1)$$

Where

d= pipe inner diameter, m

Q = Flow rate, m^3/s

S_g = Fluid specific gravity, dimensionless

ρ= Fluid density, kg/m^3

II. Determination of volumetric flow rate (Q)

We have already chosen a specific pipe diameter d, therefore the volumetric flow rate Q, can be obtained from equation (4.1)

$$Q= \left(\frac{\rho 0.33 \times d}{0.73}\right)^2 \times Sg^{-1} \qquad (4.2)$$

Substituting the values given above into equation 4.2

Q = 0.0223 m^3 / s

3.3.2.3 Determination of pipe cross sectional area, A

$$A = \frac{\pi d^2}{4} \qquad (4.3)$$

$$A = \frac{\pi 0.1016^2}{4}$$

A = 0.0081 m^2

III. Determination of air velocity (V)

Since the air flow rate Q and the pipe diameter are known, the air velocity V can be calculated from the flow equation:

$$Q = AV \qquad (4.4)$$

Where

Q = volumetric flow rate, m^3/s

A = cross sectional area of pipe, m^2

From eqn (4.4)

$$V = \frac{Q}{A} \qquad (4.5)$$

$$V = \frac{0.0223}{0.0081}$$

V = 2.6 m/s

IV. Pressure drop rate pipe (ΔP)

The magnitude of the loss in pipe depends on the flow conditions and it depends on the mean velocity of air flow V, the duct diameter d, and the kinematic viscosity of the air µ, it is expressed as a function of the Reynolds number Re which is given by

$$Re = \frac{V \times d}{\mu} \qquad (4.6)$$

$$Re = \frac{2.75 \times 0.1016}{15.68 \times 10^{\wedge}-6}$$

Re = 17,818

The flow with Reynolds number between 2,000 and 4000 is considered critical Residential, and flow with Reynolds number between 4,000 and 10,000 is called the transitional Residential and Reynolds number greater than 10,000 is referred to as the **Turbulent Flow.** Therefore from the result above, our air flow can be regarded as turbulent flow.

The pressure drop rate can be determined by an expression due to Colebrook and White (1939)

$$\Delta P = \frac{4f\rho Q^2}{(Dh)\, A^2} \qquad (4.7)$$

Where

ΔP = pressure drop rate, Pa m^{-1}

f = a dimensionless coefficient of friction

D_h = mean hydraulic diameter, mm

The D_h for a circular hollow pipe = 2r =d (4.8)

f can be gotten from the relation in Equation (4.9) given by Colebrook and White (1937 and 1939)

$$\frac{1}{\sqrt{f}} = -4 \log \left(\frac{Ks}{3.7d} + \frac{1.255}{Re\sqrt{f}} \right) \qquad (4.9)$$

Where Ks = absolute pipe roughness of PVC pipe, mm

$$\frac{1}{\sqrt{f}} = -4 \log \left(\frac{0.0015}{3.7(101.6)} + \frac{1.255}{17818\sqrt{f}} \right)$$

$f = 0.522$

Using Eqn. (4.7) ΔP can be determined equation,

$$\Delta P = \frac{4 \times 0.522 \times 1.2 \times 0.0223^{2}}{(101.6)\ 0.0081^{2}}$$

$\Delta P = 0.2 \text{ Pa m}^{-1}$

V. Determination of fan power (P_f)

Specific fan power is a parameter that quantifies the energy-efficiency of fan air movement systems. It is a measure of the electric power that is needed to drive a fan relative to the amount of air that is circulated through the fan.

It is not constant for a given fan but changes with both air flow rate and fan pressure rise.

Fan power = voltage supplied × current dissipated

$$P_f = VI \qquad (4.10)$$

Where: P_f = fan power

V = voltage

I = current

But, $V = IR$

$I = V/R$

Substitute $I = V/R$ into $P_f = VI$

$P_f = V^2/R$

From the electronic control system, the voltage supplied by 2 batteries of 6V each = 2 × 6 = 12V and the resistance of the resistor in the component is 146Ω

$P_f = V^2/R = 12^2/146 \quad = 144/146 \quad = 0.986\text{Watt} \quad \approx 1\text{Watt}$

4.8.2 Baking pan design

The baking pan is made from aluminum due to its high thermal conductivity and its ability to withstand high temperature without deformation. Aluminum baking pan keeps its properties for temperature lower than 800˚C and would not react with adsorbent at such temperature. The baking pan would be subjected to temperature between 450-500˚C in the oven. Figure 4.4 shows the baking pan.

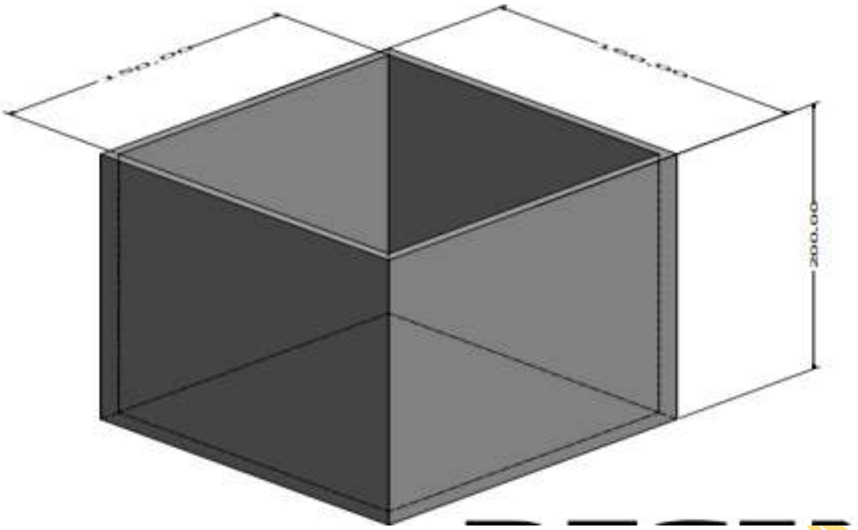


Fig 4. 4: Aluminum baking pan

4.8.3 Metal housing design

The metal housing which is the outermost structure of the machine is made from aluminum due to it being corrosion-resistant and light in weight. It would hold the adsorbent housing, the adsorbent, the inlet and outlet pipes, the directional fans, and the electrical unit.

Its dimension is as shown below:

Length, L = 533.4 mm
Breadth, W = 457.2mm
Height, H = 533.4mm

4.8.4 Costing of the carbon dioxide extractor

Table 4.14 presents the cost of the production of a unit of a Carbon Dioxide Extractor which is about Forty One Thousand Naira Only (N 41,000.00).

4.8.5 Electronic control system

The control system takes care of the resilience timing of the carbon dioxide extractor. It is programmed for the inlet fan to suck in air for ten minutes and the reaction between the sucked air and the adsorbent is allowed to occur for another ten minutes, blowing out of the carbon dioxide free air for another ten minutes by the outlet fan.

The electrical control system consists of the following;

a) Power supply (battery)

Table 4.14: Cost estimates for the fabrication of the carbon dioxide extractor

S/No	Component	Material	Specification	Qty	Rate (N)	Amount (N)
1	Metal Box Housing	Galvanized Iron Sheet (1 mm)	21x21x21”	5	1570.00	7850.00
2	Leg Support	Angle Iron	6x0.5x0.5”	4	600.00	2400.00
3	Hinges	Metal		2	50.00	100.00
4	Pipes	PVC	4”	2	400.00	800.00
5	Adsorbent Housing	Plastic	15x15x15”	1	1000.00	1000.00
6	Baking Pan	Aluminum	3.1x3.1x3.9”	3	450.00	1350.00
7	Electrical Components	Battery	3 Volts	2	1250.00	2500.00
		Controller	-	1	12000.00	12000.00
8	Workmanship (Fabrication)	- -	- -	1	5000.00	5000.00
9	Workmanship (Electrical)	-	-	1	10000.00	10000.00
	Total					**41000.00**

b) Controller
c) Fan driver (relay circuit)
d) Fan
e) Software

Figure 4.5 shows the block diagram various components of the system of the carbon dioxide extractor and how they are inter-related while Figure 4.6 shows the schematic diagram of the electronic circuit.

4.8.6 Power supply

The power supply consists of two electronic devices that supplies electric energy to the load (fan and controller). This is the main source supply of power of the system. It consists of two six (6) volts battery making a total of twelve (12) volts. They are secondary batteries (rechargeable battery) which can be discharged and recharged multiple times; the original composition of the electrodes can be restored by reverse current. It supplies twelve (12) volts directly to fan. The source of power supply which is a battery is shown in Plate 4.1

4.8.7 Voltage regulator

The voltage regulator is an LM7805, the LM7805 gets twelve (12) volts from the battery and outputs five (5) volts to the controller. It's a three-pin IC.
Pin 1 (input pin): the input pin accepts the incoming DC voltage (12 volts) from the battery
Pin 2 (Ground): Ground pin establishes the ground for the regulator
Pin 3 (output pin): the output pin is the regulated five (5) volts DC supplied to the controller. The regulator is reflected in Figure 4.7 while Table 4.15 shows the voltage regulation of the device.

4.8.8 Electronic micro controller

The micro-controller serves as the main control of the system; it consists of a processor core, programed memory and programmable input/output peripherals. It is designed for embedded applications. The compilers and assemblers in it are used to convert high –level language (mikroC PRO for PIC) and assembler's language codes into a compact machine code for storage in the controller's memory. The programme

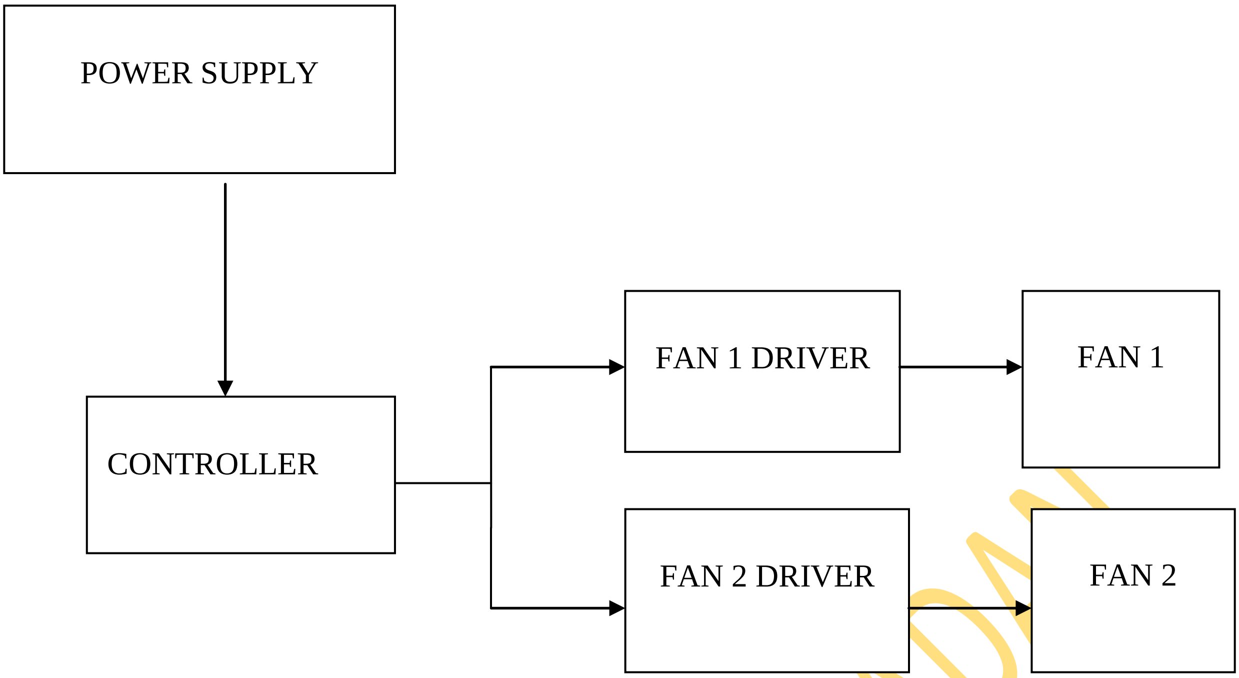


Fig 4.5: Block diagram of the system of the components of the carbon dioxide extractor

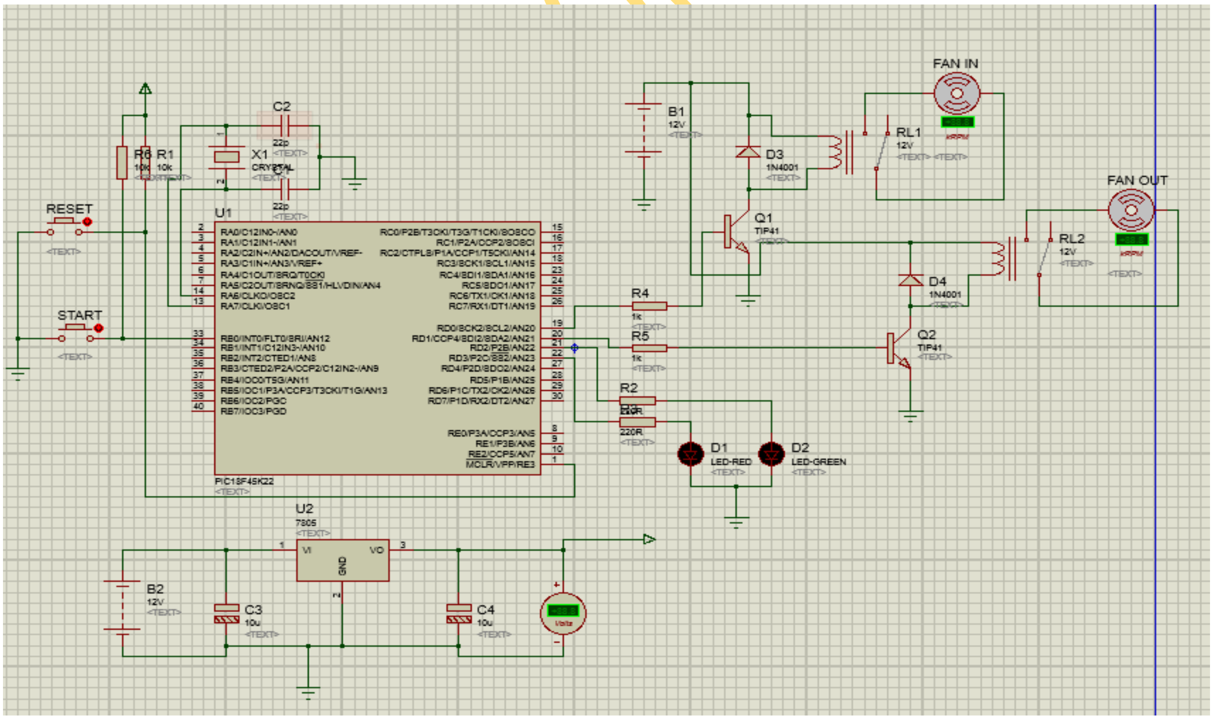


Fig 4.6: Schematic diagram of the electronic circuit

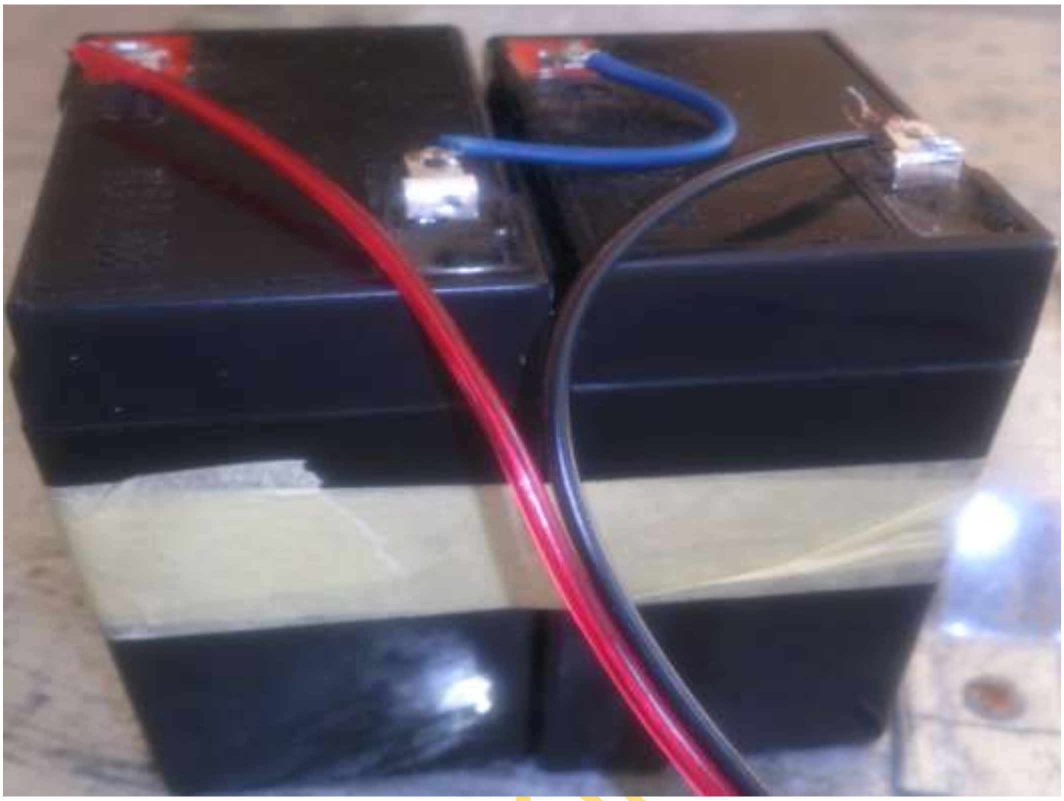


Plate 4.1: Rechargeable battery as source of power supply to the carbon dioxide extractor

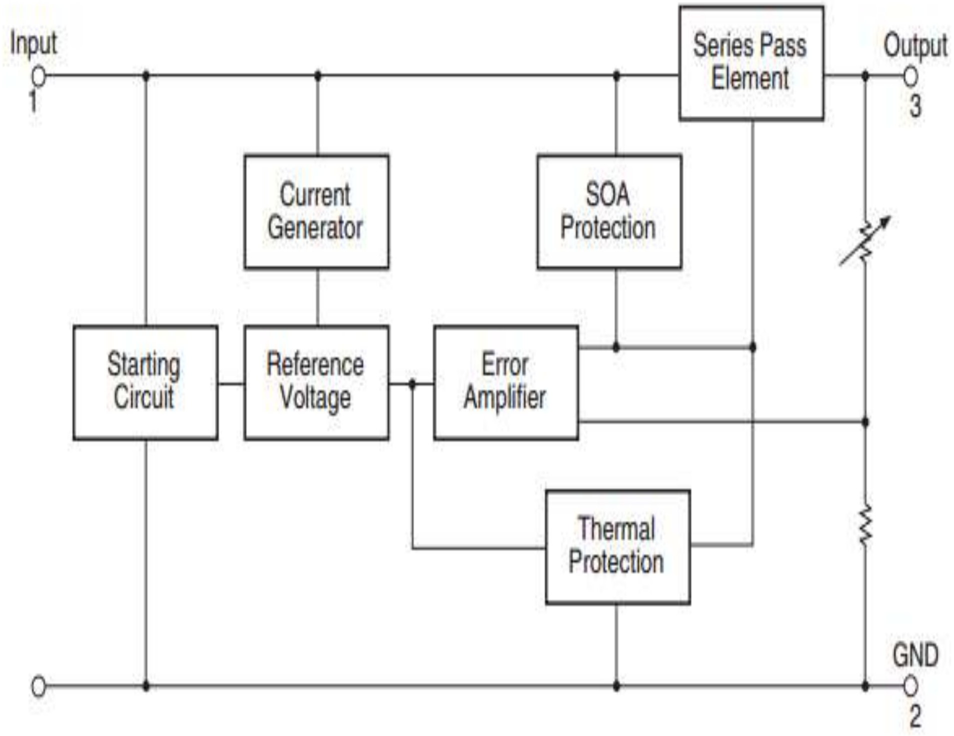


Fig 4.7: Voltage regulator

Table 4.15: Voltage regulation

Symbol	Parameter	Conditions		Min.	Typ.	Max.	Unit
V_o	Output Voltage	$T_j = +25^o$ C		4.8	5.0	5.2	V
		$5mA \leq I_o \leq 1A$, $P_o \leq 15W$,		4.75	5.0	5.25	
		$V_i = 7V$ to $20V$					
Regline	Line Regulation (1)		$V_o = 7V$ to $25V$	-	4.0	100	mV
		$T_j = +25^o$ C	$V_i = 8V$ to $12V$	-	1.6	50.0	
Regload	Load Regulation (1)		$I_o = 5mA$ to $1.5mA$	-	9.0	100	mV
		$T_j = +25^o$ C	$I_o = 250mA$ to $750mA$	-	4.0	50.0	
I_o	Quiescent Current	$T_j = +25^o$ C			5.0	8.0	mA
ΔI_o	Quiescent Current Change	$I_o = 5mA$ to $1A$		-	0.03	0.5	mA
		$V_i = 7V$ to $20V$		-	0.3	1.3	
$\Delta V_o/\Delta T$	Output Voltage Drift (2)	$I_o = 5mA$		-	-0.8	-	mV/°C
V_N	Output Noise Voltage	f =10Hz to 100kHz, $T_A = +25^oC$		-	42.0	-	$\mu V/V_o$
RR	Ripple Rejection (2)	f =120Hz, $V_o = 8V$ to $18V$		62.0	73.0	-	dB
V_{DROP}	Dropout Voltage	$I_o = 1A$, $T_j = +25^o C$		-	2.0	-	V
r_o	Output Resistance (2)	f =1kHz		-	15.0	-	mΩ
I_{SC}	Short Circuit Current	$V_i = 35V$, $T_A = +25^o C$		-	230	-	mA
I_{PK}	Peak Current (2)	$T_j = +25^oC$		-	2.2	-	A

code written with the mikroC PRO for PIC, which the system is to follow, is embedded into the controller’s memory. It sends signals to the relays for the operation of the fans. Plate 4.2 shows the Micro controller while Plate 4.3 reflects the controller on the electronic circuit.

4.8.9 Fan driver (relay circuit)

The relays are used as remote control switches in the system, basically the control signals that must be electrically isolated from the controlling circuit (controller). It receives signals from the controller to control the operation of the fans. It switches the inlet fan on to operate for ten minutes, then a reaction time of ten minutes follows before switching the outlet fan on to blow out the carbon dioxide free air. Figure 4.8 show the schematic diagrams of the fan driver relay.

4.8.10 Software

For every hardware, the need for a software to control and give instructions to the parts to perform specific operations. The micro-controller has a set of programs embedded on it to control the system. This was written by a software application known as mikroC PRO for PIC. The mikroC PRO for PIC is a powerful, feature-rich development tool for PIC microcontrollers. It is designed to provide the programmer with the easiest possible solution to develop applications for embedded systems, without compromising performance or control. Figure 4.9 is the flow chart for the set of instructions embedded in the software application.

4.9 Evaluation of performance of carbon dioxide extractor

4.9.1 *Characterization of burnt and unburnt waste*

Figure 4.10 shows the components of wastes that was burnt during the evaluation of the carbon-dioxide extractor. The percentage composition by weight of the physical components that were burnt were as follows: Organic waste 46.0 Sawdust 26.0 Paper 9.0, Nylon 7.0, Leaves 7.0 and wood 5.0% respectively.

Plate 4.2: Micro-controller

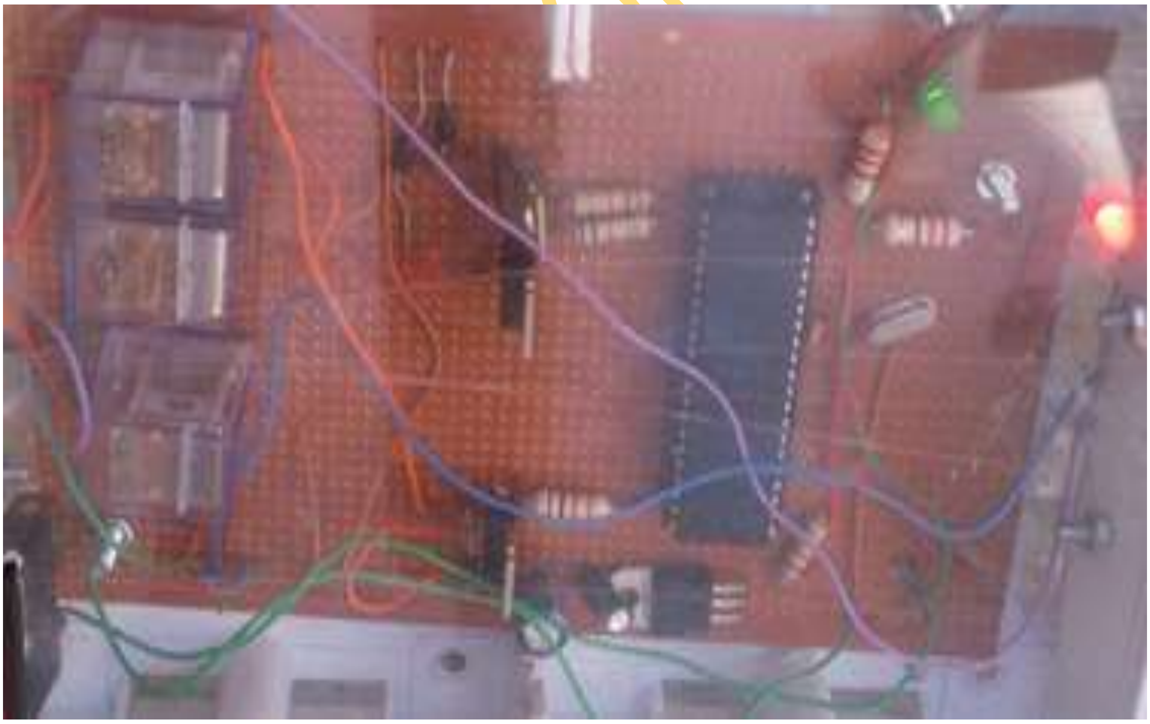


Plate 4.3: Controller on circuit board

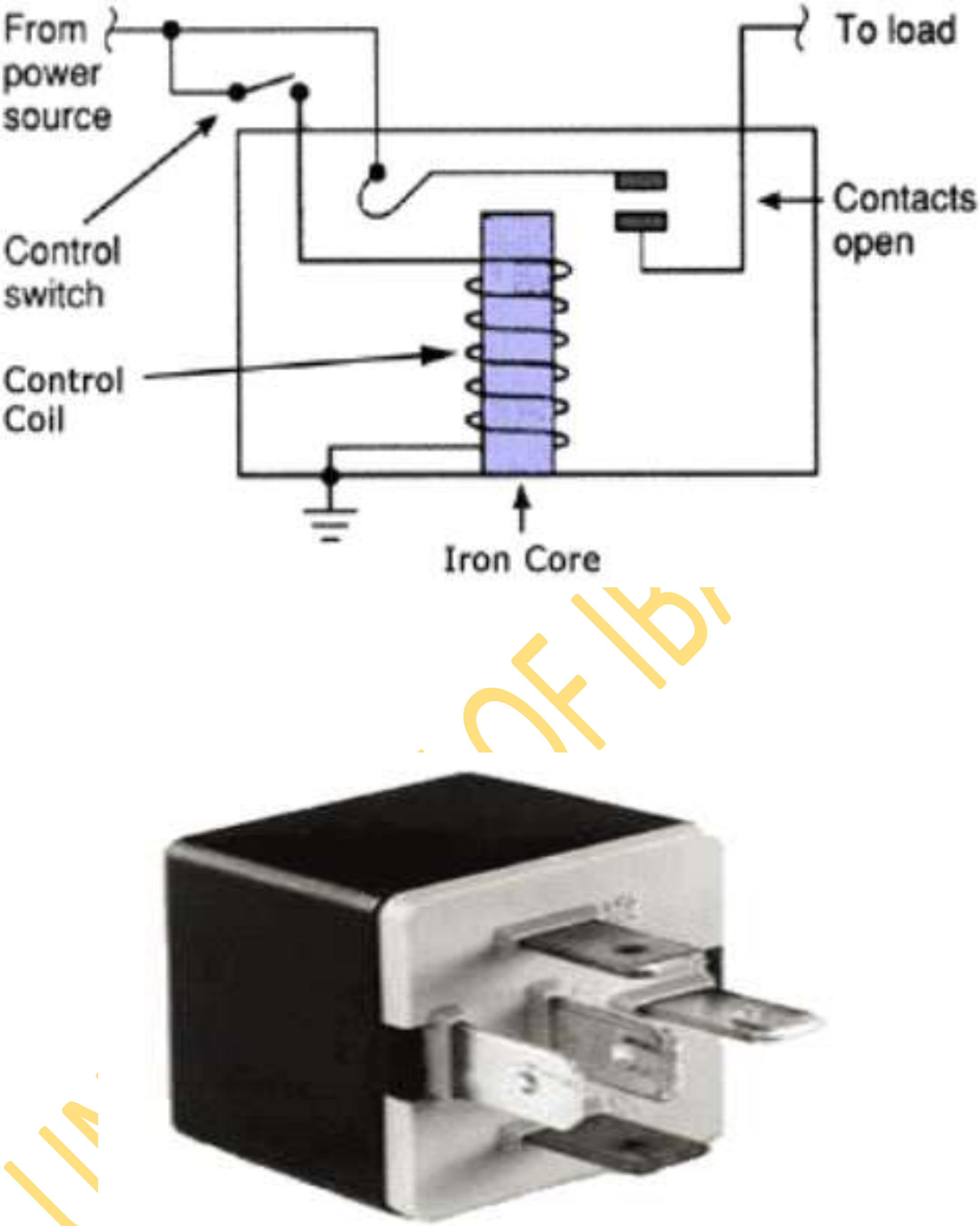
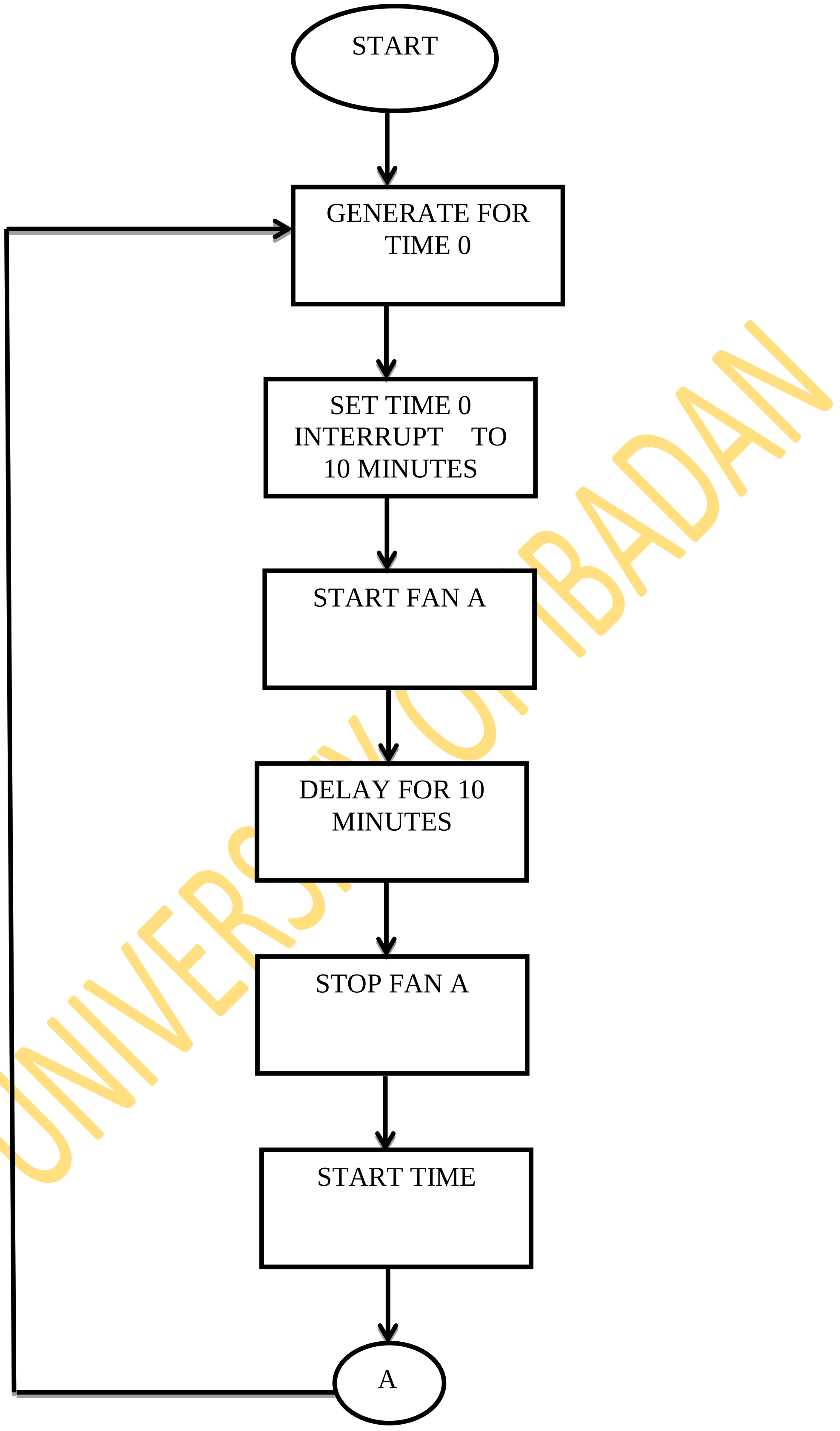


Fig 4.8: Schematic diagram of relay


START
GENERATE FOR TIME 0
SET TIME 0 INTERRUPT TO 10 MINUTES
START FAN A
DELAY FOR 10 MINUTES
STOP FAN A
START TIME
A

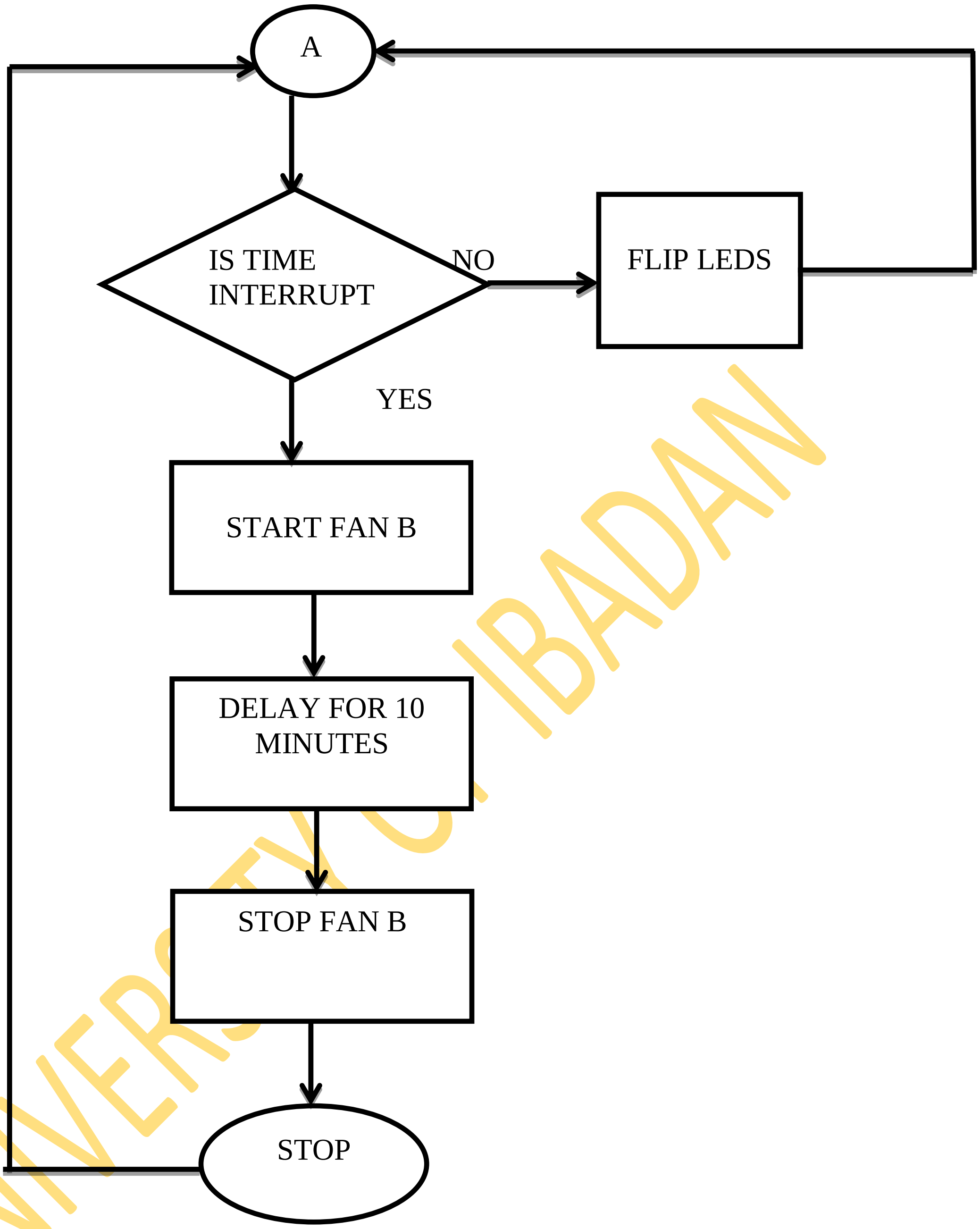


Fig. 4.9: Flow chart of software programme

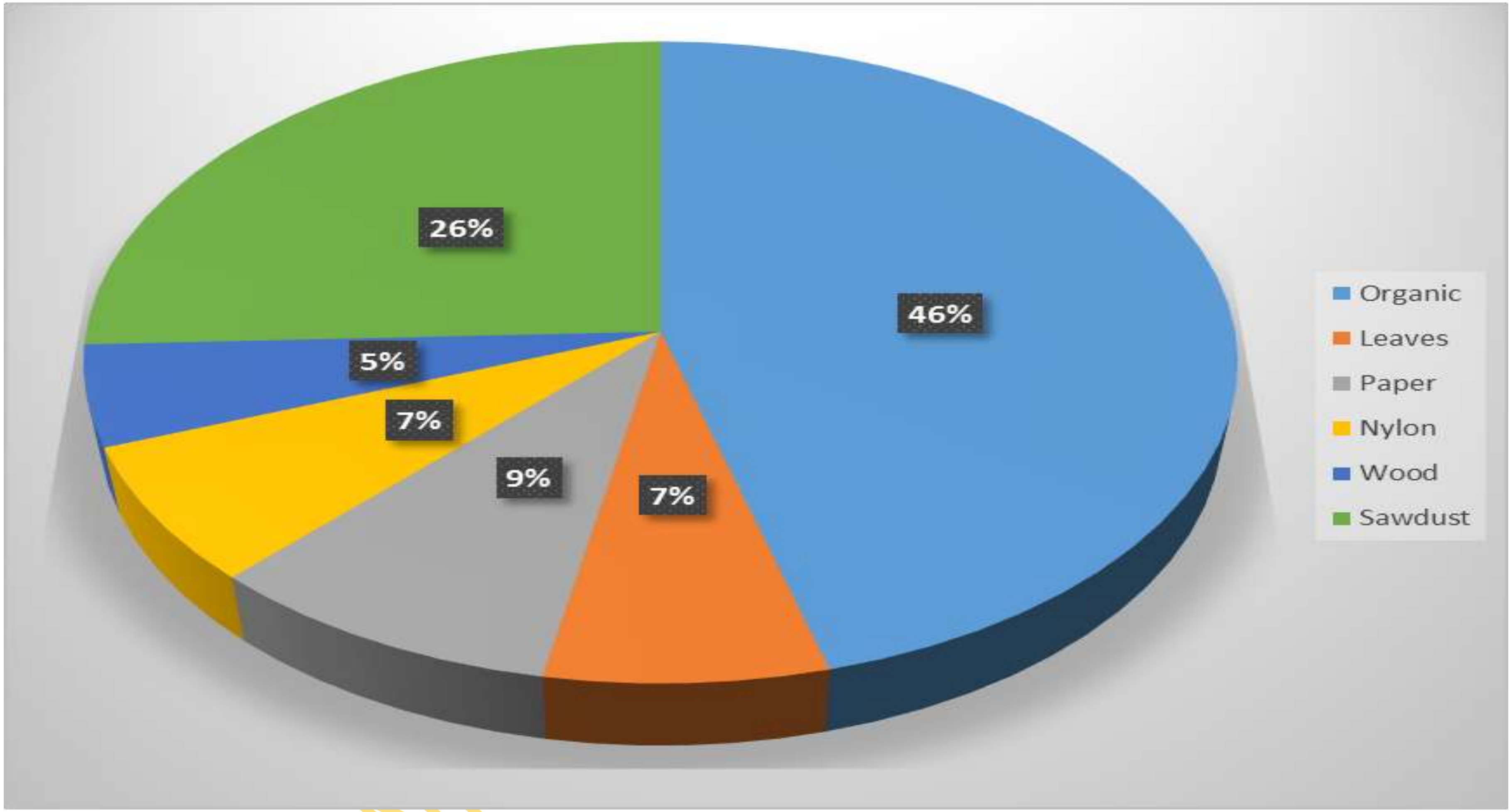


Fig 4.10: Percentage composition of burnt solid waste

4.9.2 Ultimate analysis of unburnt and burnt waste

The Ultimate Analysis of the unburnt and burnt waste was reflected in Figures 4.11 and 4.12. For % carbon, 41.6 and 57.5% were obtained for the unburnt and burnt refuse respectively, 7.3 and 5.6% were obtained for hydrogen, while 35.8 and 33.8% for % oxygen; 0.17 and 0.06% for nitrogen and 0.021 and 0.037% for carbon-dioxide for unburnt and burnt refuse respectively. For the energy content, it shows 24.9 and 19.7KJ/g for the unburnt and burnt refuse respectively.

4.9.3 Proximate analysis of the unburnt and burnt waste

Figure 4.13 reflects the proximate analysis of the unburnt and burnt waste. For moisture content, 26.6 and 18.7% were obtained for the unburnt and burnt waste. 51.9 and 42.4% were obtained for volatile matter; while 18.0 and 36.4% were obtained for fixed carbon for unburnt and burnt waste respectively. For the ash content, 3.5 and 2.6% were obtained for the unburnt and burnt refuse respectively.

4.9.4 Performance of carbon dioxide extractor and the chemically activated carbon

I. Characterization of the Different Activated carbon

Table 4.16 shows the particle properties of the various adorbents produced. For the properties weighted by volume the circle equivalent diameter were 88.0, 47.5 and 27.7µm for sawdust with KOH, sawdust with NaOH and swadust with $Ca(OH)_2$ resectively. For the properties weighted by count the circle equivalent diameter were 34.2, 27.3 and 20.8µm for sawdust with KOH, sawdust with NaOH and sawdust with $Ca(OH)_2$ resectively. Plates 4.4, 4.5 and 4.6 shows the scanning electron microscopy images for sawdust with KOH, sawdust with NaOH and sawdust with $Ca(OH)_2$ respectively.

II. Monitoring of carbon dioxide adsorbed by the extractor and different activated carbon

Table 4.17 shows the carbon dioxide adsorbed by the extractor for different activated carbon. For sawdust with KOH, at the inlet chamber the difference in the pre and post concentration of the carbon dioxide were 66.0, 95.0, 125.0, 135.0 and 121.0 ppm for 0.50, 0.75, 1.00, 1.25 and 1.50 m^3 respectively with an average value of 108.4 $\underline{+}$ 27.9 ppm, while at the outlet chamber of 0.75 m^3 the difference in the pre and post

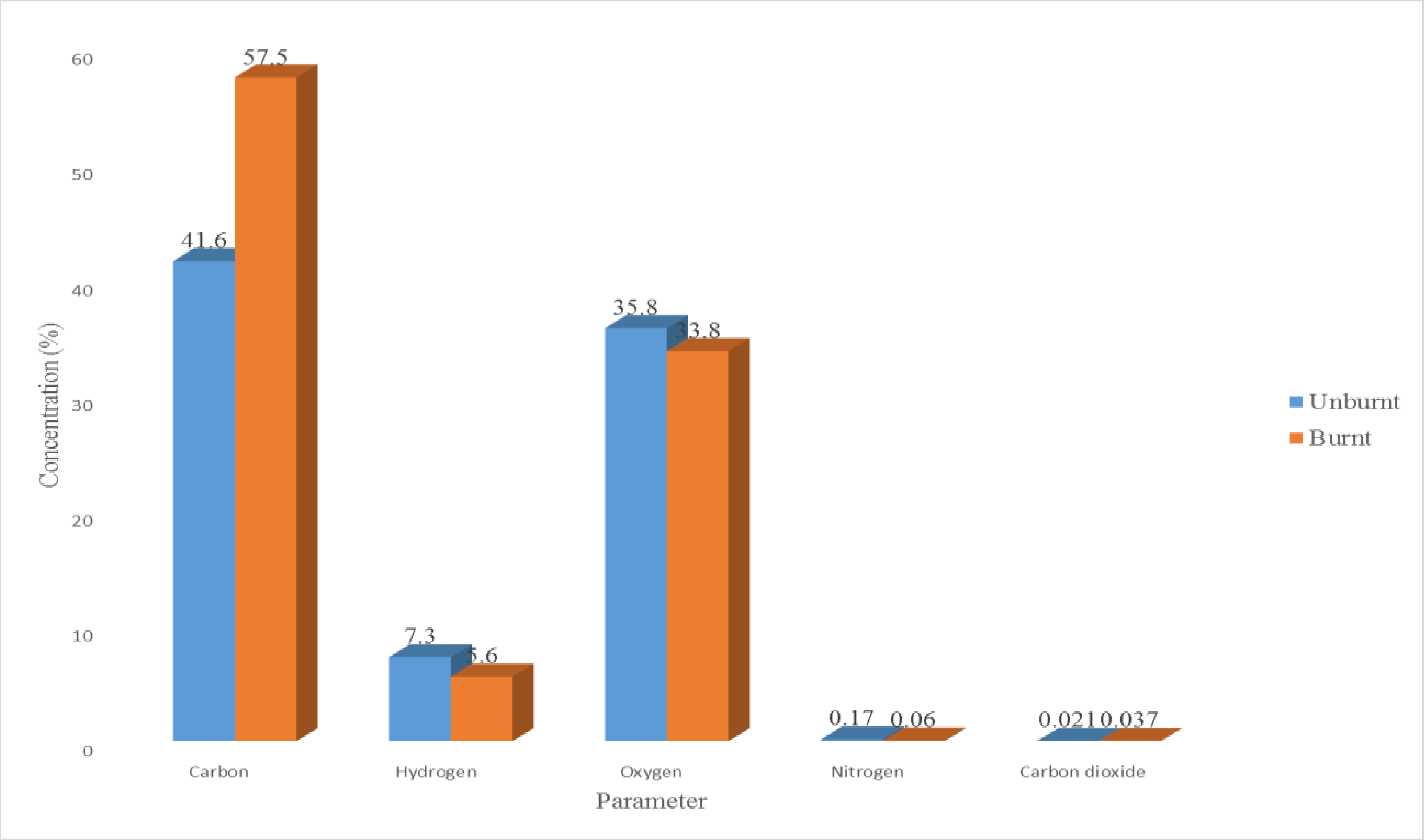


Fig 4.11. Ultimate analysis of burnt and unburnt solid waste

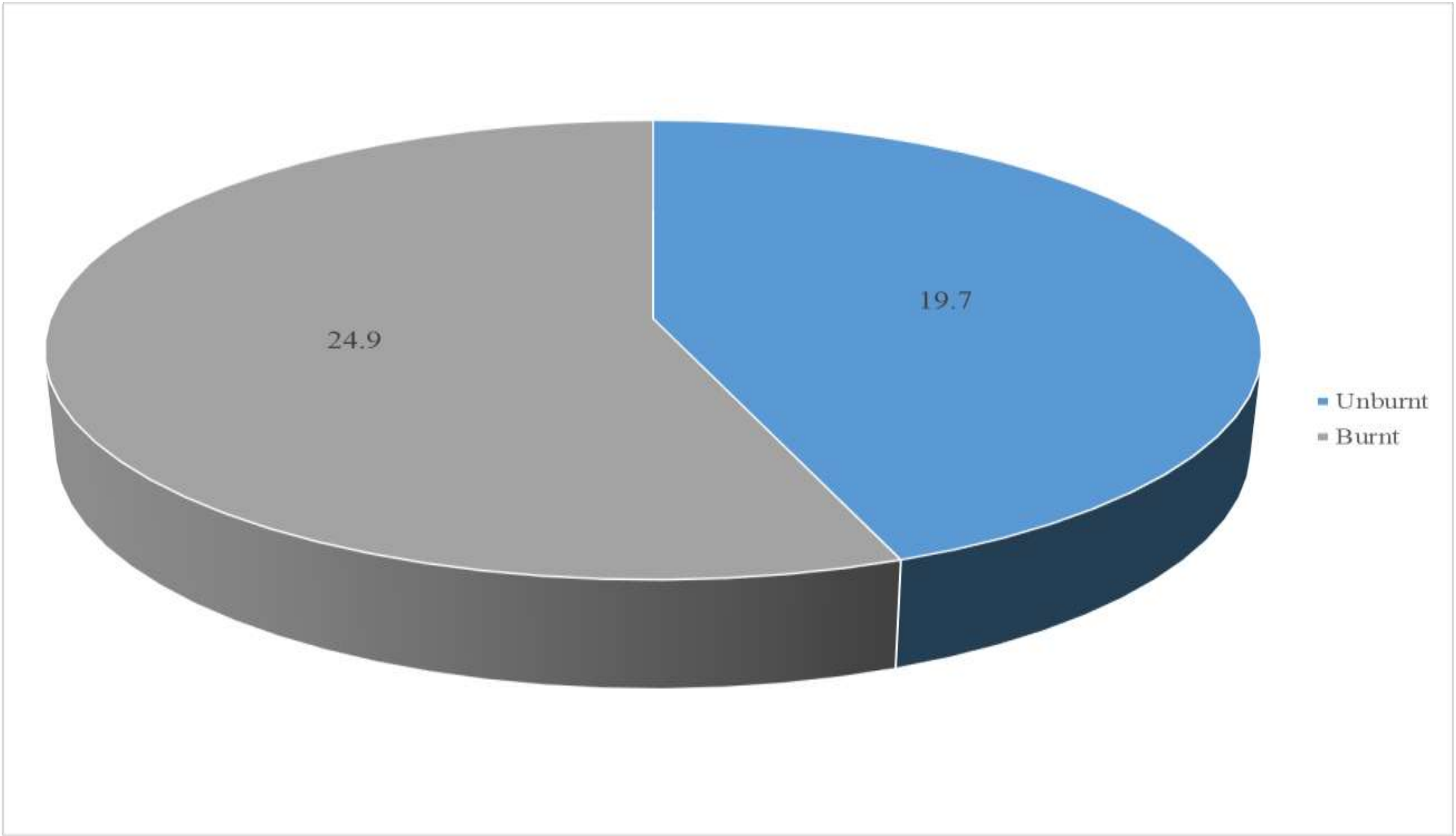


Fig 4.12: Energy content of burnt and unburnt solid waste (expressed in kJ/g)

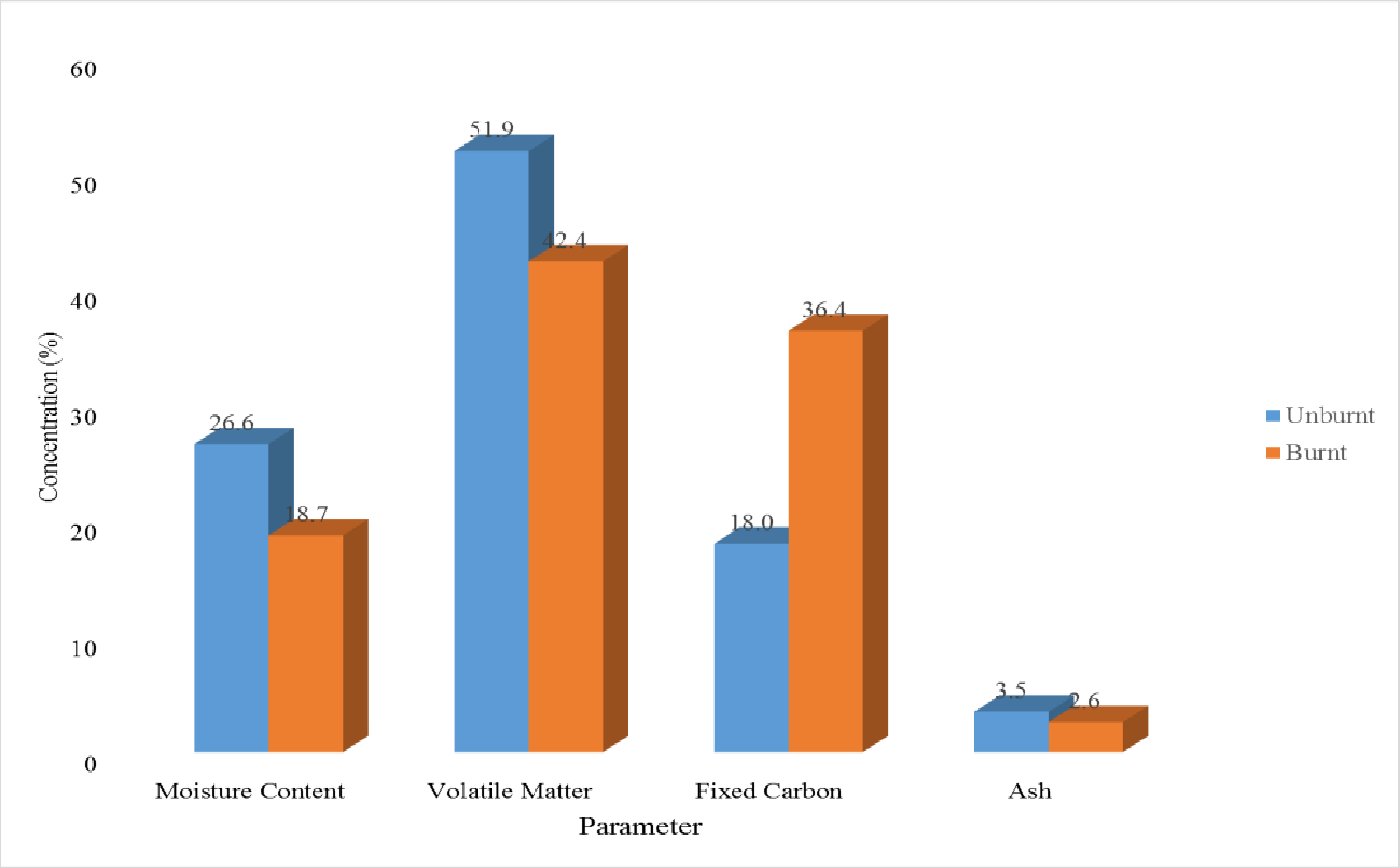


Fig 4.13: Proximate analysis of burnt and unburnt solid wastes

Table 4.16: Particle properties of various adsorbents

Parameter	Average (µm)		
	Sawdust + KOH	Sawdust +NaOH	Sawdust + $Ca(OH)_2$
CED weighted by volume	88.0	47.5	27.7
CED weighted by count	34.2	27.3	20.8

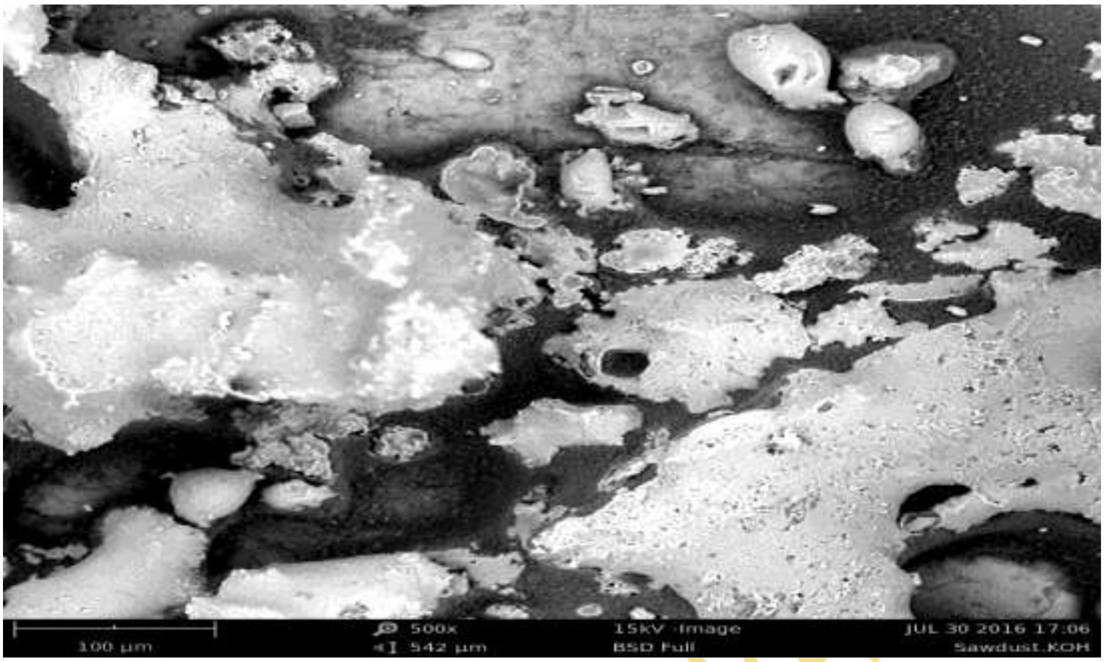


Plate 4.4: SEM Image of activated carbon from sawdust and KOH at 500 times magnification showing the particle size weighted by volume

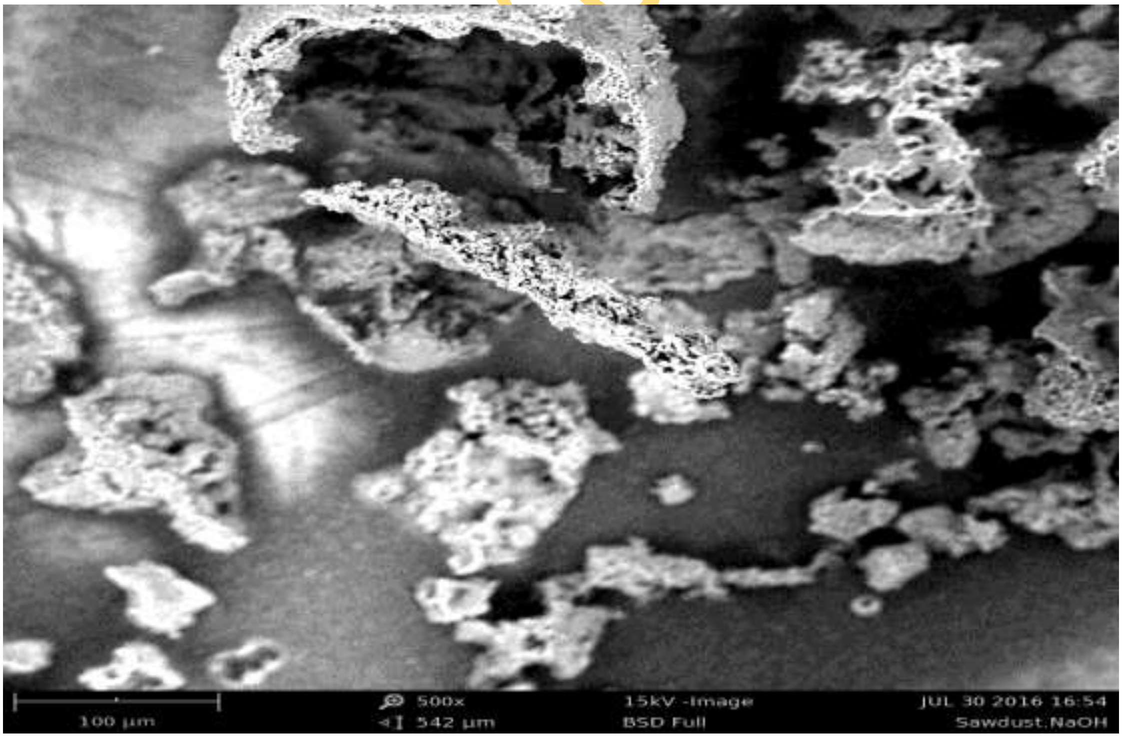


Plate 4.5: SEM Image of activated carbon from sawdust and NaOH at 500 times magnification showing the particle size weighted by volume

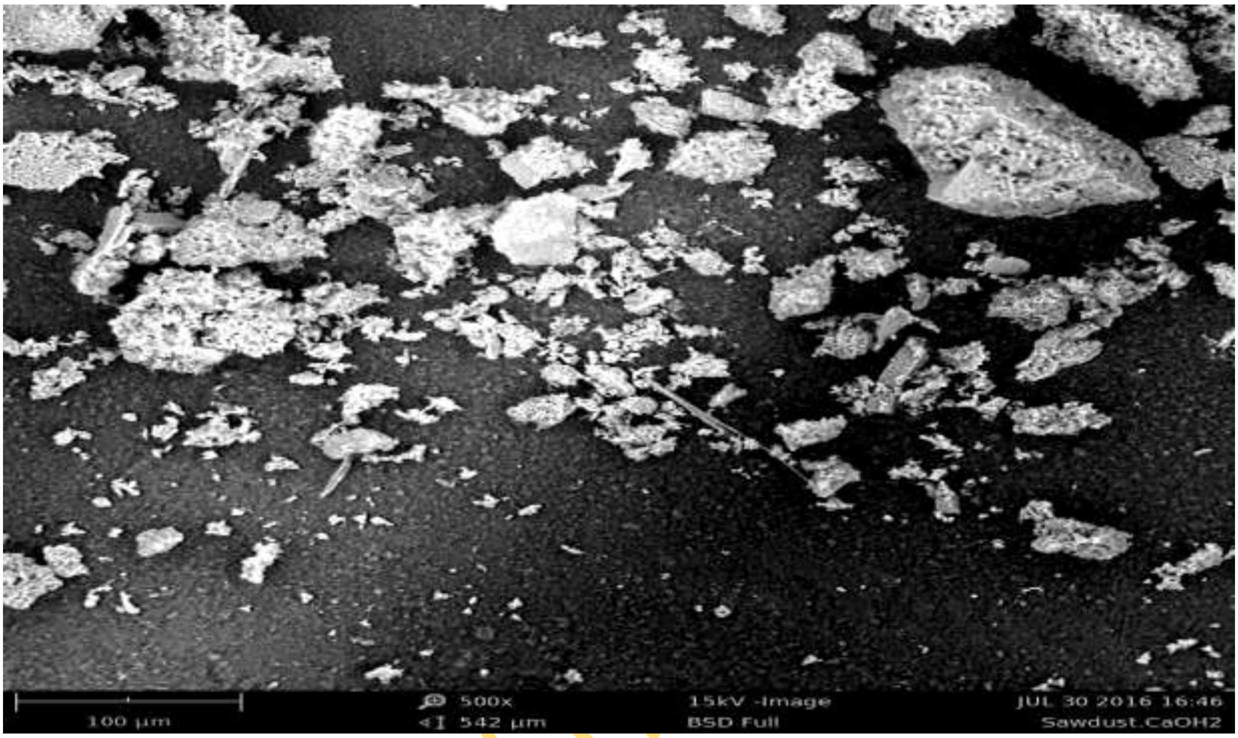


Plate 4.6: SEM Image of activated carbon from sawdust and $Ca(OH)_2$ at 500 Times magnification showing the particle size weighted by volume

Table 4.17: Carbon dioxide adsorbed by extractor combined with different activated carbon

Size (M^3)	Inlet CO_2 (ppm)			Outlet CO_2 (ppm)			Concentration of CO_2 Adsorbed (ppm)
	Pre	Post	Difference	Post	Pre	Difference	
Saw Dust With KOH							
1.50	584	518	66.0	470	466	4.0	62.0
1.25	595	500	95.0	465	458	7.0	88.0
1.00	592	467	125.0	467	458	9.0	116.0
0.75	585	450	135.0	482	467	15.0	120.0
0.50	590	469	121.0	495	482	13.0	108.0
Mean			**108.4± 27.9**			**9.6 ± 4.5**	**99.0 ± 24.0**
Saw Dust With NaOH							
1.50	560	534	26.0	485	469	16.0	10.0
1.25	572	512	60.0	508	482	22.0	38.0
1.00	580	496	84.0	510	471	39.0	45.0
0.75	592	498	94.0	539	499	40.0	54.0
0.50	601	511	90.0	533	519	14.0	76.0
Mean			**70.8 ± 28.3**			**26.2 ± 12.5**	**45.0 ± 24.1**
Saw Dust With $Ca(OH)_2$							
1.50	581	534	47.0	478	444	34.0	13.0
1.25	585	509	76.0	532	482	50.0	26.0
1.00	573	467	106.0	538	461	77.0	29.0
0.75	597	481	116.0	566	482	84.0	32.0
0.50	569	467	102.0	533	479	54.0	48.0
Mean			**89.4± 27.9**			**59.8± 20.5**	**30.0 ± 13.0**

concentration of the CO_2 were 4.0, 7.0, 9.0, 15.0 and 13.0 ppm respectively with an average value of 9.6 ± 4.5 ppm implying that the concentration of carbon dioxide adsorbed were 62.0, 88.0, 116.0, 120.0 and 108.0 ppm respectively with an average value of 99.0 ± 24.0 ppm. For Sawdust with NaOH, at the inlet chamber the difference in the pre and post concentration of the carbon dioxide were 26.0, 60.0, 84.0, 94.0 and 90.0 ppm for 0.50, 0.75, 1.00, 1.25 and 1.50 m^3 respectively with an average value of 70.8 ± 28.3 ppm, while at the outlet chamber of 0.75 m^3 the difference in the pre and post concentration of the carbon dioxide were 16.0, 22.0, 39.0, 40.0 and 14.0 ppm respectively with an average value of 26.2 ± 12.5 ppm implying that the concentration of carbon dioxide adsorbed were 10.0, 38.0, 45.0, 54.0 and 76.0 ppm respectively with an average value of 45.0 ± 24.1 ppm. For Sawdust with $Ca(OH)_2$, at the inlet chamber the difference in the pre and post concentration of the carbon dioxide were 47.0, 76.0, 106.0, 116.0 and 102.0 ppm for 0.50, 0.75, 1.00, 1.25 and 1.50 m^3 respectively with an average value of 89.4±27.9 ppm, while at the outlet chamber of 0.75 m^3 the difference in the pre and post concentration of the carbon dioxide were 34.0, 50.0, 77.0, 84.0 and 54.0 ppm respectively with an average value of 59.8±20.5 ppm implying that the concentration of carbon dioxide adsorbed were 13.0, 26.0, 29.0, 32.0 and 48.0 ppm respectively with an average value of 30.0 ± 13.0 ppm.

III. Prediction of concentration of carbon dioxide adsorbed from size of inlet Chamber

A. Sample sawdust with KOH

Figure 4.14 reflects the relationship between the volume size of the inlet chamber (in m^3) and the concentration of carbon dioxide adsorbed (ppm) by saw dust with KOH From the graph, the polynomial equation showing is given as:

$C_a = 0.036V_i{}^4 - 0.00\ 14\ V_i{}^3 + 0.0017\ V_i{}^2 - 0.08\ V_i + 0.024$

Where, C_a is the Concentration of CO_2 Adsorbed and V_i is the volume size of CO_2 inlet chamber.

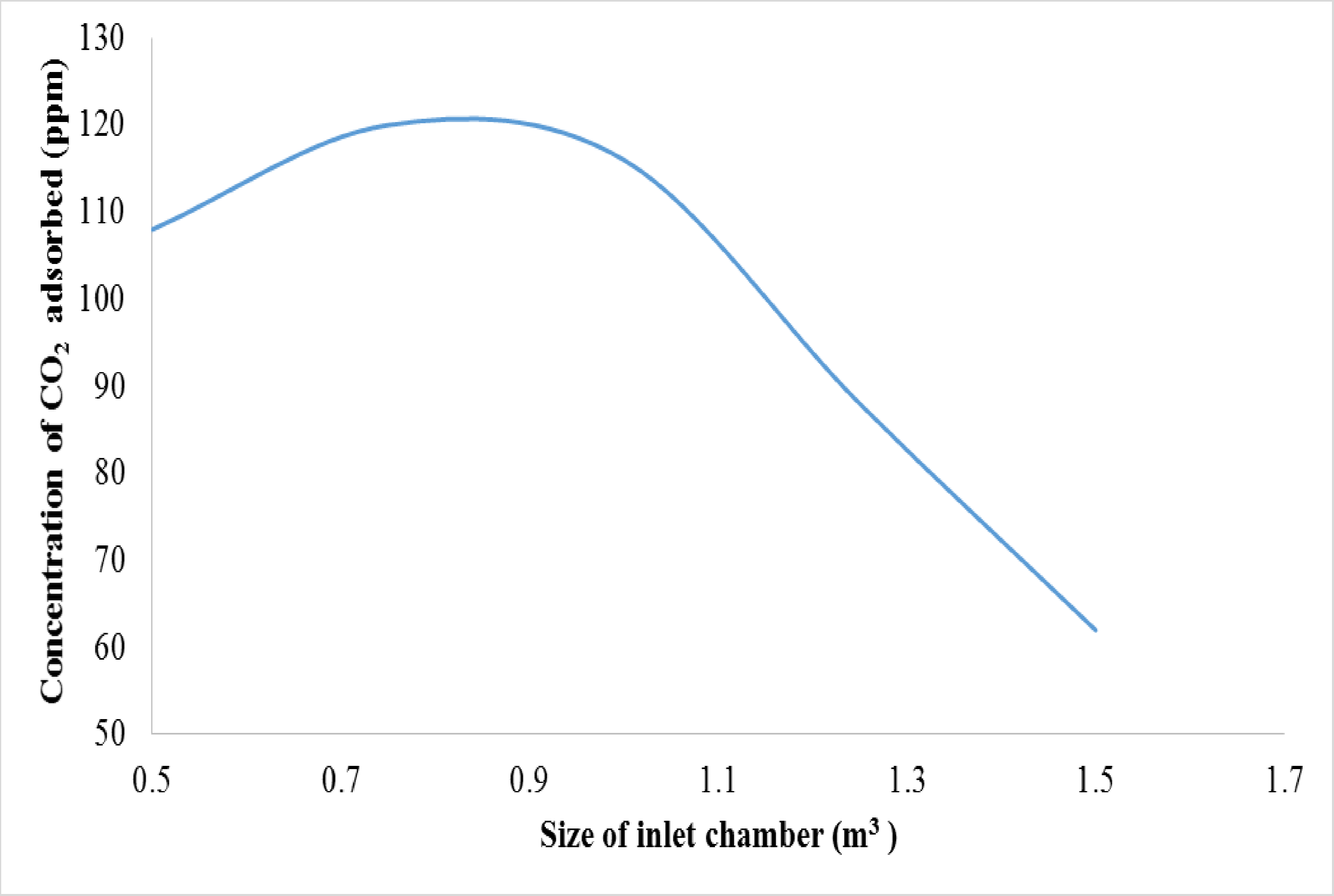


Fig 4.14: Graph of concentration of CO_2 adsorbed (ppm) against volume size of inlet chamber (m^3) for sawdust with KOH

B. *Sample sawdust with NaOH*

Figure 4.15 reflects the relationship between the volume size of the inlet chamber (in m^3) and the concentration of carbon dioxide Adsorbed (ppm) by Saw Dust with NaOH. From the graph, the polynomial equation showing is given as:

$C_a=0.0012V_i^4-0.0047\ V_i^{\ 3}+0.0068\ V_i^{\ 2}-0.0041\ V_i+0.086$

Where, C_a is the Concentration of CO_2 Adsorbed and V_i is the volume size of CO_2 inlet chamber.

C. *Sample sawdust with Ca (OH)$_2$*

Figure 4.16 reflects the relationship between the volume size of the inlet chamber (in m^3) and the concentration of carbon dioxide Adsorbed (ppm) by Saw Dust with $Ca(OH)_2$. From the graph, the polynomial equation showing is given as:

$C_a=0.089V_i^{\ 4}-0.0036\ V_i^{\ 3}+0.0051\ V_i^{\ 2}-0.003\ V_i+0.063$

Where, C_a is the Concentration of CO_2 Adsorbed and V_i is the volume size of CO_2 inlet chamber.

IV. *Assessment of the effectiveness of extractor combined with adsorbents in the extraction of carbon dioxide*

Table 4.18 reflects the comparism of adsorbed carbon dioxide with potential carbon dioxide from burnt and urburnt solid waste while Table 4.19 reflects the effectiveness of the extractor combined with the chemically activated sawdust. This was obtained by the comparison of adsorbed carbon dioxide by each treatment of chemically activated carbon from sawdust with the potential carbon dioxide from the burnt solid waste in ppm. 99.0 ± 24.0 ppm of carbon dioxide out of the potential 160.0 ppm which makes the effectiveness of the extractor combined with sawdust chemically activated with potassium hydroxide to be 61.9% as againt 45.0 ± 24.1 ppm of carbodioxide out of the potential 160.0 ppm which makes the effectiveness of the extractor combined with sawdust chemically activated with sodium hydroxide to be 28.1% and 30.0 ± 13.0 ppm of carbodioxide out of the potential 160.0 ppm which makes the effectiveness of the extractor combined with sawdust chemically activated with calcium potassium hydroxide to be 18.8% respectively.

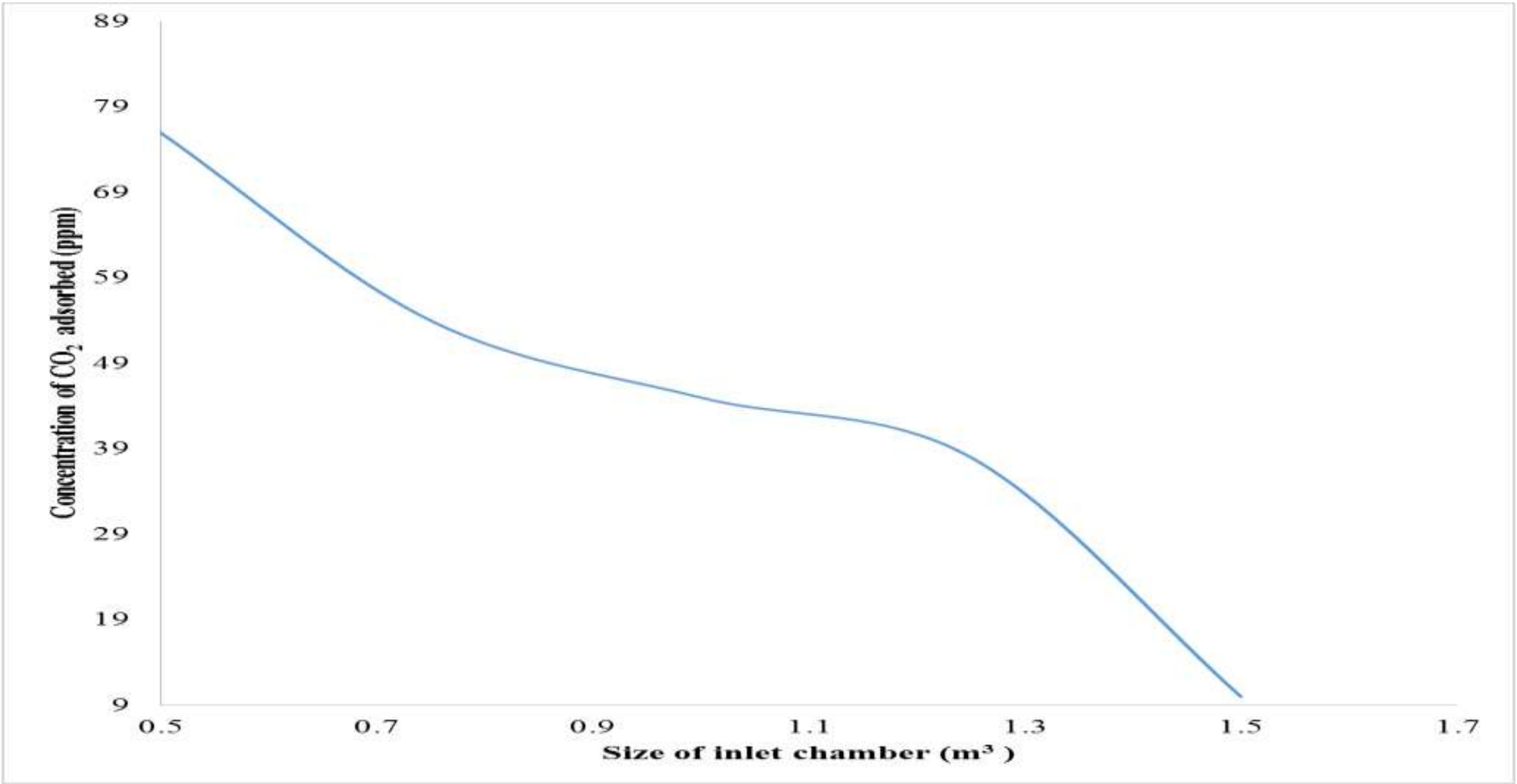


Fig 4.15: Graph of concentration of CO_2 adsorbed (ppm) against volume size of inlet chamber (m^3) for sawdust with NaOH

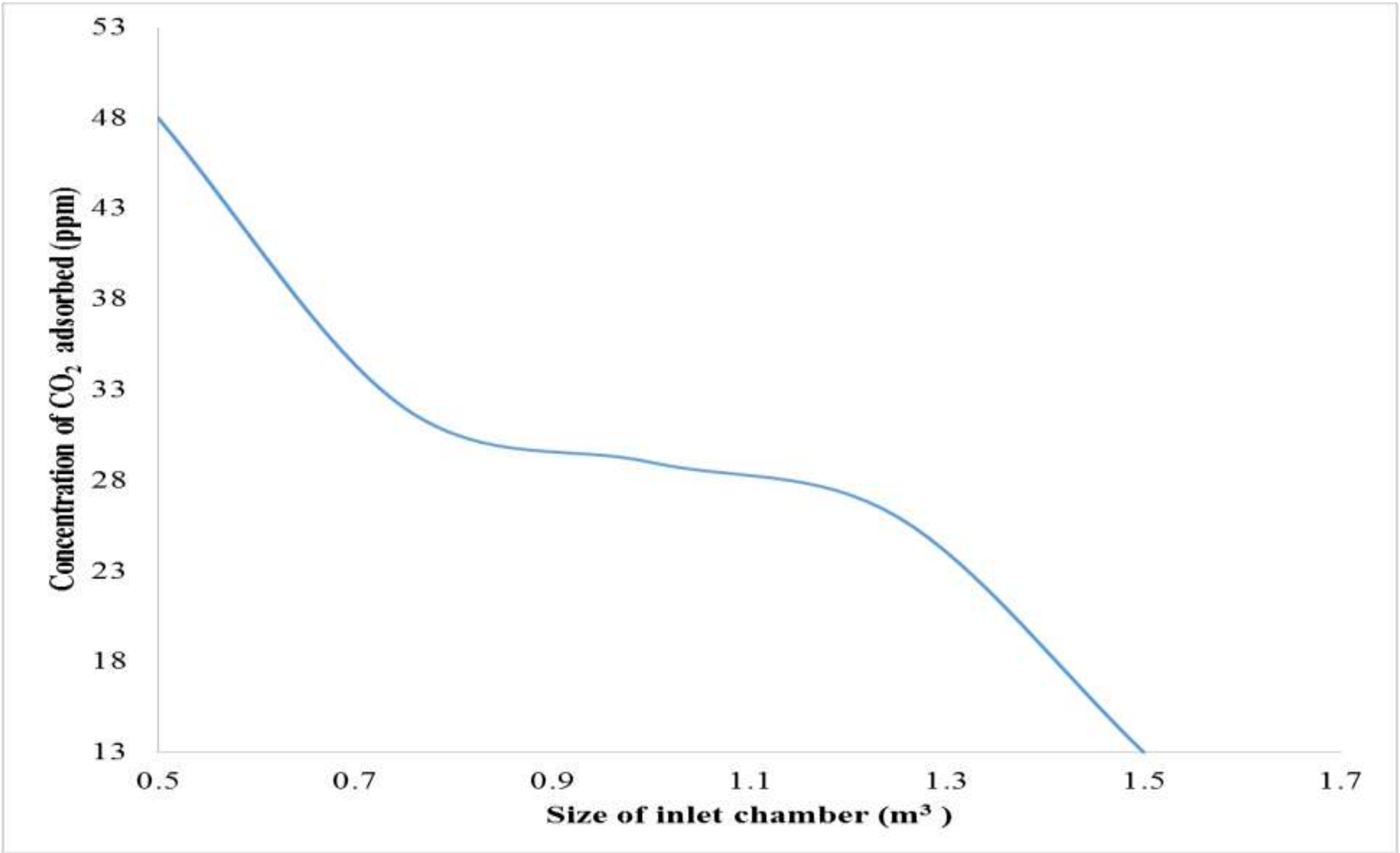


Fig 4.16: Graph of concentration of CO_2 adsorbed (ppm) against volume size of inlet chamber (m^3) for sawdust with $Ca(OH)_2$

Table 4.18: Comparison of adsorbed CO_2 with potential CO_2 from burnt and unburnt solid waste

Size (m^3)	**$C0_2$ (ppm)**			**$C0_2$ (ppm)**		
	KOH	**NaOH**	**$Ca(OH)_2$**	**Unburnt**	**Burnt**	**Difference**
1.50	62.0	10.0	13.0	210.0	370.0	160.0
1.25	88.0	38.0	26.0			
1.00	116.0	45.0	29.0			
0.75	120.0	54.0	32.0			
0.50	108.0	76.0	48.0			
Mean	**99.0± 24.0**	**45.0± 24.0**	**30.0± 13.0**			

Table 4.19: Effectiveness of CO_2 adsorption by the extractor combined with adsorbents

Activated Carbon	Mean CO_2 Adsorbed (ppm)	Potential CO_2 In Waste (ppm)	Effectiveness of Extractor combined with Adsorbents= (Mean CO_2 Adsorbed / Potential CO_2 In Waste * 100) (%)	$P < 0.05$
KOH	99.0	160.0	61.9	0.00
Na OH	45.0	160.0	28.0	
Ca $(OH)_2$	30.0	160.0	18.8	

It was observed that the extractor combined with sawdust chemically activated by potassium hydroxide (KOH) performed optimally with an effectiveness of 61.9%. This was followed by the extractor combined with sawdust chemically activated with sodium hydroxide (NaOH) with an effectiveness of 28.1% and extractor combined with sawdust chemically activated with calcium hydroxide $Ca(OH)_2$ with an effectiveness of 18.8%. What obtained was in agreement with the findings of Sevilla and Fuertes (2011) who stated and concluded that a porous carbon material made from sawdust and KOH performs better than the currently available ones. The reasons adduced is that the KOH treatment creates pores in the sawdust structure by oxidation of carbon and carbon gasification from K_2CO_3 decomposition. This is evidenced in the circle equivalent diameter weighted by volume of 88.0 µm as compared to 47.5 and 27.7 µm and the circle equivalent diameter weighted by count of 34.2 µm as compared to 27.3 and 20.8 µm of the adsorbent produced from sawdust and NaOH and sawdust with $Ca(OH)_2$ respectively. The big pores sizes are responsible for material uptake capabilities bestowing it with capacity as high as 4.8 mmol CO_2/g.

The material has good selectivity for carbon dioxide over Nitrogen and fast adsorption rates and can easily be regenerated. This also agrees with Zhu *et al*, (2015) that starch cellulose and sawdust derived carbon sorbents prepared through KOH activation are reported to have carbon dioxide uptakes of up to 21.2% under 1 bar carbon dioxide and 25^o C respectively. The reasons adduced for a better performance of KOH activated sawdust according to Shih *et al*, (2005) was that KOH had more tendency to bind with carbon dioxide than NaOH and $Ca(OH)_2$. Such interactions leads to cross linking reactions with some volatility thereby retaining them in the solid matrix. This would result in increase in the net mass of the sample thereby lading to increase in density thereby encouraging higher adsorption of the gas.

The activation with KOH according to Wang *et al*, (2012) reported a series of porous carbon with adjustable surface areas and narrower micropore size distribution. This encourages a high uptake carbon dioxide and CO_2/N_2 sensitivity which makes such carbon activated with KOH more promising for CO_2 capture and separation. Similarly Sevilla *et al*, (2011) reported a chemically activated synthesis (KOH) as activated agent of highly porous N-doped carbon for CO_2 capture. This ensures the chemically activated carbon with KOH to have a large CO_2 adsorption capacity. Furthermore, the capture of CO_2 with this kind of carbon takes place at high adsorption rates more than 95% of the CO_2 in two minutes.

The performance of the carbon dioxide extractor as evidenced by 61.9% which was obtained with the combination of the extractor with adsorbent made from sawdust and potassium hydroxide was in agreement with Lackner et al, 1999 who posited that it was possible to move air mechanically but only at speeds that are easily achieved by natural flows. The method of considering chemical adsorption from natural air flow passing over some recyclable sorbents such as sawdust chemically activated with potassium hydroxide was also confirmed in agreement with Lackner, 1999.

The utilization of a rechargeable battery to power the extractor also made more appreciable because it prevented the device to also be a source of emission as there is no need for fuel. Also the production of a unit of the extractor is more cost effective than the use of a wind mill because the extractor was designed to operate at a natural air low velocity of 2.75 m/s than that of 10 m/s which is wind stronger than is usually assumed to prevail in wind mill operations (Gipe, 1995).

The approach of utilizing the device for extracting carbon dioxide from the air was also effective because of the property which enables carbon dioxide to mix easily with air. This does not distort atmospheric carbon dioxide concentrations. The carbon dioxide enriched air mixes rapidly with ambient air to maintain constant levels of carbon dioxide. Air depleted in carbon dioxide will also mix rapidly and return to ambient conditions. This mixing rates sets the limit of how one could space carbon dioxide extraction (Elliot, 2001). To maximize extractability of carbon dioxide by the devise as stated, the designed contact time of 10 minutes for the extractor was selected.

The major advantage of carbon capture from air is that it does not require abandonment of existing facilities and infrastructure. Extraction from the air could therefore be introduced in parallel to other methods that sequester carbon dioxide directly captured at source (Lackner et al, 1999). Another advantage of the extractor compared to other methods of carbon sequestration is its portability, which enables to be movable. Most methods are usually stationary. From the aforementioned, if more efforts are concentrated on the improvement of the carbon dioxide extractor, it would go a long way of mitigating the menace of high atmospheric carbon dioxide levels and its attendant effects on the environment

In this study, the performance of the carbon dioxide extractor was quite low compared to the established literatures referred to, the reason being that the extractor was utilized in an outdoor environment while the referred works were conducted in the laboratory. Furthermore, the tendency in losses of gas due to leakages on the casing and factors such as power loss based on the efficiency of the battery affected the fan power thereby reducing extraction capacity of the extractor. Plates 4.7 and 4.8 shows the fabricated carbon dioxide extractor.

Plate 4.7: Side view of extractor with inlet fan

Plate 4.8: Back view of extractor with controller and batteries

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

It was observed during the course of study that not much work had been done on the capture of atmospheric carbon dioxide from the solid wastes management sector, especially in developing countries like Nigeria. At the end of the study, the following conclusions were drawn:

1. A large volume of 40,558,278 kg per year for organic waste and 37,560.126 kg per year for paper and textiles generated in Akure provide a good source of raw materials for the establishment of a recycling plant.
2. The carbon-dioxide emission potential estimated at the Facility was 1.2 Gg/Yr which is quite high.
3. The overall emission under the present conditions at the facility is 119,938 $MtCO_2eq$ which is quite high.
4. If aerobic composting for biodegradable waste combined with recycling of valuables was adopted, there will be reduction of emissions of 43,816 $MtCO_2eq$ while anaerobic digestion combined with recycling of valuables was adopted, there will reduction of emissions of 42,846 $MtCO_2eq$
5. The emission estimates calculated with the two methods of IPCC default method and first order decay method are not comparable. The values of 80.8 Gg/year and 42.3 Gg/year and 2.9 Gg/year and 1.5 Gg/year were estimated for the wet and dry seasons respectively reflecting a variation and thus making the solid waste disposal facility a significant source of methane in Akure.
6. The atmospheric carbon dioxide data in the study area showed clear seasonal and diurnal variations as evidenced in values of 438.0 to 630.0 ppm in the dry season and 407.3 and 506.9 ppm for wet season for environmental carbon dioxide levels which were all above the regulatory limit of 400.0 ppm.

7. Adsorbent prepared from sawdust with KOH had pore size of 88.0 and 34.2 µm for circle equivalent diameter for properties weighted by volume and properties weighted by count respectively compared with 47.5 and 27.3 µm and 27.7 and20.8 µm for circle equivalent diameter for properties weighted by volume and properties weighted by count for sawdust prepared with NaOH and sawdust prepared with $Ca(OH)_2$ respectively.
8. Incorporation of sawdust chemically activated with KOH combined with the carbon dioxide extractor improves the effectiveness of carbon dioxide extraction as the effectiveness of the extractor combined with KOH was 61.9% as against 20.8% and 18.8% of sawdust and NaOH and sawdust and $Ca(OH)_2$ respectively.

5.2 Recommendations

Based on the findings and observations during the course of the study, the following are recommended to promote effective waste management in Akure.

1. Further studies should be carried out to extend the characterization of solid waste generated in Akure beyond one year to verify the seasonal variation of solid waste.
2. Further studies should be carried to provide methane specific properties of the solid waste generated in Akure in order to build an inventory of methane emission parameters.
3. The monitoring of air carbon dioxide should extend beyond one calendar year to verify the seasonal variations of air levels carbon dioxide.
4. Further investigations should be carried out to confirm the actual quantity of carbon dioxide adsorbed by the activated carbon.
5. Further investigations should also be carried out on the effect of the concentrations of the alkalis on the concentration of carbon dioxide adsorbed.
6. Investigations should be extended into the capturing of other greenhouse gases such as N_xO, SO_x etc.
7. More efforts should be geared in the development of prototype carbon dioxide extractors to capture carbon dioxide at model open dumps and landfill sites in the country.

REFERENCES

Aaron, D. and C. Tsouris, (2005) "Separation of CO_2 from Flue Gas: A Review" *Separation Science Technology* 40: 321-348

Adedeji, Y. M.D. (2005). "Outdoor Space Planning and Landscape Qualities of Religious Centre in Akure, Nigeria". *Inter-World Journal of Science and Technology, R. Durson Associates, Owerri*, 2 (1): 40-51

Adewumi, I K, Ogedengbe, M O, Adepetu, J A, Fabiyi, Y L (2005). "Planning Organic Fertilizer Industries for Municipal Solid Wastes Management". *Journal of Applied Sciences Research*, 1(3): 285-291

Adewumi, J.R and Babatola, J.O (2006) "Solid Waste Management Problems in some Nigerian Cities" *Inter Research Journal in Engineering, Science and Technology (IREJEST)* 3(1): 1-6

Akaninyere, M. and Atser, J. (2001). "Solid Waste Characterization and Management Issues in Uyo Municipalities, Nigeria". Libro-Gem, Lagos, Nigeria.

Akinola, S. and Salami, R. (2001). "An Assessment Of The effectiveness of Private Sector Participation Initiatives in Solid Waste Management in Mushin Local Government Area, Lagos State". *Nigerian Journal of Social and Educational Research*. 25: 256- 267

Adejuwon, S. A. (2004). "Impacts of Climate Variability and Climate Change on Crop Yield in Nigeria". *Stakeholders' Workshop on Assessment of Impacts and Adaptation to Climate Change (AIACC)*, Ife, Nigeria.

Adesida, A.A. and Igbuku, A.O. (1998) "Solid Waste Management: Shell Petroleum Development Company (SPDC) Approach": A Paper Presented at the Nigerian Environmental Society Meeting. February 21st 15-21 (unpublished)

Akpovi, S.U and Sridhar, M.K.C (1985) "Solid Waste Management. African Technical Review". *Scottish Journal of Arts, Social Sciences and Scientific Studies* 21(1): 18-20.

APHA (1992) "Standard Methods for Examination of Water and Wastewater". 18th Edition, American Public Health Association, Washington, DC 465-469

APHA (2008) "Standard Methods for Examination of Water and Wastewater". 19th Edition, American Public Health Association, Washington, DC 458-497

Askeland, D.R (1994) "The Science and Engineering of Materials". 3rd Edition, PWS Publishing Company, Boston 35

Ashton, W., M. Chertow, and M. Shenoy (2009). *Industrial Ecology – Developing Systemic Solutions to Climate Change and other Environmental Challenges in Indian Industry.* Sustainability Tomorrow, October-December 2009.

Astrup, T., T. Fruergaard, and T.H. Christensen (2009). "Recycling of Plastic: Accounting of Greenhouse Gases and Global Warming Contributions". *Waste Management and Research*: 27: 763-772.

Auta, M. and B.H. Hameed, (2014). "Adsorption of Carbon Dioxide by Diethanolamine Activated Alumina Beads in a Fixed Bed". *Chemical Engineering Journal* 253: 350-355.

Awosika, L. F., French, G. T., Nicholls, R. J. and Ibe, C. E. (1992). "The Impact of Sea Level Rise on the Coastline of Nigeria". .*Proceedings of IPCC Symposium on the Rising Challenges of the Sea*. Magaritta, Venezuela.

Baksi, S., Biswas, S. and Mahajan, S. (2003). "Activated Carbon from Bamboo Technology Development towards Commercialization" Paper Presented in BAMTECH" March, Guwahati

Baldasano, J. M. and Soriano, C. (2000). "Emission of Greenhouse Gases from Anaerobic Digestion Processes: Comparison with Other Municipal Solid Waste Treatments". *Journal of Water Science and Technology*, 41(3): 275-283.

Bartnes, J., J.E. Frøiland-Jensen, T. Williksen, Norconsult (1998) "Development of a National Inter-Active Calculation Model and Estimation of Methane Emissions from Norwegian SW landfills". Report Prepared by Norconsult for Norwegian State Pollution Control (SFT).

Barton, JR, Issaias I, Stentiford EI (2008). "Carbon –Making the right Choice for Waste Management in Developing Countries. Waste Management, 28: 690-698

Beb, J. and Kersey, J. (2003). *"Potential Impact of Climate Change on Waste Managemen"*. Northwich, Cheshire: Entec UK Ltd.

Berge, N.D., Ro, K.S., Mao, J.D., Flora, J.R.V., Chappell, M.A., Bae, S.Y., (2011) Hydrothermal Carbonization of Municipal Waste Streams. *Environmental Science and Technology*, 45 (13):5696-5703

Bergius, F., (1913). "Formation of Anthracite". *Zeitschrift Fur Elektrochemie Und Ang ewandte Physikalische Chemie*, 19: 858-860.

Bingemer, H.G and Crutzen, P.J (1987) "Production of Methane from Solid Wastes" *Journal of Geophysical Research* 92:2181-2187

Bhide, B and Sunderasan, H (1983) "Solid Waste Management in Developing Countries" New Delhi: Indian National Scientific Documentation Centre: 221-225

Bogner, J., M. Abdelrafie Ahmed, C. Diaz, A. Faaij, Q. Gao, S. Hashimoto, K Mareckova, R. Pipatti, T. Zhang (2007), "Waste Management, in Climate Change Mitigation. Contribution of Working Group III to The Fourth Assessment Report of the Intergovernmental Panel on Climate Change [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. 235-250

Bogner, J, Pipatti R, Hashimoto S, Diaz C, Mareckova K, Diaz L (2008) "Mitigation of Global Greenhouse Gas Emissions from Waste: Conclusions and Strategies from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report". *Journal of Waste Management and Research* 26:11-32.

Boldrin, A., J.K. Andersen, J. Moller, E. Favoino, and T.H. Christensen (2009). "Composting and Compost Utilization: Accounting of Greenhouse Gases and Global Warming Potentials". *Journal of Waste Management and Research* 27: 800-812.

BREF (2005) "European IPPC Bureau. Reference Document on the Best Available Technology for Waste Incineration", Seville, July.

Haug, A, Roger, T, Arbor, A (1994) Compost Engineering Principles and Practices, Science Publishers, First Edition

Chertow, M.R. (2009). "The Ecology of Recycling". *The UN Chronicle Online*, Special Climate Change Issue.

Chertow, M.R. and D.R. Lombardi (2005). "Quantifying Economic and Environmental Benefits of Co-Located Firms". *Journal of Environmental Science Technology*. 39 (17): 6535–6541.

Chilton, N, Jack N Losso, Wayne E, Marshall and Ramu M Rao. (2002). "Physical and Chemical Properties of Selected Agricultural By- Product-Based Activated Carbons and their Ability to Adsorb Geomin."*Journal of Bioresource Technology* .84: 177-185.

Chintan, Q.T (2009). "Cooling Agents": An Analysis of Climate Change Mitigation By The Informal Recycling Sector in India. Report prepared in Association with the Advocacy Project, Washington DC.

Christensen, T.H., Gentil, E Boldrin, A. Larsen, A.W. Weidema B.P., and Hauschild, M. (2009). “Carbon Balance, Carbon Dioxide Emissions and Global Warming Potentials in LCA- Modelling of Waste Management Systems”. *Journal of Waste Management and Research* 27: 707-715.

Cimino, J.A. (1975) “Health and Safety in the Solid Waste Industry”. *American Journal of Public Health*.32:16

Coker, A.O., Akanmu, A.M., Sridhar, M.K.C. and Aladenola, I.O. (2000). “Management of Pollution from an Hospital Incinerator in Nigeria” in: Air Pollution, WIT Press, Southampton, UK, ISBN: 1-85312-822-8, 253-260.

CPL Caron Link (2006) "Properties of Activated Carbon", Accessed 2nd May, 2013

Damgaard, A., Larsen, A. W.and Christensen, T.H. (2009). “Recycling of Metals: Accounting of Greenhouse Gases and Global Warming Contributions”. *Waste Management and Research*: 27: 773-780.

Dehoust; (Oko-Institut e.V.) and Vogt and Giegrich (ifeu-Heidelberg GmbH) (2005). “Status Report on the Waste Sector’s Contribution to Climate Protection and Possible Potentials”. Commissioned by the German Federal Environmental Agency, August.

Demirbas, A., (2000). “Mechanisms of Liquefaction and Pyrolysis Reactions of Biomass. *Energy Conversion and Management*, 41: 633-646

Demirbas, A., Arin, G. (2002). “An Overview of Biomass Pyrolysis”. *Energy Sources.* 24: 471-482.

Department for Environment Food and Rural Affairs (2008) “*Future Water. The Government’s Water Strategy for England”* (Stationery Office).

Department of Research and Statistics, Ondo State Ministry of Finance, Economic Planning and Budget (2000) “2011, Census Projection from Digest of Demographic Statistics of Ondo State”

Diaz, L.F. and Golueke, C.G. (1985) “Solid Waste Management in Developing Countries” *Bio-Cycle*, 26: 46-52

Doorn, M, Liles D, Thorneloe S (2000). “Quantification of Methane Emissions from Latrines, Septic Tanks and Stagnant, Open Sewers in the World”. In: J van Ham, APM Baede, LA Meyer, R Ybema (eds). Non-CO2 Greenhouse Gases: Scientific Understanding, Control and Implementation. Kluwer Academic Publishers, Drodrecht ISBN 0-7923-6199-7

Drage, T.C., Smith, K.M. Pevida, C. Arenillas A and Snape, C.E. (2009). "Development of Adsorbent Technologies for Post-Combustion CO_2 Capture". *Energy Processes*. 1: 881-884.

Dreisbach, F., Staudt, R. and Keller, J.U. (1999). "High Pressure Adsorption Data of Methane, Nitrogen, Carbon Dioxide and Their Binary and Ternary Mixtures on Activated Carbon". *Adsorption* 5:215-227.

Elliott, S (2001) "Compensation of Atmospheric CO_2 Buildup through Engineered Chemical Sinkage". *Geophysical Research Letters*, 28(7): 1235-1238.

Encarta, 2008. Microsoft Encarta Dictionary. Redmond, WA, United State of America

Energy Information Agency (EIA) (2009) *Table 2.1* "Energy Consumption by Sector", eia.doe.gov.emeu/mer/consump.html: Assessed on 15th March, 2013

Erlach, B., Harder, B., Tsatsaronis, G., (2012). "Combined Hydrothermal Carbonization and Gasification of Biomass with Carbon Capture". *Energy*, 45: 329-338.

Escala, M., Zumbuehl, T., Koller, C., Junge, R., Krebs, R., (2013). "Hydrothermal Carbonization as an Energy-Efficient Alternative to Established Drying Technologies for Sewage Sludge: A Feasibility Study on a Laboratory Scale". *Energy and Fuels,* 27: 454-460.

Eunomia Research and Consulting (ERC) (2002), "Economic Analysis of Options for Managing Biodegradable Municipal Waste" – Final Report to the European Commission.

Eunomia Research and Consulting (ERC) (2008a). "Greenhouse Gas Balances of Waste Management Scenarios" – *Report for the Greater London Authority.*

Eunomia Research and Consulting (ERC) (2008b). "Meeting Ireland's Waste Targets"*: The Role of MBT – Final report to Greenstar.*

Fakere, A., Fadairo G and Oriye O (2012) "Domestic Waste Management and Urban Residential Environment: Focus on Akure, Nigeria". *International Journal of Engineering and Technology* 2(5):878-887

Favoino, E. and Hogg, D. (2008). "The Potential Role of Compost in Reducing Greenhouse Gases". *Journal of Waste Management and Research* 26: 61-69.

Federal Environmental Protection Agency: FEPA (1995) "Nigerian Ambient Air Quality Standard".

Fowles, M. (2007). "Black Carbon Sequestration as an Alternative to Bioenergy". *Biomass and Bioenergy*.31: 426-432.

Gadkaree, K.P (1998) "Carbon Honeycomb Structures for Adsorption Applications." Carbon, 25: 981-989,

Gartner Lee. (1991) "Procedural Manual for Municipal Solid Waste Composition Analysis". Report GL 90-738. Prepared for British Columbia Ministry of Environment, Gartner Lee Limited. 1-35

Gipe, P (1995) "Wind Energy Comes of Age", New York: John Wiley & Sons. 117-123

Global Alliance of Waste Pickers/Recyclers and Allies (2009). "Various Statements Issued at the 15th Council of Parties Meetings, Copenhagen, December.

Gonzalez, T., Terron, M.C Yague, S. Junca H. and. Carbajo J.M (2008). "Melanoidin-Containing Wastewaters Induce Selective Laccase Gene Expression in the White-Rot Fungus*trametes* sp. I-62". *Residual Microbiology* 159: 103-109.

Goto, M., Obuchi, R., Hiroshi, T., Sakaki, T., Shibata, M., (2004). "Hydrothermal Conversion of Municipal Organic Waste into Resources". *Bioresource Technology*, 93: 279-284.

Gribben, J (1986) "Temperature Rise in Global Green House". *New Scientist*, 15: 31-32.

Gyalpo, T (2008) "Quantification of Methane Emissions from Uncontrolled Dumping Solid Waste and from Different Sanitation Systems in Developing Countries". Term Paper Institute of Biogeochemistry and Pollutants Dynamics, Department of Environment Sciences, ETH Zurich. Assessed on 13th March, 2013

Hansen, J., (2004). "Riscaldamento Globale: Una Bomba da Disinnescare". (Global Warming: a Bomb to be defused). Le Scienze, 428: 76.

Hao, W., Björkman, E., Lilliestråle, M., Hedin, N., (2013). "Activated Carbons Prepared from Hydrothermally Carbonized Waste Biomass used as Adsorbents for CO_2".*Applied Energy*, 112: 562-532.

Harris, S. (2007). "The Potential Role of Industrial Symbiosis in Combating Global Warming". Proceedings of the International Conference on Climate Change, 29-31 May 2007, Hong Kong.

Hao, W. Bjorkman, E Lilliestrale, M. and Hedin, N. (2013). “Activated Carbons Prepared from Hydrothermally Carbonized Waste Biomass used as Adsorbents for CO_2”. *Applied Energy*, 112: 526-532.

Haug X, Traina S and Logan T. (1994). “Physico-Chemical Properties of Municipal Solid Waste Composts”. *Journal of Environmental Quality* 21:318-329

Heidari, A, Younesi, H. Rashidi, A. and Ghoreyshi, A. (2014). “Adsorptive Removal of CO_2 on Highly Microporous Activated Carbons Prepared from *Eucalyptus Camaldulensis* Wood: Effect of Chemical Activation”. *Journal of Taiwan Institution of Chemical Engineering*, 45: 579-588

Hoornweg D. (1999). “What a Waste: Solid Waste Management in Asia”. The International Bank for Reconstruction and Development for The World Bank. Washington, D.C 4-25

Hoornweg, D., Thomas L and Otten, L (1999). “Composting and its Applicability in Developing Countries”. Urban Waste Management Working Paper Series 8.Washington, DC; 46

Houghton, J.T (1995), “Climate Change 1994, Radiative Forcing of Climate Change and an Evaluation of the IPCC IS92 Emission Scenario”, ed. Cambridge: Cambridge University Press.

Hwang, I.H., Matsuto, T., Nakagishi, T., Matsuo, T., (2010). “Recovery of Solid Fuel From Municipal Solid Waste Using Hydrothermal Treatment” Third International Symposium on Energy from Biomass and Waste, Venice, Italy.

Hwang, I.H., Aoyama, H., Matsuto, T., Nakagishi, T., Matsuo, T. (2012) Recovery of Solid Fuel from Municipal Solid Waste by Hydrothermal Treatment Using Subcritical Water. *Waste Management*, 32(3): 410-416.

International Energy Agency (2000) World Energy Outlook

International Energy Agency (2005). “CO_2 Emissions from Fuel Combustion” 191.2003.2005 Edition. Paris, France: IEA

Intergovernmental Panel on Climate Change (IPCC) (2006). “2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 5 Waste. Chapter 3, Solid Waste Disposal. IPCC/OECD/IEA, Paris, France

International Solid Waste Association (ISWA) (2009). “Waste and Climate Change” ISWA White Paper. AKA Print, Aarhus, Denmark

IUPAC. (1972) "Manual of Symbols and Terminology, Application 2, Part 1, Colloid and Surface Chemistry." *Journal of Pure and Applied Chemistry*, 31: 578.

Kelleher, M. (2007), "Anaerobic Digestion Outlook for Municipal Solid Wastes Streams" *Bio Cycle* 48(8): 51.

Khalil, M.A.K., 1999. "Non-CO_2 Greenhouse Gases in the Atmosphere". *Journal of Energy and the Environment* 24: 645–661.

Khan, I.H and Ahsan, N (2003) "Textbook of Solid Wastes Management" First Edition CPS Publishers, Darya Ganj, New Delhi 22

Kim, S. and B.E. Dale (2004). "Global Potential Bioethanol Production from Wasted Crops and Crop Residues". *Biomass and Bioenergy*: 26(4):361-375.

Kumar, S, Gaikwad SA, Shekdar AV (2004). "Estimation Method for National Methane Emission from Solid Waste Landfills". *Journal of Atmospheric Environment*, 38: 3481-3487

Kruse, A., Funke, A., Titirici, M.-M., (2013). "Hydrothermal Conversion of Biomass to Fuels and Energetic Materials". *Current Opinion in Chemical Biology*, 17: 515-521.

Lackner, K.S., Ziock, H and P. Grimes (1999). "Carbon Dioxide Extraction from Air: Is it an Option?" In Proceedings of the 24th International Conference on Coal Utilization and Fuel Systems. Clearwater, Florida.

Lackner, K.S., Grimes, P and Ziock, H (1999). "The Case for Carbon Dioxide Extraction from Air. Source Book" *The Energy Industry's Journal of Issues*, 57(9): 6-10.

Lacoste, E. and Chalmin, P. (2006). "From Waste to Resource –2006 World Waste Survey", Economica Editions. Paris

Larsen, A. W., H. Merrild, and T.H. Christensen (2009). "Recycling of Glass Accounting of Greenhouse Gases and Global Warming Contributions". *Journal of Waste Management and Research* 27: 754-762.

Lehmann, J., Gaunt, J., Rondon, M. (2006). "Bio-char Sequestration in Terrestrial Ecosystems - A Review" .*Mitigation and Adaptation Strategies for Global Change.* 11: 403-427.

Lehmann, J., Joseph, S. (2009). "Biochar for Environmental Management". Earth Scan, London. 234-256

Leton, T.G and Omotosho, O (2004) “Landfill Operations in the Niger Delta Region of Nigeria”. *Journal of Engineering Geology* 73(1-2): 171-177

Li, L., Diederick, R., Flora, J.R.V., Berge, N.D., (2013). “Hydrothermal Carbonization of Food Waste and Associated Packaging Materials for Energy Source Generation”. *Waste Management,* 33: 2478-2492.

Li, L., Liu, S. and Zhu, T (2010). “Application of Activated Carbon Derived from Scrap Tires for Adsorption of Rhodamine *Journal of Environmental Science* 22: 1273-1280

Libra, J.A., Ro, K.S., Kammann, C., Funke, A., Berge, N.D., Neubauer, Y., Titirici, M.M., Führer, C., Bens, O., Jürgen, K., K.-H., E., (2011). “Hydrothermal Carbonization of Biomass Residuals: A Comparative Review of the Chemistry, Processes and Applications of Wet and Dry Pyrolysis”. *Biofuels*, 2: 89-124.

Linares-Solano, A., Martı´n-Gullon, I., C. Salinas-Martínez de Lecea, B. Serrano Talavera (2000). “Activated Carbons from Bituminous Co*al;* Effect of Mineral Matter Content” Fuel. 79(6): 635–643.

Liu, Z.G., Zhang, F.S., Wu, J.Z., (2010). “Characterization and Application of Chars Produced from Pinewood Pyrolysis and Hydrothermal Treatment”. *Fuel,* 89: 510-514.

Lou, X.F. and Nair J. (2009). “The Impact of Landfilling and Composting on Greenhouse Gas Emissions – A Review”, *Journal of Bioresource Technology,* 100: 3792–3798.

Malghani, S., Gleixner, G., Trumbore, S.E., (2013). “Chars Produced by Slow Pyrolysis and Hydrothermal Carbonization Vary in Carbon Sequestration Potential and Greenhouse Gases Emissions. *Soil Biology & Biochemistry,* 62: 137-146.

Medina, M. (2008). “The informal Recycling Sector in Developing Countries – Organizing Waste Pickers to Enhance Their Impact”. Public-Private Infrastructure Advisory Facility, Gridlines, Note No 44.

Meisen, A. and Shuai, X. (1997). “Research and Development Issues in CO_2 Capture. *Energy Conversion Management* 38: S37-S42.

Merrild, H., A. Damgaard, T. H. Christensen (2009). “Recycling of Paper: Accounting of Greenhouse Gases and Global Warming Contributions”. *Waste Management and Research*: 27:746-753.

Minkova, V, Razvigorova M, Goranova M, Ljutzkanov L and Angelova G. (2001)“Effect of Water Vapour on the Pyrolysis of Solid Fuels” *Fuel,* 70:713-719.

Møller, L (2009). "Anaerobic Digestion and Digestate Use: Accounting of Greenhouse Gases and Global Warming Contribution". *Journal* of *Waste Management and Research*: 27: 813-824.

Monni, S., Pipatti, R., Lehtilla, A., Savolainen, I. and Syri, S. (2006). "Global Climate Change Mitigation Scenarios for Solid Waste Management". Technical Research Centre of Finland: VTT Publications. Espoo.

Mor, S., De Visscher, A., Ravindra, K., Dahiya, R.P., Chandra A., Van Cleemput, O., (2006a). "Induction of Enhanced Methane Oxidation in Compost: Temperature and Moisture Response". *Journal of Waste Management*, 26(4): 381-388.

Nabegu, A.B (2011) "Solid Waste and Its Implications for Climate Change in Nigeria". *Journal of Human Ecology* 34(2): 67-73

National Population Commission (Nigeria). 2004: "National Policy on Population For Sustainable Development 2004". Abuja: NPC.

Ogedengbe, P. S and Oyedele, J. B. (2006). "Effect of Waste Management on Property Values in Ibadan, Nigeria". *Journal of Land Use and Development Studies*, 2(1): 133-144

Ogwueleka, T. (2009). "Municipal Solid Waste Management in Nigeria" *Iran Journal of Environmental Health, Science and Engineering*, 6(3):173-180

Okudo, O. B (2010). "Comparative Analysis of Solid Waste Management Strategies in Some Cities in Nigeria". (Unpublished Masters in .Engineering Thesis). University of Nigeria, Nsukka.

Olanrewaju, O. O. and Ilemobade, A. A. (2009). "Waste to Wealth: A Case Study of the Ondo State Integrated Waste Recycling and Treatment Project, Nigeria". *European Journal of Social Sciences*, 8(1): 2-7

Ondo State Ministry of Finance Department of Research and Statistics (ODMOFDRS) (2009) "Demography and Vital Statistics of Ondo State" 10

Organization for Economic Cooperation and Development (OECD), International Energy Agency (IEA) (1998) World Energy Outlook, International Institute for Applied System Analysis/World Energy Council Global Energy Perspectives.

Oreyomi. M.K. (1998). "Selective Topic on Environmental Health Technology". Term Paper Presented to the Department of Environmental Health and Epidemiology UNIFE. Unpublished

Otowa, T, Nojima, Y. & Miyazaki T. (1997) “Development of KOH Activated High Surface Area Carbon and Its Application to Drinking Water Purification”. *Carbon*. 35(9): 1315–1319.

Oyinlola. A. K. (1998). “Waste Reuse and Recycling”. A Paper Presented at the Petroleum (Special) Trust Fund Stakeholders Technical Workshop, PTF Head Office, Abuja.

Papageorgiou, A., Barton J.R. and Karagiannidis A (2009). “Assessment of the Greenhouse Effect Impact of Technologies used for Energy Recovery from Municipal Waste: A Case for England”, *Journal of Environmental Management*, 90: 2999–3012.

Paraknowitsch, J.P., Thomas, A., Antonietti, M., (2009). “Carbon Colloids Prepared By Hydrothermal Carbonization as Efficient Fuel for Indirect Carbon Fuel Cells”.*Chemistry of Materials*, 21: 1170-1172

Peavy, S.H, Rowe, D.R and Tchobanoglous, G. (1985) “Environmental Engineering” McGraw-Hill International Editions, Civil Engineering Series, McGraw-Hill Book Company, New York, 573-652

Peter, J F., Harris, L, Liu, Z., & Suenaga, K (2008) “Imaging the Atomic Structure of Activated Carbon” *Journal of Physics*, 20 362201 (5pp), Centre for Advanced Microscopy, J J Thomson Physical Laboratory, University of Reading, UK, and Research Centre for Advanced Carbon Materials, National Institute of Advanced Industrial Science and Technology (AIST), Japan ,Published by Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH (German Technical Cooperation), (July 2009). “Selection and safe use of alternatives to CTC Activated Carbon Testing,” National CTC Phase-out Plan Edition 1, Philippe Serp, José Luis Figueiredo,(2009) Carbon Materials for Catalysis, Wiley,550

Pidwirny, M. (2006). “Causes of Climate Change”. Fundamentals of Physical Geography (2nd Ed) .Retrieved from http://www.physical geography.net/fundamentals/7y.html. Assessed on 15th April, 2014

Pimenteira, C.A.P., Pereira, A.S. Oliveira, L.B. Rosa, L.P. Reis, M.M and. Henriques R.M (2004), “Energy Conservation and CO_2 Emission Reductions Due to Recycling in Brazil”. *Waste Management* 24:889-897.

PROGNOS (2008). Resource Savings and CO_2 Reduction Potential in Waste Management in Europe and its Possible Contribution to the CO_2 Reduction Target in 2020.

Qureshi, K., Bhatti, I., Kazi R Abdul Khalique Ansari. (2008) “Physical and Chemical Analysis of Activated Carbon Prepared from Sugarcane

Bagasse and Use for Sugar Decolourization." *International Journal of Chemical and Biological Engineering.* 1:144-148

Ramke, H.G., Blöhse, D., Lehmann, H.J., Fettig, J., (2009). "Hydrothermal Carbonization of Organic Waste. *20th International Waste Management and Landfill Symposium*

Recycled Organics Unit (ROU), The University of New South Wales (2006). "Life Cycle Inventory and Life Cycle Assessment for Windrow Composting Systems". Report for the Department of Environment and Climate Change, NSW.

Rosenzweig, C., Iglesias, A., Yang, X.B., Epstein, P.R., Chivian,E .(2002). "Climate Change and Extreme Weather Events: Implications for Food Production, Plant Diseases, and Pests". *Global Change Human Health* 2(2): 90 – 104.

Royal Melbourne Institute of Technology (RMIT) (2009). "Extended Environmental Benefits of Recycling Project".

Ranney, J.W. and Cushman J.H, (1991) "Energy from Biomass", in the Energy Source Book Howes and A. Fainberg, Editors. American Institute of Physics: New York.

Romanos, J (2012). "Nanospace Engineering of KOH Activated Carbon". *Nanotechnology* 23(1) 5-11 http://iopscience.iop.org/0957-4484/23/1/015401/. Assessed on March 13th, 2013

Savas, E. S. (1977) "The Organization and Efficiency of Solid Wastes Collection". Lexington Books, England 13-24

Savova, D, Apak E, Ekina E, Yardim F, Petrov N, Budinova T, Razvigorova M and Minkovo V. (2001) "Biomass Conversion to Carbon Adsorbents and Gas" *Journal of Biomass and Bioenergy*, 21: 133-142.

Scheutz, C., P. Kjeldsen, E. Gentil (2009). "Greenhouse Gases, Radioactive Forcing, Global Warming Potential and Waste Management – an Introduction". *Waste Management and Research* 27: 716-723.

Seifritz, W. (1993), "Partial and Total Reduction of CO_2 Emissions of Automobiles Using Carbon Dioxide Traps". *International Journal of Hydrogen Energy*, 18: 243-251.

Sevilla, M and Fuertes A.B (2011) "Sustainable Porous Carbons with Superior Performance for Carbon Dioxide Capture". *Journal of Energy Environment Sciences 4: 1765 - 1771*

Sevilla, M., Macia´-Agullo´, J.A., Fuertes, A.B., (2011b.) "Hydrothermal

Carbonization of Biomass as a Route for the Sequestration of CO_2: Chemical and Structural Properties of the Carbonized Products. *Biomass and Bioenergy*, 35: 3152-3159

Sevilla, M, Valle-Vigon P, Fuerte AB (2011) "N-doped Polypyrrole-Based Porous Carbons for Carbon Dioxide Capture". *Journal of Advance Function Material* 21:2781–2787

Sharholy, M., K. Ahmad, G. Mahmood, R.C. Trivedi (2008). "*Municipal Solid Waste Management in Indian Cities – A Review". Waste Management* 28:459-467.

Shigley, J.E and Mischke, C.R (1989) "Standard Handbook of Machine Design" Second Edition Mac. Graw Hill New York 1234-1236

Shih, C.C. and Chang, J.R., (2005), "Genesis and Growth of Platinum Subnano-Particles on Activated-Carbon Characterized by X-ray Adsorption Spectroscopy: Effects of Preparation Conditions", *Journal of Materials. Chemistry and Physics* 92: 89-97.

Smith, A., Brown, K., Ogilvie, S., Rushton, K. and Bates,J. (2001). "Waste Management Options and Climate Change. Final Report to the European Commission, DG Environment" Brussels: 205.

Sridhar, M.K.C (1998) "Wastes- Their Impact on Environment" Paper presented at a Training Workshop on Planning and Management of Wastes Systems and Environmental Care held at IBWMA Hall, Ibadan and Sponsored by UNICEF B Residential, November 18-19: 2-3

Suzuki, T., Suzuki, K., Takahashi, Y., Okimoto, M., Yamada, T., Okazaki, N (2007). "Nickel-Catalyzed Carbonization of Wood for Coproduction of Functional Carbon and Fluid Fuels I: Production of Crystallized Mesoporous Carbon" *The Japan Wood Research Society*, 53(1):54-56

Tamilarasan, P. and Ramaprabhu, S. (2012). "Polyaniline-Magnetite Nanocapsules Based Nanocomposite for Carbon Dioxide Adsorption". *International Journal Greenhouse Gas Control*, 10: 486-493

Teukolsky, S.A. and Vetterling, W.T. (1987). "Numerical Recipes", University Press, Cambridge, UK.

Tchobanoglous, G., Thiessen, H., Vigil, S., 1993. McGraw-Hill Series in *Water Resources and* 5 *Environmental Engineering*, McGraw-Hill, New York (Chapters 3 and 11).

The MathWorks Inc. (2005) MATLAB 7.0 (R14SP2)

U.S. Department of Energy, (1993) “Emission of Greenhouse Gases in the United States 1985-1990”, 4

UNCHS (Habitat)/UNEP (1997) “City Experiences and International Support”. 2: 67-70

UNEP (2009). RIM Background Paper for Consultations, 3rd Draft – October 2009.

UNFCCC (2000): “National Communications from Parties included in Annex I to the Convention: Greenhouse Gas Inventory Data from 1990 to 1999” Retrieved from https://www.scribd.com/document/249484418/ Methane-From-Solid-Waste. Assessed on 17th March 2013

United States Environmental Protection Agency. (2006). “Global Anthropogenic Non-Co Greenhouse Gas Emissions”*: 1990020*. Retrieved from http://www.epa.gov/climatechange/economics/downloads /EPA_NonCO2_Projections_2011_draft.pdf. Assessed on 15th April, 2013

United States Environmental Protection Agency. (2009). “Opportunities to Reduce Greenhouse Gas Emissions through Materials and Land Management Practices”. Retrieved from www.epa.gov/oswer/docs/ghg_land_ and_materials_management.pdf. Assessed on 25th February, 2013

United Nations Environment Programme (2009). “Waste and Climate Change: Global Trends and Strategy Framework”. Retrieved from http://www.unep.or.jp/ietc/ Publications/spc/Waste&ClimateChange /Waste&ClimateChange.pdf Assessed on 25th February, 2013

Utsev, J. T. (2011). “Modelling the Optimum Conditions for Solar Enhanced Waste Stabilization Pond”. Unpublished Ph.D Thesis University of Nigeria, Nsukka.

Visvanathan, C (2006). “Solid Waste Management in Asian Perspectives”. School of Environment, Resources and Development, Asian Institute of Technology. http://www.swlf.ait.ac.th/NewInterface/Research%20 Reports.htm Accessed 17th December, 2014.

Wang, R, Wang P, Yan X, Lang J, Peng C, Xue Q (2012) “Promising Porous Carbon Derived from Celtuce Leaves with Outstanding Super Capacitance and CO_2 Capture Performance”. *ACS Applied Mater Interfaces* 4:5800–5806

Wikipedia (2010) “Akure Kingdom” www.tenwikipedia.org/wiki/mainpage Assessed on 12th January, 2013.

WRAP (2006) "Environmental Benefits of Recycling" An International Review of Life Cycle Comparisons for Key Materials In the UK Recycling Sector. Retrieved from http://www.wrap.org.uk/sites/files/wrap /Environmental_benefits_of_recycling_2010_update.3b174d59.8816.pdf. Assessed on 11th February, 2013.

WRAP (2008), "Carbon Dioxide Impacts of Transporting the UK's Recovered Paper and Plastic Bottles to China" Retrieved from http://www.envirocentre.ie/includes/documents/CO2_Impact_of_Export_Report_v8_1Aug08.1bd19928.pdf. Assessed on 11th February, 2013

Xu, X., Song, C. Andresen, J.M. and Miller, M.G. (2002). Novel Polyethylenimine-Modified Mesoporous Molecular Sieve of MCM-41 Type as High-Capacity Adsorbent for CO_2 Capture". *Energy Fuels* 16: 1463-1469.

Yashuhiro, M, Hisayuki Y.I, Yousuke S, Hidekazu M and Shoichi T (2007) "Diurnal and Seasonal Variations in Atmospheric CO_2 in Sapporo, Japan: Anthropogenic Sources and Biogenic Sinks" *Geochemical Journal* 41: 429 - 436

Zafar, S (2009) "Gasification of Municipal Solid Waste" *Energy Manager* 2(1): 47-51

Zhao, A., (2012). "Adsorptive Removal of CO_2 by Amine Functionalized Sorbents: Experimental and Kinetics Study". M.Sc. Thesis, University of Alberta, Alberta, Canada.

Zhu, B, Qiu, K, Shang, C and Guo, Z (2015) "Naturally Derived Porous Carbon with Selective Metal- and/or Nitrogen-Doping for Efficient Carbon Dioxide Capture and Oxygen Reduction" *Journal of Materials Chemistry*. 72: 234 – 245