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EFFECT OF POST-TREATMENT (COMPOSTING) METHODS OF DIGESTATE FROM DRY FERMENTATION ON COMPOST QUALITY

BY

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DECLARATION

I hereby declare that this submission is my own work towards the MSc. and that, to the best of my knowledge, it contains no material previously published by another person nor material which has been accepted for the award of any other degree of the University, except where due acknowledgement has been made in the text.

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DEDICATION

I dedicate this study to my supervisor Prof. Ebenezer Mensah, for his continuous support throughout this study. I also dedicate this to my parents, Mr. and Mrs. Kukah and my siblings, Mawuena Akosua Kukah and Seyram Ohenewaa Kukah.

ABSTRACT

Over the years, the volume of municipal solid waste (MSW) from various communities has been increasing day by day as a result of rapid growth in population and urbanization. This has brought about major sanitation problems in towns and cities in the country. The growing waste quantity and its detrimental effects on humans and their environment has led to the invention of various processes for treating the organic fraction of municipal solid waste stream.

Dry anaerobic digestion is currently gaining prominence because of its easy application. However, digestate, the by-product of digestion, if not utilized will add up to various waste streams. Composting, which involves the aerobic biological decomposition of organic materials, can be employed to post-treat the digestate to produce a stable humus-like product.

The objective of this study was to conduct a comparative study of untreated digestate and post-treated digestate from three different methods of post-treatments (composting). To achieve the objective, the physicochemical parameters of the digestate from a dry anaerobic digestion plant at Kwame Nkrumah University of Science and Technology (KNUST) were analyzed after which the digestate was post-treated for 58 days with three different methods of composting: vermicomposting, turned windrow composting and co-composting digestate with fresh food waste. Temperature was monitored daily and the physicochemical parameters of the composts produced were analyzed to determine the effects of each of the composting methods on the quality of composts produced.

At the end of the study, it was realized that vermicomposting yielded the best quality compost and considered the best method for composting of the digestate, since it had all

its physicochemical parameters falling within the standard values required for composts. The co-compost, however, produced the lowest quality compost.

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CHAPTER ONE

INTRODUCTION

1.1 Background of Study

Over the years, the volume of municipal solid waste (MSW) from various communities has been increasing day by day as a result of rapid growth in population and urbanization. A considerable fraction of this solid waste stream is biodegradable. In Ghana, very few of these wastes are sent to dump sites but the majority ends up in drains, water bodies and open places due to improper waste management systems. This leads to drainage channels becoming blocked with solid waste, thus contributing to environmentally related sicknesses like malaria and cholera, as the drains become the breeding grounds for disease causing organisms. Open dumping, open burning, controlled burning and tipping at dumpsites have become popular processes of waste disposal. This has brought about major sanitation problems in towns and cities as they have been inundated with management of municipal solid matter. Untreated and unmanaged biodegradable waste creates odour, and leads to adverse environmental impacts like air pollution. For instance, Bentil (2013) reported that in Accra, the dumping of garbage at the Achimota dump site had to be suspended from the 10th of January 2013 as a result of the stench that emanated from the dumpsite. The Accra Metropolitan Assembly (AMA) consequently had to cover the dump site with laterite as part of measures to reduce the nauseating stench which had engulfed the area and its surrounding communities.

The current state of waste management in Ghana is of great concern. The traditionally applied methods of waste disposal where about 58 % waste from households are disposed at public dump sites, a quarter of households dispose of their solid waste at places like valleys, pits, bushes, in and around water bodies, open gutters or on undeveloped plots of land, 8 % burn openly, 4 % bury, and only about 5 % of households have their solid waste collected in an organized way, as stated by the United Nations' Human Development Report (2007) have been unsuccessful. This has resulted in contamination of water and land. The absence of an integrated approach to waste management in the country is therefore of major concern.

Anaerobic digestion (AD) constitutes one of the main alternatives to manage these wastes and is based on the anaerobic conversion of organic waste, obtaining biogas and a digested substrate called digestate. AD is a process whereby in the absence of oxygen, microbiological organisms decompose organic matter into methane and carbon-dioxide (Burri and Martius, 2011). It combines biogas production with treatment of the organic fraction of waste materials and residues, and the process can be dry or wet. Dry Anaerobic Digestion (DAD) is particularly promising technology (Robbiani, 2012), as its simple design allows construction and operation at low cost. It is increasingly being implemented in Europe.

A locally adapted DAD plant has been developed, built and tested at the Kwame Nkrumah University of Science and Technology (KNUST) campus in Ghana, for further studies and to implement biogas production into the management of biodegradable waste in Kumasi. The plant was built and used between 2010 and 2012 as a result of a collaborative study between the Swiss Federal Institute of Aquatic Sciences and Technology (Eawag), Department for Water and Sanitation in Developing Countries (SANDEC) in Switzerland and the Department of Agricultural Engineering, Kwame

Nkrumah University of Science and Technology (KNUST), Ghana. During the first phase, two Swiss students, Matthias Burri and Gregor Martius built and tested the biogas plant. In the second phase, Renate Diggelmann and Lucien Biolley, who are also Swiss students, ran additional test and tried to optimize the digestion process. Their test also led to the production of digestate that could be processed for further use in agriculture and also could be reused in subsequent batches as inoculants for further production of biogas. The current phase of the project looked at processing the digestate into compost for agricultural use.

Dry anaerobic digestion offers the possibility to produce renewable energy, and at the same time generates a digestate which can be improved by composting for use on agricultural lands to reduce the quantity of waste being disposed of. The ability to utilize the residues of AD as soil amendment improves the economics and environmental benefits of the AD process.

Currently the most common strategy for management of MSW worldwide is tipping at landfill sites. However, in Ghana there are only two engineered landfills, located in Kumasi and Tamale. These cannot hold the ever increasing waste being generated in the two cities and it will be impossible to transport waste generated in other parts of the country to these points. As a result of higher environmental awareness, recycling and recovery, and efficient use of organic materials have now become the order of the day. It is to this effect that DAD is being considered. However, the digestates produced after the DAD, if not processed for further agricultural use, will still go back to dump sites and the landfill sites to add up to the ever increasing waste being generated. The growing interest in MSW composting has been stimulated by a desire to minimize the amount of waste entering landfills so as to extend the lifespan of landfills (Dunning *et al*., 1993).

According to Nogoh (2011), over 50 % of MSW in developing countries can be readily composted. Composting is the controlled biological decomposition of organic waste. It ensures that organic substances are reduced from large volumes to rapidly decomposable materials to small volumes of materials which continue to decompose slowly. Composting could therefore lead to reduction in environmental pollution and provide job opportunities.

In Ghana about 60-70% of the materials in waste stream are organic (NESSAP, 2010; Carboo and Fobil, 2006) and it is increasingly becoming a major source of environmental pollution in urban areas (Fobil *et al*., 2008).

Currently, Kumasi produces 1,500 metric tons of waste per day (KMA, 2010). Of this, 600 tons (40%) is organic waste. Primarily, organic waste is a major source of contamination in urban water supply and environmental pollution when left unattended to (Everett, 1992). This generates considerable quantities of leachates and obnoxious odour (Everett, 1992). Also, biodegradable wastes are not very well suited for incineration because of their high water content (Beffa, 2002). Under such circumstances, organic waste may also act as an important breeding site for disease causing organisms like flies, insects and rodents, which are vectors of diseases such as cholera, diarrhoea, dysentery and typhoid fever (Fobil *et al*., 2008). Therefore, the management of organic waste in Ghana is a key strategy for urban environmental health promotion and disease control (Fobil *et al*., 2008).

The application of composts, as sources of organic matter and plant nutrients, is a practice to improve soil physical and chemical properties that ultimately improve soil fertility status and hence reduces the need for inorganic fertilizers (Hargreaves *et al*., 2008). Composting therefore increases agricultural productivity, improves soil biodiversity and reduces ecological risks. This makes composting an attractive proposition.

1.2 Problem statement

During digestion, a large portion of nitrogen is converted into ammonium (Fricke *et al*., 2007) which can lead to potentially phyto-toxic digestates or to ammonia emissions after digestion. Digestate can also be odorous, too wet or too concentrated in phyto-toxic volatile fatty acids, preventing a direct land application (Walker *et al*., 2009). Thus, to ensure characteristics suitable for agricultural use, the digestate must be post-treated. Composting can be an adequate post-treatment for digestate since it can: stabilize their residual organic matter, reduce their phyto-toxicity (Salminen *et al*., 2001), bring changes to the heavy metal concentrations (Li and Zhang, 2000) and improve their humic potential (Meissl and Smidt, 2007).

For digestate to qualify as a soil conditioner or compost it depends on the compliance with the governing quality standards. Ability to obtain a useful product out of digestate for stable compost for agricultural use depends on the treatment given to it. Therefore, it is important to identify a method of post-treatment (composting) that will produce high quality compost for soil fertility improvement.

Generally conditions in Ghana are very conducive for composting in terms of waste composition and weather conditions. However, composting has never flourished as an option for refuse treatment and disposal. Most local authorities based on local experience, perceive the running costs of composting plants to be excessive and unjustifiable. Composting of digestate under this study is expected to be cost effective because simple and less expensive methods will be employed.

1.3 Main Objective

The main objective of the project was to undertake a comparative study of untreated digestate and post-treated digestate from three different methods of post-treatments

1.3.1 Specific Objectives

The specific objectives of the study were to:

1. Evaluate the physicochemical parameters of the fresh digestate produced from the dry anaerobic digestion plant.
2. To determine the effect of three different post-treatment (composting) methods on the quality of compost.
3. To compare the physicochemical parameters of the digestate with the composts produced.

1.4 Justification

Land degradation, threat to eco-systems from inappropriate and over use of inorganic fertilizers, pollution of the atmosphere, and loss of soil biodiversity as a result improper waste management practices have increased the global interest in organic recycling practices like composting. The potential of composting to turn waste materials into useful agricultural products makes it laudable. Composting enhances soil fertility and soil health thus increasing agricultural productivity. The availability of organic compost from various sources will have a direct positive impact on agriculture as well as improve soil biodiversity and reduce ecological risks.

Since Ghana has only two engineered landfill sites, composting digestate will imply diverting biodegradable fraction of waste from landfills to agricultural lands. This, when done, will prolong the lifespan of the landfills. Converting organic wastes into compost can substantially reduce greenhouse gas emissions, as well as reduce the negative environmental impacts.

CHAPTER TWO

LITERATURE REVIEW

2.1. Waste Management in Kumasi

The large quantities of waste generated in Kumasi are managed by dumping at landfills, and incineration. The Kumasi Metropolitan Assembly (KMA) is tasked with the management of waste in Kumasi. It does this by giving out contracts to waste management institutions including: Zoomlion Ghana Limited, Meskworld Company Limited, SAK-M Company Limited, Waste Group Company Limited, Kumasi Waste Management Limited, ABC Company Limited and Anthoco Company Limited. Two systems of collection are employed, the house-to-house collection system and the communal collection system, where waste from households are sent to centralized collection points, and the collected waste is dumped at the landfill sites (KMA, 2009).

Some of these contracted solid waste management institutions in the Metropolis do not have the requisite implement to ensure that the waste generated in the metropolis is collected, stored and transported to the final disposal site at Dompoase effectively.

The percentage composition of MSW in Kumasi is shown in Figure 2.1. The waste is characterized largely by biodegradable materials. Of the 1,500 tons of MSW generated per day, 600 tons, that is 40% of the total waste generated is organic/biodegradable. There is also a high percentage of inert materials consisting mainly of demolition waste, wood ash, sand and charcoal (Burri and Martius, 2011).

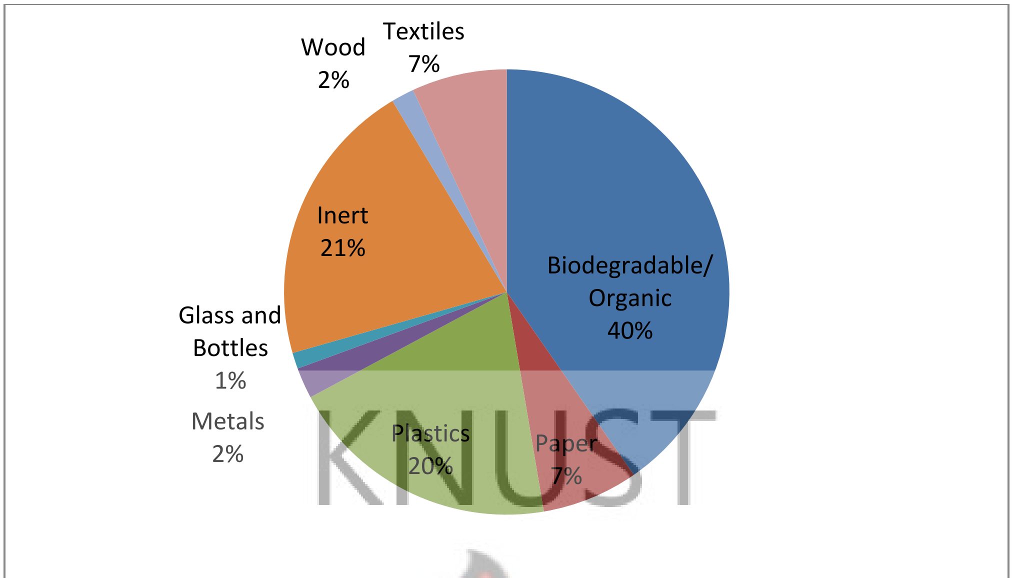

Fig 2.1 Percentage MSW composite (Ofori, 2011)

The composition of the waste is an indication that large quantities of the waste generated in Kumasi can be processed for reuse to prevent dumping them at landfills. The landfills in the metropolis are also getting filled up and waste management goes beyond disposal activities to management of all processes and resources. It includes recovery of energy from the waste, maintenance of waste, transporting vehicles and disposal and dumping facilities as well as compliance with environmental and health regulations. Waste management also ensures that resources are recaptured from the waste (Zurbrugg, 2002). These factors have led to the increasing interest in implementing integrated waste management systems. Thus attention is being drawn to the solid waste management hierarchy which is a holistic way of approaching the waste problem.

The concept of waste hierarchy (Fig 2.2) seeks first and foremost to reduce waste at source. In source reduction/minimization, waste is minimized at the point of generation by efficiently using resources to ensure that less waste is being generated. Also, using processes and technologies that require less material in the end products and produce less waste during manufacture ensures that waste is reduced at source (Nogoh, 2011). Source reduction is the most preferred waste management option.

Fig 2.2: Hierarchy of integrated solid waste management (Palczynski, 2002)

Some waste materials can be recycled and reused. Recycling ensures prolongation of the time requirement before a resource eventually goes to the dumpsite. In recycling, marketable products are produced from waste materials (Nogoh, 2011). Examples of these include the production of female sandals and shoes as well as dressing bags from pure water sachets and polythene bags and furniture from plastic bottles. Recycling methods like composting and incineration reduce large volumes of waste.

Land filling is the most economical, especially in developing countries. This involves dumping refuse into depression or closed mining site (Daskalopoulous and Auschutz, 1998). However, in recent times, acquiring land for land filling purpose is a major challenge due to increasing population and the ever increasing competition for the various uses of land. These reasons make land filling the least preferred waste management intervention. AD is therefore gaining grounds since it does not require large quantities of land for its operations.

2.2 Anaerobic Digestion (AD)

AD is a process whereby organic feedstock under anaerobic conditions produce a methane-rich gas as a renewable energy resource, and a liquid or solid digestion residues (digestate) that can be used as organic soil amendment (Barth *et al*., 2008). The digestion process can be dry, with dry solid content of about 25-30%, or wet, with solids content less than 15% (Ostrem, 2004). Apart from energy crops that are planted intentionally for AD, leftovers and residue from the food industry (Gupta *et al*., 2011), harvest residues from agricultural activities (Chen *et al*., 2010), organic fraction of MSW (Kumar and Ting, 2010) and slaughterhouse waste (Cuetos *et al*., 2010) can be used as feedstock for AD.

There are numerous designs of digestion systems all over the world, adjusted to local conditions and feedstock types. The digestion process independent of the design is influenced by the symbiotic relationship of different types of bacteria and affected by factors that include: temperature, pH, dry matter or water content, organic dry matter content (loss on ignition), total content of nitrogen, phosphorus, potassium, magnesium and sulphur, as well as the heavy metals content (lead, cadmium, chromium, copper, nickel, zinc, mercury).

2.2.1 Stages in Anaerobic Digestion

Hydrolysis

Complex organic materials like carbohydrates, proteins and fats are broken down into their constituent parts, resulting in soluble monomers. After this process, carbohydrates are converted into simple sugars, proteins to amino acids and fats to fatty acids, glycerol and triglycerides (Ostrem, 2004). Hydrolytic bacteria present form the monomers (Chaudhary, 2008). The monomers formed then become available to the next group of bacteria. $C_6H_{10}O_4$ is a chemical formula for the mixture of organic waste (Ostrem, 2004).

Acidogenesis

Obligate anaerobes and facultative bacteria are responsible for acidogenesis. Results of hydrolysis are further broken down into volatile fatty acids (acetic, propionic, butyric, valeric acids), neutral compounds (ethanol, methanol) and ammonia (Ostrem, 2004). There is also the evolution of carbon dioxide and hydrogen due to catabolism of carbohydrates. pH decreases at this level. Thus, this stage is also known as acidification (Siddharth, 2006).

Acetagenesis

The products of acidogenesis are converted into acetic acids, hydrogen, and carbon dioxide by acetogenic bacteria. The biological oxygen demand and the chemical oxygen demand of the digestion system become stabilized (Ostrem, 2004).

Methanogenesis

There is the conversion of the soluble matter into methane. Two thirds of this methane is derived from acetate conversion or the fermentation of an alcohol, such as methyl alcohol, and one third from the reduction of carbon dioxide by hydrogen. Microorganisms involved in this process are similar to those found in rumen of herbivores or in sediments (Siddharth, 2006).

2.2.2 Dry Anaerobic Digestion (DAD)

Dry anaerobic digestion involves the digestion of solid, stackable biomass and organic waste, which cannot be pumped. Its dry matter content is high ranging from 20-50 % at mesophilic temperatures and their operation is batch wise (Köttner, 2002). There are different systems in operation throughout Europe and Africa. The one staged batch process is the most common method. It does not require the mixing of biomass during fermentation, nor frequent addition of water or liquid compounds, as compared to the conventional wet fermentation systems.

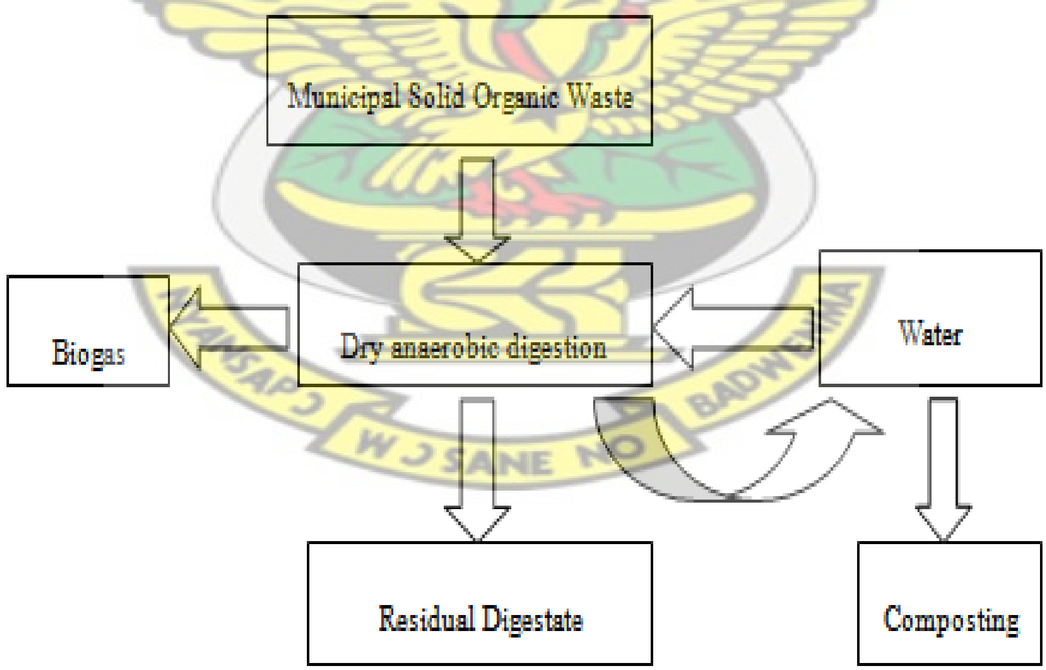

Fig. 2.3: Flow chart for the digestion process

Figure 2.3 represents the digestion process. Biogas with high energy content is produced from dry fermentation. This energy can be converted into electricity and heat in cogeneration plants, or can be used directly for cooking, lighting, heating or cooling.

Through the utilization of biomass from agriculture and communities, the waste products, that is the digestates which would have been disposed of, can be utilized directly for agriculture in soil amendment (Teglia *et al*., 2011). Most digestates are applied on agricultural land because of their high nutrient content (Salminen *et al*., 2001). An adequate technology for the digestate treatment plays also a major role in enhancing the potential to use the digestate for agricultural purposes.

The quality and composition of the digestate is dependent on the feedstock used as well as the fermentation process employed (Ostrem, 2004). A high solid retention time at thermophilic temperatures ensures that the digestate produced is safe since there is destruction of the pathogens present in the system; however, lower solid retention time at mesophilic temperatures also results in pathogen destruction (Ostrem, 2004).

Digestates are characterized with high moisture content, may contain indigested material including lignin and cell debris, have inorganic nutrients (ammonium-N and P) and may contain potentially toxic elements (PTEs) such as heavy metals (Williams and Esteves, 2011).Teglia *et al*. (2011) reported that solid digestate can be used for a directly agricultural purposes after anaerobic digestion only if it has the following characteristics:

1. It should have organic amendment property by helping in the restoration of previously degraded soil quality. This is done by improving physical attributes of the soil, like permeability and water infiltration capacity.

2. The digestate should give a fertilizing effect by providing macro and micro nutrients required for soil fertility and plant growth.
3. The digestate should not have any adverse effect on the environment.

The digestate can be converted into highly valuable compost by composting. The high quality compost, which is produced through the process, can be used as a valuable fertilizer and soil conditioner for agricultural and horticultural purposes.

2.3 Composting

Composting is the natural breakdown process of organic residues by microorganisms. It is a controlled decomposition which transforms biodegradable waste materials into biologically stable, humic substances that make excellent soil amendments (Cooperband, 2002). It is an aerobic (oxygen loving) biological manufacturing process (Coker, 2010). The microorganisms require water and nutrients, and they generate heat as they decompose wastes exothermally (Franklin County Planning Commission, 1999). Composting may begin as soon as raw materials are mixed (Pace *et al.*, 1995) and for a successful composting, substrate, moisture content, oxygen, temperature, and pH should be favourable.

2.3.1 Substrate

The substrate is made up of the feedstock, the waste to be composted. It provides the nutrients necessary for biological decomposition. It also determines the particle size of the composting materials.

Carbon/Nitrogen (C/N) Ratio

The organisms that aid in the decomposition of organic matter utilize about 30 parts of carbon of each part of nitrogen. Hence an initial C/N ratio of 25:1 to 30:1 is most favourable for composting. An appropriate C/N ratio usually ensures that other nutrients that are required for the composting process are present in adequate proportions. Lower C/N ratios increase the loss of ammonia by volatilization. However, higher ratios lead to longer composting times. The C/N ratio considers the available carbon as well as the available nitrogen. The carbon and nitrogen content in MSW may vary from sample to sample. Organisms that decompose organic matter use carbon as a source of energy, as well as for growth and nitrogen for building cell structure and reproduction (Pace *et al.*, 1995). After composting, a C/N ratio of ≤25 is required as standard (Italian Consortium Composters, 2006).

Particle size

Decomposition of organic matter by the microorganisms occurs on the surface of the organic particle. The particle size of the composting system determines the ratio of mass-to-surface and, hence, amount of a particle's mass that is exposed to microbial attack. Reducing the particle size of the composting system can help improve degradability, since the surface area of the materials is increased. However, very small particles compress together, limiting porosity as well as the movement of water and oxygen. Furthermore, the size reduction of some waste types like fresh vegetation turns the waste into a slurry material. This makes managing the composting system very difficult. Optimum composting conditions are usually obtained with particle sizes ranging from

12.7mm to 50mm average diameter (Pace *et al*., 1995) and after composting, particle size of the compost should be <25mm (Fuchs *et al*., 2001).

2.3.2 Moisture

Water is a very important requirement for the metabolic processes of microorganisms. It provides the medium for chemical reactions, transport nutrients and aid in the movement of microorganisms from one place to another. It also helps in the regulation of temperature in compost systems. Too much moisture leads to anaerobic conditions as water fills all pore spaces in the mixture leaving no room for air, a condition that is not favourable for microorganisms that require oxygen while at the same time creating ideal conditions for anaerobic microorganisms. This can result in the production of offensive odours.

Moisture content should range between 40-60 % for the compost pile and range between 35-60 % when compost is ready for agricultural use (Saifeldin *et al*., 2011). Compost which is too dry can be dusty and irritating to work with while compost which is excessively wet can be heavy and difficult to uniformly apply.

2.3.3 Oxygen

The microorganisms responsible for composting are aerobic. Composting therefore occurs in the presence of oxygen. An adequate supply of air is necessary for rapid decomposition of organic material. Aeration is also useful in reducing high initial moisture content in composting materials. Several different aeration techniques can be used. Turning the compost pile is the most common method of aeration. The compost piles when turned moves air in the compost and brings about heat removal by cooling as the water in the compost evaporates (Beffa, 2002). Hand turning of the compost piles or in units is most commonly used for small garden operations. Mechanical turning or static piles with a forced air system are most economical in large municipal or commercial operations. The oxygen concentration in air is about 21%. Oxygen concentrations of about 10-14% in compost mass are ideal and results in optimum composting conditions. Aerobic microorganisms will die at oxygen concentrations below about 5% (Recycle Organics Unit, 2007). Below the oxygen level of 10 %, parts of the compost can become anaerobic. Fermentation and anaerobic respiration reactions take over. Undesirable products such as acetic acid, ethanol, methane, and ethane will form. These are odoriferous and may inactivate beneficial compost microorganisms. Therefore, maintaining an adequate oxygen supply is essential to proper compost operations.

2.3.4 Temperature

Under aerobic conditions, temperature is the major factor that determines the types of microorganisms, species diversity, and the rate of metabolic activities. The temperature of the pile is directly related to the microorganism activity of the windrow and is a good indicator of what is going on inside (Pace *et al*., 1995). Heat, which is very important in rapid composting, is supplied by the respiration of the microorganisms as they break down the organic materials. There is a direct relationship between microbial activity and temperature of the pile. High temperatures result from biological activity, that is, heat liberated from microbial respiration and the resultant breaking of chemical bonds of substrate compounds. This heat builds up within the pile; dispersal of this heat is limited due to the insulating effects of the pile. However, moving air in the compost as a result of turning leads to heat removal by cooling as the water in the compost evaporates (Beffa, 2002).

2.3.5 pH

pH gives an idea about the survival and types of microorganisms that might be dominating the compost pile, either neutrophiles, acidophiles or alkalophiles (Norbu, 2002). The optimum pH range for composting is between 5.5 and 8. Whereas bacteria prefer a nearly neutral pH, fungi develop better in fairly acid environments. In practice, it is not easy to change the pH level in a pile. Generally, the pH drops during the composting process due to the activity of acid-producing bacteria that break down complex organic material to organic acid intermediates (Afifi *et al.*, 2012). In some cases, the pH may indicate that the process is malfunctioning. For example, if conditions within the composting mass begin to turn anaerobic, the pH may fall to about 4.5 due to the accumulation of organic acids and shifts towards neutrality as the process of composting approaches stability. The Italian Consortium Composters (2006) states that pH for compost when matured should range between 6 and 8.5.

2.4 Benefits of Composting

Composting can reduce the volume of organic waste that would have previously gone to the landfill or have ended up in gutters and water bodies. Composting converts the nitrogen contained in manure into a more stable organic form and the nitrogen that remains is less susceptible to leaching and further ammonia losses (Moon, 1997).

During composting, there is generation of heat, and large quantities of carbon dioxide (CO_2) and water vapour are released into the air. The CO_2 and water losses can amount to half the weight of the initial materials (Pace *et al*., 1995). Composting therefore reduces the weight and moisture content of the initial materials, thereby reducing the volume and mass of the final produce. It is easier to handle than manure and stores well without odours or fly problems. Because of its storage qualities, compost can be applied at convenient times of the year. The heat generated by the composting process reduces the number of weed seeds contained in the manure, resulting in a significant reduction of weeds over several years of application. Compost is an excellent soil conditioner. When applied to cropland, compost adds organic matter, improves moisture retention and soil structure, reduces fertilizer requirements and reduces the potential for soil erosion (Timmermann *et al*., 1999).

2.5 Phases of Composting

The composting process consists of four phases: the mesophilic, thermophilic, cooling and curing phases. Composting is made up of a succession of microbial activities. The environment created by one group of microorganisms ultimately promotes the activity of successor groups. The most active players in composting are bacteria, actinomycetes, fungi, and protozoa. These microorganisms are naturally present in most organic materials. Different types of microorganisms are active at different phases in the composting pile. Bacteria have the most significant effect on decomposition; they are the first to become established in the pile, processing readily decomposable substrates like proteins, carbohydrates and sugars faster than any other group.

2.5.1 Mesophilic Phase

The mesophilic phase is the first stage of the composting process with temperature ranging between 10°C and 41°C (Moon, 1997). During this stage, mesophilic bacteria which include E. coli and other bacteria from the human intestinal tract, combine carbon with oxygen to produce carbon dioxide and energy. Some of the energy produced is used by microorganisms for reproduction and growth. The rest of the energy produced is generated as heat.

At the start of the composting process, mesophilic bacteria proliferate, raising the temperature of the composting mass up till it gets to the thermophilic phase.

2.5.2 Thermophilic or High-Temperature Phase

The thermophilic phase is the second stage of the composting process. Soon after the mesophilic bacteria, thermophilic bacteria take over in the transition range of 41-52°C and can continue up to about 71°C (Moon, 1997), where there is destruction of pathogens and weed seed (Polprasert, 1996). This is because the microorganisms are very active and produce heat and occurs quickly and may last only a few days, weeks, or months. The compost pile appears to have been digested after the thermophilic stage.

2.5.3 Cooling Phase

During this phase, the mesophilic microorganisms move back into the compost pile to replace the thermophiles. The more resistant organic materials are digested. Fungi as well as macroorganisms such as centipedes, sow bugs, snails, millipedes, springtails, spiders, slugs, beetles and ants feed on the earlier inhabitants of the compost piles, and break the coarser elements down into humus.

2.5. 4 Curing Phase

During curing, the compost becomes biologically stable and microbial activity occurs at a slower rate than that during actual composting (Pace *et al*., 1995). At this stage, materials continue to break down until the last easily decomposed raw materials are consumed by the remaining microorganisms and may take three to four week (Pace *et al*., 1995).

2.6 Compost Maturity and Stability

Maturity is a term used in describing the fitness of compost for a particular end use. Stability however, refers exclusively to the ability of compost organic matter to resist further degradation (Sullivan and Miller, 2001). There is the formation of humus when compost is mature and stable. Applying unstable/immature compost on agricultural lands can be harmful to plant health. This compost when applied to soil continues to break down. Uncured compost produces phytotoxins, which deprive the soil of oxygen and nitrogen and contain high levels of organic acids. Immature composts require large amounts of oxygen due to their microbial activity. Oxygen is therefore pulled from the surrounding soil, leading to the suffocation of plant roots.

The Canadian Council of Ministers of the Environment (2005) state that compost can only be considered as mature and stable after it has under gone a minimum of 21days of curing and has met one of the following:

a) The respiration rate is less than, or equal to, 400 milligrams of oxygen per kilogram of volatile solids (or organic matter) per hour; or,

b) The carbon dioxide evolution rate is less than, or equal to, 4 milligrams of carbon in the form of carbon dioxide per gram of organic matter per day; or,

c) The temperature rise of the compost above ambient temperature is less than 8 °C.

2.7 Methods of Composting

A large number of different composting systems exist. These include passive windrows, turned windrows, aerated static piles, in-vessel channels and vermicomposting. The system used depends on the time to complete composting, the materials and volume to be decomposed, space available, the resources available and the quality of finished product required.

2.7.1 Windrow Composting

Windrow composting can be passive or turned. Turned windrows are elongated compost piles. They have cross-section that may be trapezoidal or triangular that are turned frequently to maintain aerobic conditions (Moon, 1997). Forming windrows of the appropriate size helps in maintaining the desired temperature and oxygen levels. Windrows operate most effectively at a height of 1.5 to 1.8 m. This height allows the feedstock to be insulated but prevents the buildup of excessive heat. Windrow heights vary, however, based on the feedstock. Passive windrow composting involves the compost being produced by natural aeration, over long periods of time. It is a low technology and labour approach. Aerated static pile composting is the production of compost in piles or windrows with mechanical aeration. The windrow or pile is located above air ducts, and aeration is achieved by blowing or drawing air through the composting material.

2.7.2 Vermicomposting

In many ecosystems and in agricultural systems, earthworms are highly beneficial to soil processes. Earthworms are keystone detritivores that can act as ecosystem engineers and have the potential to change fundamental soil properties, with cascading effects on ecosystem functioning and biodiversity (Hendrix and Bohlen, 2002). Earthworms may be segmented and bilaterally symmetrical. They are invertebrates and have a clitellum. There exists a prostomium which is the sensory lobe in front of the mouth and an anus at the posterior end of the body. They reproduce by copulation and cross fertilization and each individual produces cocoons with about one to twenty fertilized eggs (Domínguez, 2004).

Vermicomposting involves the stabilization of organic solid waste through earthworm consumption which converts the material into worm castings. It is the result of the combined activity of microorganisms and earthworms (Domínguez, 2004). Microbial decomposition of biodegradable organic matter occurs through extracellular enzymatic activities (primary decomposition) whereas decomposition in earthworm occurs in alimentary tract by microorganisms inhabiting the gut. Microbes such as fungi, actinomycetes, and protozoa are reported to inhabit the gut of earthworms. Ingested feed substrates are subjected to grinding in the anterior part of the worms gut resulting in particle size reduction.

One thousand adult worms weigh approximately one kilogram. They can convert up to 5 kilograms of waste per day. Approximately ten kilograms of adults can convert one ton waste per month and one thousand earthworms and their descendants, under ideal conditions, could convert approximately one ton of organic waste into high yield fertilizer in one year (Medany, 2011). This makes earthworms very effective for vermicomposting. The resulting earthworm castings (worm manure) are rich in microbial activity and plant growth regulators, and fortified with pest repellence attributes as well (Munroe, 2007). The vermicompost is relatively more stabilized and harmonizes with soil system without any ill effects.

Earthworms are classified within the *phylum Annelida*, class *Clitellata*, subclass *Oligochaeta*, and order Opisthophora. There are 16 families worldwide. Six of these families (*cohort Aquamegadrili* plus *suborder Alluroidina*) comprise aquatic or semiaquatic worms, whereas the other 10 (*cohort Terrimegadrili*) consist of the terrestrial forms commonly known as earthworms. Two families (*Lutodrilidae* and *Komarekionidae*, both *monospecific*) and genera from three or four others (*Sparganophilidae*, *Lumbricidae*, *Megascolecidae*, and possibly *Ocnerodrilidae*) are Nearctic.

Even though there are so many families of earthworms, not all species are suitable for vermicomposting. Certain specific biological and ecological characteristics make an earthworm suitable. It should be able to colonize organic wastes naturally; consume organic matter at high rates, have a high rate of digestion and assimilation of organic matter, and tolerate a wide range of environmental factors. It should have a high fecundity and it should be strong, resistant and survive handling. Few earthworm species have the above characteristics (Medany, 2011). Earthworms with these features and thus favourable for vermicomposting include; *Eisenia fetida* “Tiger Worm”, *Eisenia andrei* “Red Tiger Worm”; *Perionyx excavatus* “Indian Blue”; *Eudrilus eugeniae* “African Night crawler"; *Eisenia hortensis* and *Eisenia veneta* "European Night crawlers"; and *Lampito mauritii* "Mauritius Worm (Medany, 2011).

Eudrilus eugeniae (African Night Crawler) is one of the common types of earthworms used for vermicomposting in the tropics (Somniyam and Suwanwaree, 2009). Even though it is indigenous to Africa, in USA, Canada, Europe and Asia some have been bred. Its growth is favoured by temperatures between 25-30°C (Viljoen, and Reinecke, 1992). They may be 10cm to over 12cm long (Segun, 1998) with a total number of segments varying from about 80 to over 100 with the location of a thick cylindrical collar, the clitellum between 13th and 20th segments (Vijaya *et al*., 2012). The posterior segments evenly taper to a point. *Eudrilus eugeniae* is reddish brown in colour, cylindrical in shape and metamerically segmented. It has an epilobus prostomium. On the ventro lateral surface, between the eighth and twelve segments, there is a pair of male genital openings present, below the clitellum (Vijaya *et al*., 2012). There is a pair of female genital openings on the twelve segments. These characteristics make *Eudrilus eugeniae* a good choice for vermicomposting.

Vermicomposting systems are influenced by the abiotic factors such as temperature, moisture and aeration (Domínguez, 2004). Conditions unfavourable to aerobic decomposition, like, particle size of biomass and extent of its decomposition, very large temperature increase, anaerobic condition, toxicity of decomposition products, results in mortality of earthworms and subsequently no vermicomposting occurs. Earthworms have fairly complex responses to changes in temperature. They may thrive well in cold and moist conditions far better than they can in hot and dry conditions. Earthworms do well at moisture contents optimum range of 50-90 % (Edwards, 1998). Low moisture content of vermicomposting systems can also retard sexual development.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Description of the Study Area

The study was conducted at the premises of KNUST Sewage Treatment Plant in Kumasi, which is located in the Ashanti Region, in the rain forest. Kumasi is approximately 480 km north of the Equator and 160 km north of the Gulf of Guinea. Its geographical coordinates are approximately 6°41'00" North, 1°37'00" West. The city is at an altitude of about 287m above sea level. The Metropolis falls within the wet sub-equatorial type of climate, and its average temperature is 25.6°C (78 °F) with an average of 1484 mm precipitation annually (Climatemps.com, 2012).

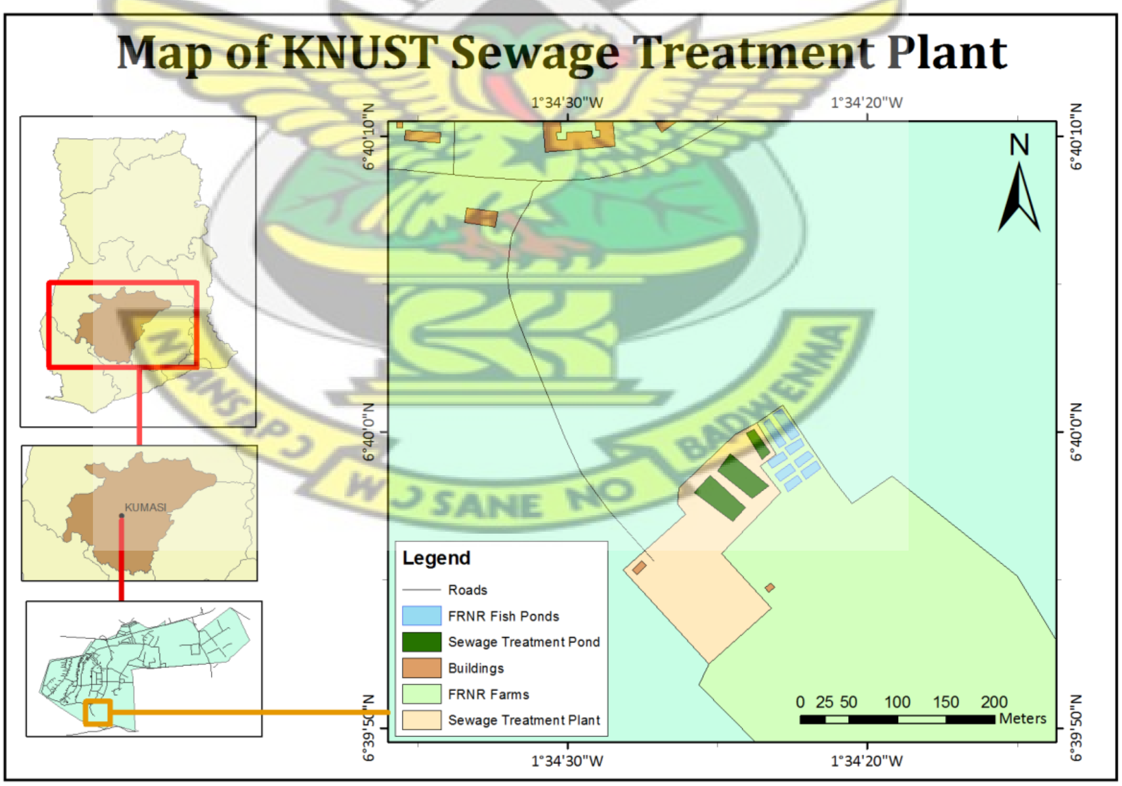

Fig 3.1: Map of KNUST Sewage Treatment Plant

3.2. Preparation of Digestate for Composting

A feedstock of organic fraction of MSW was obtained from the Dompoase landfill site, one of the two engineered landfills in Ghana The waste was separated at the landfill site and delivered at the premises of the KNUST Sewage Treatment Plant. The feedstock was made up of plantain peels, sugarcane peels, pineapple, pear, watermelon, kenkey, pawpaw, maize husk, coconut fibre, banana peels, food leftovers and oranges. A total volume of 13.12m^3 was loaded into the designed biogas plant which is made from a shipping container (Robbiani, 2012).

For inoculation, the feedstock was mixed with digestate from the previous fermentation, which consisted of cow dung and other biodegradable organic waste. Five kilogram of calcium carbonate was then added to the mixture to serve as a buffer. Three replicates of the mixtures were then taken to the lab for the analysis of total solids, volatile solids and COD. Six hundred litres of fresh water was added to serve as percolate. The biogas plant was then closed for a period of 40 days for the production of biogas. After the 40 day retention period of the feedstock in the biogas plant, the digestate feedstock was sampled for composting on the premises of KNUST Sewage Plant.

A digital thermometer was used to measure the temperature of the digestate while a pH meter was used to measure the pH. Bulk density was determined on site. Three composite samples were put into plastic bags and taken to the Water Resources laboratory, and the Renewable Natural Resources laboratory, KNUST for analysis of the parameters that characterize compost as soil amendment for agricultural production. These parameters included

a. **Physical Parameters:** Particle size, total volatile solids.

b. **Chemical Parameters:** Electrical conductivity, pH, Nitrogen, Phosphorus, Potassium, Carbon, Nitrogen, Copper, Lead, Zinc, Cadmium, Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD).

Fig. 3.2: Digestion and composting processes

Some of the fresh digestate was divided into three portions for post-treatment (composting), for two months. Three different treatments were used; Turned windrow composting, Co-composting and Vermicomposting. Each treatment was replicated three times.

3.3 Composting the Digestate

3.3.1 Turned Windrow Composting

Three elongated piles of digestate, about 1.5 metres (5 feet) wide and 0.6 metres (2 feet) high were made, and they weighed 200kg each. The piles were made under a shed to protect them from excessive sun and rain, and then covered with mosquito nets to prevent fowls from spreading out the piles. The piles were turned manually to allow aeration throughout the composting period. During the first two weeks, there were three turnings per week. In the third and fourth weeks, there were two and one turnings respectively. Turning was done once each in the fifth and sixth weeks. Temperature changes in the compost piles were monitored twice daily: morning and evening. The temperature checking points were three different places, the top surface, mid portions and the bottom in each pile. Measurements of temperature inside the windrows were used to gauge the need for turning to stimulate or control heat production. Using the temperature in the piles as a gauge, the piles were watered once every week to speed up the composting process by creating conducive environment for the micro organisms. By the end of the fourth week of composting, temperature of the piles began to stabilize. Composite samples were taken to the Water Resources laboratory and the Renewable Natural Resources laboratory for physicochemical analysis after four weeks of composting.

The compost was then left for four weeks for curing, that is, it was given time to become extremely stable. Composite samples were taken after the fourth week for the analysis of:

a. **Physical Parameters;** particle size, bulk density, total volatile solids.
b. **Chemical Parameters:** Nitrogen, Phosphorus, Potassium, Carbon, Nitrogen, Copper, Lead, Zinc, Cadmium, Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD), Electrical Conductivity.

3.3.2 Vermicomposting

Earthworms were used to convert the fresh digestate into worm casting. *Eudrilus eugenia*, that is, African Night crawlers earthworms were obtained from subsurface of soil, wastewater and the bank of River Wiwi flowing through KNUST campus and cultured. *Eudrillus eugeniae* is a fast-growing earthworm that could convert organic waste rapidly (Domínguez *et al*., 2001). The earthworms were identified according to Segun (1998).

The experiments were conducted in triplicate in wooden boxes of size 65cm×45cm×50cm each, with air spaces in between and under them. The boxes were lined with mosquito net to prevent the earthworms from crawling out. Moist loose shredded papers were placed in the boxes to serve as beddings for the worms. Four kilograms of earthworms and 200 kg of digestates were put into each of the three boxes. Medany (2011) reported that 1 kg can convert up to 5 kg of waste per day, thus 4 kg of earthworms was used for the conversion of 200 kg of the digestate in about 42 days.

The temperature in the boxes was maintained between 25-30^{o}C (Viljoen, and Reinecke, 1992), and moisture content was maintained between 40-60% during the study by watering the contents of the boxes daily. The duration of experiments was eight weeks. Temperature of the worm castings produced was monitored daily, in the morning and evening. Samples of worm casts produced were taken to the lab for physicochemical analysis.

Fig 3.2: Earthworms in vermicompost

Fig 3.3: Setup for Vermicomposting

3.3.3 Co-composting

Digestate of weight 150 kg was mixed with 50 kg of kitchen waste containing equal proportion of food waste and green waste, and formed into piles fresh digestate. The kitchen waste was made of plantain peels, cassava leaves, sugarcane peels, onion peels, pineapple, oranges, pear, watermelon, maize husks, pawpaw, Fanti kenkey peels, and cooked food remains were obtained from the Kumasi Centre for Collaborative Research in Tropical Medicine (KCCR) cafeteria, Brunei cafeteria, and Akuzi Food Joint, all on KNUST campus. This was done in triplicate. The waste piles were made under a shed to prevent them from excessive rain and sunshine. They were turned manually to allow aeration throughout the composting period. Turning and watering were done at the same time as that for the windrow composting. During the first two weeks, there were three turnings per week. In the third and fourth weeks, there were two and one turnings respectively. Turning was done once each in the fifth and sixth weeks. Temperature changes in the compost piles were monitored as done for the co-compost and turned windrow compost.

Fig 3.4: Measuring the temperature of the composting pile

The temperature checking points were three different places, the top surface, mid portions and the bottom in each pile. Measurements of temperature inside the windrows were used to gauge the need for turning to stimulate or control heat production. Using the temperature in the piles as a determinant, the piles were watered once every week to speed up the composting process by creating conducive environment for the micro organisms. By the end of the fourth week, temperature of the piles began dropping until the compost reached ambient air temperatures. Composite samples were taken to the Water Resources lab and the Renewable Natural Resources lab for physicochemical analysis after four weeks of composting.

The compost was then left for four weeks for curing. Composite samples were taken after the fourth week for the analysis of:

a. **Physical Parameters;** Particle sizes, bulk density, total volatile solids.

b. **Chemical Parameters:** Electrical conductivity, Nitrogen, Phosphorus, Potassium, Carbon, Nitrogen, Copper, Lead, Zinc, Cadmium, Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD).

3.4 Analysis of Physicochemical Parameters

Samples of the windrow compost, co-compost, and vermicompost produced were sieved with net of mesh size <5mm, and 5-25mm, air-dried and ground for the laboratory analysis. Each analysis was done three times and the American Public Health Association (1992) standards for the examination of water and wastewater were followed.

Fig 3.5: Compost being ground for analysis

For the determination of pH and electrical conductivity, a PC 300 waterproof handheld pH/Conductivity/TDS/Temperature meter at the Water Resources and Environmental Sanitation laboratory, KNUST was used.

Fifty millilitres of deionised water was added to 20g of compost. It was stirred for 30min, allowed to stand for 30 min, stirred again for 2 min before the pH of the suspension taken with the pH meter. It was allowed to settle for 1h and the conductivity of the supernatant liquid then measured by reading the values of electrical conductivity.

Moisture content was determined after drying to constant weight at 105^{o}C for 24 hours at the Materials Engineering laboratory, KNUST.

The concentration of total nitrogen was determined at the Renewable Natural Resources laboratory, KNUST, by using the Kjeldahl method. This involved digestion, distillation and titration. For digestion, 10g compost was put into 500ml long-necked kjeldahl flask and 10ml distilled water was added to moisten the sample. A spatula full of kjeldahl catalyst (mixture of 1 part selenium + 10 parts $CUSO_4$ + 100 parts Na_2SO_4), and 20ml conc. H_2SO_4 were added and digested until the solution became clear and colourless. The flask was allowed to cool and the supernatant decanted into a 100ml volumetric flask and made up to the mark with distilled water. An aliquot of 10ml fluid from the digested sample by means of a pipette was transferred into kjeldahl distillation flask for distillation. Ninety millilitres of distilled water was added to make it up to 100ml in the distillation flask and 20ml of 40% NaOH was added. Distillate was collected over 10ml of 4% boric acid and 3 drops of mixed indicator in a 200ml conical flask. The collected distillate (about 100ml) was titrated with 0.1N HCL till the blue colour changed to grey and then to pink. The above procedure was repeated but at this time with a blank solution.

Total nitrogen was computed as follows:

Weight of sample used, considering the dilution and the aliquot taken for distillation = 10g x 10ml/100ml= 1g

%N = 14X (A-B) X NX 100/(1000X1)

Where,

A=volume of standard HCL used in sample titration

B= volume of standard HCL used in blank titration

N=normality of standard HCL

% Crude Protein (CP) =% Total Nitrogen (NT) X 6.25(protein factor)

BOD was computed from the initial and final dissolved oxygen (DO) of a sample after incubation at 20°C for five days. Ten milligram of compost was weighed into a 300ml BOD bottle and mixed with distilled water until it overflowed and then stopped. Another 300ml BOD bottle was filled with distilled water to represent the blank. The initial dissolved oxygen concentrations of the blank and the compost solution prepared were determined using a DO meter. Both bottles were stored at 20°C in the incubator for five days. After 5 days the amount of dissolved oxygen remaining in the samples were measured with a DO meter.

The 5-day BOD was computed using the equation below:

$$BOD_5, mg/L = \frac{D_1 - D_2}{P}$$

D_1 = DO of percolates, mg/L,

D_2 = DO of sample after 5 day incubation at 20°C, mg/L,

P = Decimal volumetric fraction of sample used

COD was determined by transferring 1g of $HgSO_4$ into a reflux flask, followed by 10ml of the compost and mixed. Ten millilitres of 0.0417M $K_2Cr_2O_7$ solution was also added to the flask and stirred. Twenty millilitres of concentrated H_2SO_4 was added slowly to the flask whiles simultaneously cooling the outside of the flask under running water after which 1ml of silver sulphate solution was added. The procedure was repeated for the same volume of distilled water as blank. The solution was then boiled under reflux for 2 hours after which 45ml of distilled water was added and subsequently cooled under running water. About 2 to 3 drops of ferroin indicator was added after which a light blue/green colour appeared. The residual solution was titrated with 0.1M ferrous ammonium sulphate (FAS) solution to reddish brown endpoint. The COD was calculated using the equation:

$$\text{COD(mg) } O_2/L = \frac{(A - B) \times M \times 8000}{\text{sample (ml)}}$$

Where:

A = FAS used for blank (ml),

B = FAS used for sample (ml),

M = Molarity of FAS (0.1M)

8000 = milliequivalent weight of oxygen × 1000 ml/l.

Volatile solids were determined by weighing 10g of compost into an evaporating dish and drying for 24h at temperature 105^{o}C. It was then transferred to a cool muffle furnace, and the furnace was heated to 400^{o}C, and ignited for 4h. The sample was then cooled in a desiccator to balance the weight. Ignition was repeated for 30min, dried and then the weight taken.

Copper, lead, zinc and cadmium were determined using an atomic absorption spectrophotometer (AAS). One gram of ground compost sample was weighed and placed into a 300 ml volumetric flask and 10ml of di-acid mixture of HNO_3 and $HClO_4$ of ratio 9:4. The flask was then placed on a hotplate in the fume chamber and heated, at 85° C and then raised to 150° C. The heating continued until the production of red NO_2 fumes ceased. The content of the flask was cooled and the volume made up with distilled water and filtered. The resulting solution was preserved at 4°C, and the heavy metal content determined using AAS.

The concentration of dissolved organic carbon (DOC) was determined using a Formacs Total Carbon Analyzer.

Phosphorus was determined by mixing the sample with hydrochloric acid and the mixture allowed to stand for 12h at room temperature, followed by boiling under reflux for 2h. The extract was then clarified and the elements determined using Inductively Coupled Plasma (ICP).

Particle size determination

The composts produced were air dried and sieved with sieves of mesh sizes <5mm, 5-25mm, and >25mm. The percentage by weight of compost that passed each mesh size was then determined.

3.5 Maturity and Stability

Curing and Self-heating Test

The composts were left to undergo a period of 28 days curing, after which a self-heating test was done to determine if organic matter was thoroughly decomposed. After the 58 days of active composting and curing, an insulated flask was filled with compost of particle size less than 12mm and moisture content of 40–50% (Trautmann and Krasny, 1996). After seven days, the rise in temperature of the compost above ambient temperature was measured. This was done for the windrow compost, co-compost and vermicompost. And for each type of compost, the process was replicated three times. Ambient temperature was between 27-30°C.

Fig 3.7: Insulated flask for the self-heating test

3.6 Experimental Design

Completely Randomized Design (CRD) was used. Analysis of variance (ANOVA) was done to compare the physico-chemical parameters of the digestate and the three different composts produced.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the physicochemical parameters of the digestate obtained from the dry anaerobic digestion plant. The daily morning and evening temperature readings of the three different methods of composting (treatments) of the digestate namely, Co-composting, Turned windrow composting and Vermicomposting are analyzed and discussed. Also presented is the descriptive statistical analysis and discussion of the physicochemical parameters that were determined including pH, electrical conductivity, particle sizes, volatile solids, moisture content, bulk density, nutrient content (NPK), C/N ratio, heavy metals (Cu, Pb, Zn, Cd), COD, BOD and BOD/COD ratio. Ambient temperature throughout the experimental period ranged between 27°C and 30°C.

4.2 The Digestate

Table 4.1: Physicochemical properties of digestate from the dry anaerobic digestion plant

Parameter	Digestate	Standards	Reference
pH	9.16-9.20	8-8.8	Fuchs, 2001 (ASCP Guidelines 2001)
Moisture content (%)	63.89	-	-
Electrical Conductivity (mS/cm)	3.69	-	-
Total organic C (g/kg)	42.2	-	-
Total N (g/kg)	15.0	9.4-20.3	Fuchs, 2001 (ASCP Guidelines 2001)
C/N	2.8	>8	AFNOR (2006) (NF U44-051)

Parameter	Digestate	Standards	Reference
Phosphorus (P_2O_5) (%)	0.14	>0.3	Teglia *et al.*,2010 (German standards)
Potassium (K_2O) (%)	0.19	>0.5	Teglia *et al.*,2011 (German standards)
Cu (mg/kg)	49.70	≤200	BSI: PAS 110
Pb (mg/kg)	107.23	≤200	BSI: PAS 110
Zn (mg/kg)	141.37	≤400	BSI: PAS 110
Cd (mg/kg)	0.98	≤1.5	BSI: PAS 110
C.O.D (mg/l)	2080.33	700	Cossu and Raga (2008)
$B.O.D_5$ (mg/l)	680.67	-	-
COD/BOD	3.06	-	-
% V.S	58.16	>20	AFNOR (2006) NF U44-051

The pH (Table 4.1) for the digestate ranged between 9.16 and 9.20 and was outside the range of 8-8.8 considered by Fuchs *et al.* (2001) in the ASCP guidelines 2001 to be standard for direct agricultural use of digestate after digestion. EC value of 3.69mS/cm was recorded for the digestate. The carbon and nitrogen content recorded were 42.2g/kg and 15.0g/kg respectively and this resulted in a C/N ratio of 2.8:1. The nitrogen content was within the 9.4-20.3g/kg range stated by Fuchs *et al*., (2010) in the ASCP guidelines 2001 considered to be standard for digestate for direct application to agricultural lands. The C/N ratio was, however, less than the >8 value that is considered in AFNOR (2006) as standard. The phosphorus content for the digestate was 0.14% and was lower than the 0.3% value reported by Teglia *et al.* (2011), as German standard value for digestate. The digestate potassium concentration of 0.19% was lower than the >0.5% value required by

Teglia *et al.* (2011), as German standard value for digestate. The volatile solid content of the digestate as determined was 58. 16%. This value falls within the range established by AFNOR (2006) NF U44-051 as source of organic matter with potential for soil improvement. Zinc and copper concentrations of 141.37mg/kg and 49.7 mg/kg respectively were recorded for the digestate. These did not exceed the 400mg/kg and 200mg/kg limit values given by PAS 110. The digestate contains 0.98 mg/kg of cadmium and 107.2 mg/kg of lead. The limit values 1.5mg/kg and 200mg/kg respectively given by PAS 110 were not exceeded.

4.3 Temperature Monitoring During Composting

Table 4.2: Daily temperature readings for the treatment (°C)

Period	Treatment	Mean ± SD	P- Value
Morning	Co-compost	34.10 ± 0.38	
	Turned windrow compost	32.05 ± 0.20	
	Vermicompost	27.98 ± 0.08	
Evening	Co-compost	34.04 ± 4.97	
	Turned windrow compost	32.12 ± 2.73	
	Vermicompost	27.97 ± 1.01	
Total	Co-compost	34.07 ± 4.96	0.91
	Windrow compost	32.08 ± 2.67	0.98
	Vermicompost	27.97 ± 1.00	0.81

*Morning and evening temperature readings are not statistically different at level of significance equal to 0.05.

Table 4.3: Average temperature readings within treatment

Treatments	Mean temp (°C) ± SD	Range (°C)	Sample size
Co-compost	34.10±0.11	27.9-48.4	58
Turned windrow compost	32.05±0.05	27.8-38.3	58
Vermicompost	27.97±0.03	25.9-31.8	58

From Table 4.2 and 4.3, the highest mean temperature was recorded in the co-compost. A mean temperature of 34.10°C with a standard error 0.11 was recorded. Turned windrow compost and vermicompost recorded mean temperatures of 32.05°C and 27.98°C with standard errors of 0.05 and 0.03 respectively. With the level of significance equal to 0.05, the mean within samples for all treatments were statistically significant. Temperature ranged between 27.9°C and 48.4°C for the co-compost. The average temperature for the turned windrow compost and vermicompost ranged between 27.8°C-38.3°C and 25.9-31.8°C respectively.

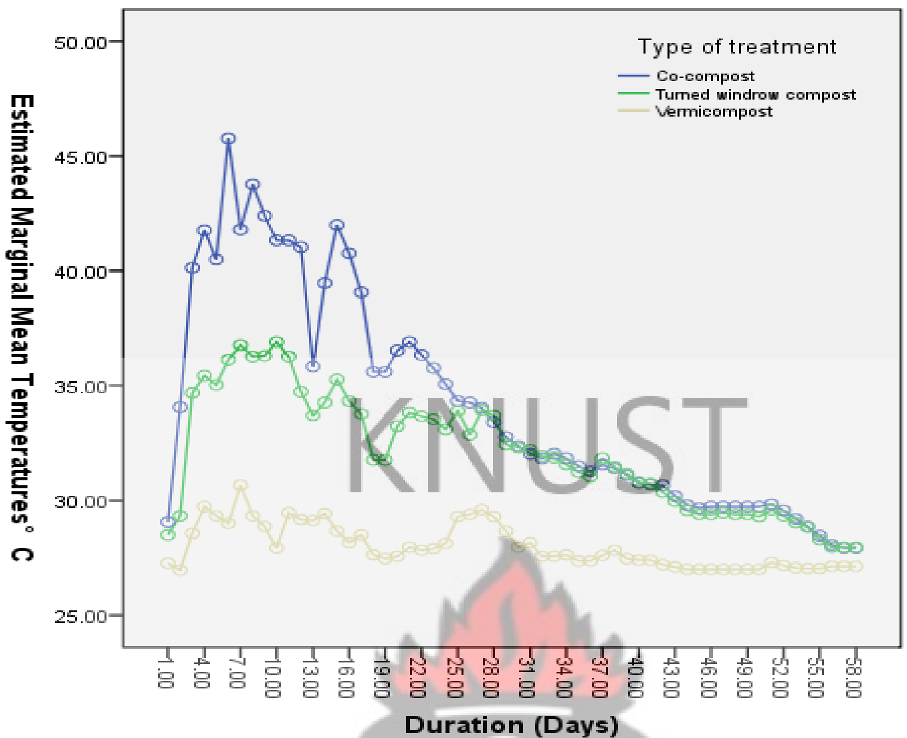

Fig 4.1: Daily average temperature readings for co-compost, turned windrow compost and vermicompost

From Figure 4.1, the co-compost recorded the highest temperature readings and was followed by the turned windrow compost and then the vermicompost.

For the temperature trend within the co-compost treatment from day 1-58, the initial temperature measured was about 29.0°C. This rose sharply and peaked on the sixth day of composting. From then, there was a gradual decrease from the peak of 46.0°C to 28.0°C at the 58th day.

Temperature rose slightly between the first and third days from an average temperature of 28.5°C to 29.3°C for the turned windrow compost. It then rose sharply and peaked on the tenth day at an average temperature of 36.9°C. It stabilized between the 45th and 50th day at 29.4°C. It then increased slightly to 29.6°C on the 51st day and decreased till the 58th day to 28.0°C.

In the vermicompost, temperature decreased slightly from an average temperature of 27.3°C on the first day to an average temperature of 27°C by the second day, and then rose sharply till the fourth day to 29.8°C. It decreased on the sixth day to an average temperature of 29.0°C and peaked at average of 30.7°C on the seventh day. Between the 44th and 50th day, the temperature stabilized at 27.0°C. It then rose slightly and stabilized again at an average of 27.1°C.

Monitoring temperature helps in assessing the progress of the composting process (Boulter-Bitzer *et al.*, 2006). Temperature of the pile normally starts from the mesophilic phase. It is then followed by the thermophilic phase where destruction of pathogens, and weed seed in the compost occur (Polprasert, 1996). For vermicomposting and turned windrow composting, temperature was within the mesophilic range. Temperature was within the mesophilic range at the initial stage and moved to the thermophilic phase, before reducing to the mesophilic range for the co-compost.

Composting may begin as soon as raw materials are mixed (Pace *et al.*, 1995). Higher temperatures may have been obtained while the waste was in the biogas plant. This might have contributed to the generalty low temperatures measured for all three treatments during composting. Low vermicomposting temperature recorded was due to the daily watering of the system to keep the temperature between 25°C-30°C, which is the temperature favourable for the survival of the earthworms (Viljoen, and Reinecke, 1992). The turned windrow compost and the co-compost were turned and watered frequently which also might have contributed to the low temperatures. This confirmed Beffa (2002) who reported that moving air in the compost as a result of turning leads to heat removal by cooling as the water in the compost evaporates.

Of the three treatments, co-compost had highest temperatures because the fresh food waste added had solid contents of 30-60% making the compost susceptible to heating up (Walker *et al.*, 1999). Also, there was an increase in heat generation by biodegradation of the fresh waste added (Miyatake and Iwabuchi, 2005).

There were noticeable reductions in digestate quantities during decomposition as temperature decreased. Volume for vermicomposting had greatly reduced by the 42nd day. This was as a result of the earthworm vigorously feeding on the digestate. This reduction was followed by the co-compost. The turned windrow compost took the longest time in quantity reduction.

4.4 pH

Table 4.4: pH of Digestate and Composts

Treatments	Range	Standard Range
Digestate	9.15-9.17	
Co-compost	8.59-8.61	6-8.5 (Italian Consortium Composters, 2006)
Turned windrow compost	8.43-8.46	
Vermicompost	7.95-7.99	

* The pH within treatments is statistically different at level of significance equal to 0.05.

From Table 4.4, the digestate recorded the highest basic pH range of 9.15-9.17. The co-compost and turned windrow compost were equally basic with pH values ranging between 8.59-8.61 and 8.43-8.46 respectively. The pH range for the vermicompost was closest to neutral with values ranging between 7.95 and 7.99.

The initial alkaline pH recorded in the digestate might have been due to the buffering effect of the bicarbonate (Caceres *et al.,* 2006), added to the feedstock before loading the biogas plant. Reduction in pH of the compost produced from the three treatments is in contrast to what was reported by Epstein (1997) and Ramaswany *et al.*, (2010) that pH levels increase during composting as a result of the reduction of volatile acids and its further combination with ammonium gas released during denaturing of protein.

Mainoo *et al.,* (2009) reported that earthworms do not affect pH. The higher reduction in pH for the vermicompost could have resulted from the degradation of easily decomposable polysaccharides and the consequent production of organic acids during the bio-oxidation phase (Afifi *et al.*, 2012). This might also have contributed to the decrease in pH of the turned windrow compost and co-compost.

The pH ranges of 8.43-8.46 and 7.95-7.99 for the turned windrow compost and vermicompost respectively, were within the range of 6-8.5 reported by the Italian Consortium Composters (2006) as the standard limit for compost hence they can be used for agricultural purpose. pH for the co-compost was however higher than the stated limit. Addition of this co-compost to the soil will modify the soil pH. Wäger-Baumann (2011) indicated that increased pH value combined with high ammonium can induce nitrogen losses due to gaseous emissions in the form of ammonia when used for agriculture.

4.5 Electrical Conductivity (EC)

Table 4.5: Electrical conductivity for digestate and composts

Treatments	Mean EC (mS/cm) ± SD	Standard value of EC (mS/cm) for compost
Digestate	3.69±0.00	
Co- compost	4.37±0.00	<4 (Fuchs, 2001) ASCP Guidelines 2001
Turned windrow compost	3.82±0.00	
Vermicompost	3.55±0.00	

* The EC within treatments is statistically different at level of significance equal to 0.05

From Table 4.5, the mean electrical conductivity for all the treatments was 3.86mS/cm. The co-compost produced had the highest salinity. This was followed by the turned windrow compost and then the digestate. A low value of 3.55mS/cm was measured in the vermicompost.

Electrical conductivity shows the salinity levels of the compost and it influences the growth of plants if used as fertilizer (Hachicha *et al.,* 2008). When EC is high, there is destruction of the plant roots (Prasad *et al*., 2012). The digestate had an EC of 3.7mS/cm and this increased in all three treatments. The increase in EC for the turned windrow and the co-compost might have been due to loss of weight as moisture content reduced and the release of mineral salts as organic matter is decomposed (Huang *et al.,* 2004). EC decreased in the vermicompost. The reduction could have been brought about by the production of metabolites such as ammonium and the precipitation of mineral salts (Vakili *et al.*, 2012). After composting, the EC for the turned windrow and the vermicompost were within the standard value of <4mS/cm stated by ASCP Guideline (2001). The EC of the co-compost was higher than the standard value, thus the co-compost when used can inhibit seed germination (Hargreaves *et al*., 2008).

4.6 Volatile Solids (VS)

Table 4.6: Volatile solids within treatment

Treatments	Mean VS (%) ± SD	Range	Standard VS for compost
Digestate	58.16±0.03	58.13 -58.19	
Co-compost	50.77±0.01	50.77- 50.78	<50 (Fuchs, 2001) ASCP Guidelines 2001
Turned windrow compost	53.16±0.01	53.15- 53.17	
Vermicompost	44.40±0.00	-	

* The VS within treatments is statistically different at level of significance equal to 0.05

From Table 4.6 the highest percentage of volatile solids in the digestate greatly reduced in the vermicompost. Loss of volatile solids in the co-compost was higher than that in the turned windrow compost.

Volatile solid is a measure of the organic matter content. At the onset of composting, the organic matter is composed of carbohydrates, proteins, lipids and ligneous compounds. These are converted into stable humic substances by the end of composting (Fuchs *et al.*, 2001). Volatile solids reduced greatly in the vermicompost and slightly in the turned windrow compost and the co-compost, due to biological activities. The initial feedstock was converted into carbon dioxide (Beffa, 2002). After composting, the organic matter content of the vermicompost was within the <50% standard value stated by the ASCP Guidelines (2001) for compost. Thus the vermicompost produced is a source of organic matter with potential for use to improve soil structural properties. The values for co-compost and turned windrow were higher than the standard value.

4.7 Moisture Content and Bulk Density

Table 4.7: Moisture content and bulk density within treatment

Treatment	Mean moisture content (%) ± SD	Bulk density(kgm-^{3}) ± SD
Digestate	63.88±1.00	680.00±80.00
Co-compost	37.78±1.49	506.00±5.29
Turned windrow compost	51.97±1.23	540.00±0.00
Vermicompost	56.54±3.71	481.67±1.53

*All values are means of three replicates with their standard errors. At ∝ equal to 0.05, all the parameters within treatments were statistically different

The digestate recorded the highest moisture content and bulk density as shown in Table 4.6. The turned windrow compost recorded the second highest bulk density followed by the co-compost and then the vermicompost. For the moisture content, vermicompost recorded the second highest value followed by the turned windrow compost and then the co-compost. The standard range for moisture content is 35-60% (Saifeldin *et al.*, 2011). The bulk density for the digestate reduced greatly after composting. The lower bulk density for the turned windrow compost and co-compost was as a result of the reduction in the initial moisture content of the digestate. The degradation of the digestate after composting reduced the organic matter which was very bulky to light weight compost. The lowest bulk density for the vermicompost was due to the fact that the earthworms converted the digestates into a much finer humified cast. The low bulk density of this compost is an indication that it will be easy for field application. Storing and transporting the vermicompost will be easy, and land will be saved on dumpsites.

Microorganisms involved in composting depend on moisture content for their growth. It is therefore a critical factor during composting. High moisture content can lead to anaerobic conditions, affecting microbial growth. Composting leads to reduction in moisture content (Walker *et al*., 2009). Moisture content of 63.9% of the digestate dropped after composting for all the three methods and ranged between 37.8%-56.5%. This falls within the range of 35%-60% reported by Saifeldin *et al.* (2011) as the standard range and close to the range of 40%-65% reported by Gajalakshmi and Abbasi (2008) in their study. The vermicompost, turned windrow compost and co-compost produced are ideal in terms of moisture content since they will not lead to anaerobic conditions and will also not lead to unpleasant odour from the growth of anaerobic sulphate reducing bacteria (Saifeldin *et al.*, 2011).

4.8 Nutrient Contents

Table 4.8: Nutrient status of the digestate, co-compost, turned windrow compost and vermicompost

Nutrients ± SD	**Treatment**				**Standards**
	Digestate	**Co-compost**	**Turned windrow compost**	**Vermi Compost**	
Carbon (%)	4.22±0.00	5.53±0.02	5.50±0.01	4.21±0.012	≥25% (Italian Consortium Composters, 2006)
C:N	2.80±0.00	2.57±0.06	2.70±0.00	1.35±0.00	≤25 (Italian Consortium Composters, 2006)
Total Nitrogen (%)	1.50±0.00	2.13±0.06	2.03±0.00	1.92±0.01	>2.5% (Italian Consortium Composters, 2006)
Phosphorus ($mgkg^{-1}$)	1.39±0.02	4.28±0.00	8.94±0.0	5.28±0.0	-
Potassium ($mgkg^{-1}$)	1.91±0.02	15.16±0.00	17.18±0.00	13.46±0.00	-

*All values are means of three replicates with their standard errors. At level of significance equal to 0.05 all the parameters within treatments are statistically different

From Table 4.8, the co-compost recorded the highest percentage of carbon followed by the turned windrow compost and then the digestate. Vermicompost contained the least carbon content as well as C: N ratio. The total nitrogen content increased from an initial value of 1.5% in the digestate, to 1.9% in the vermicompost, 2.0% in the turned windrow compost and 2.1% in co-compost. In ascending order, the percentage of phosphorus recorded was least in the digestate, co-compost, and vermicompost and turned windrow compost. Potassium recorded was lowest in the vermicompost and highest in the digestate.

Earthworms help in the reduction of C/N ratio. They achieve this by using up carbon for respiration as they consume the organic matter in waste (Ronald and Donald, 2007), and retain the nitrogen found in the waste they feed on (Norbu, 2002). The C/N ratio was greatly reduced in the vermicompost than in the other treatments, however, for this study, there was no significant change in carbon content and nitrogen increased. Increases in total nitrogen for the turned windrow compost and co-compost were brought about by the reduction of dry weight due to degradation of organic carbon compounds (Bustamante *et al.,* 2008). The carbon was used up by microbes as they consumed it as a source of energy, leading to lowering of the C/N ratio (Baharuddin *et al.*, 2009). Compost of C/N ratio less than 0.5 is very mature, from 0.5-3.0 is mature, and above 3 is considered immature. However, ratios greater than 25 will generally cause nitrogen drawdown leading to poor plant growth (Brinton, 2000). The C/N ratios for all the composts produced were within the ≤25 value stated by the Italian Consortium Composters (2006).
Phosphorus helps in the synthesis of protein and organic matter in plants (Kaosol et al, 2012). Phosphorus in the digestate increased after composting. This is similar to results observed by Afifi *et al.* (2012), who reported that phosphorus increased at the end of composting due to loss of organic matter. For the vermicompost, mobilization and mineralization of phosphorus due to bacterial and fecal phosphate activity of earthworms might have led to the in phosphorus (Ansari and Ismail, 2008). Potassium content in the digestate increased after composting similar to the study of Afifi *et al.* (2012) which reported that potassium content is expected to increase after composting. The increase is

an indication that the earthworms have symbiotic gut microflora with secreted mucus. This combines with water to increase the degradation of ingested substrate and release easily available metabolites (Khwairakpam and Bhargava, 2009).

4.9 Heavy Metals

Table 4.9: Heavy metal contents of digestate and composts

Parameter ($mgkg^{-1}$)	Digestate	Co-compost	Turned Windrow compost	Vermicompost	standards
Copper	49.70±0.01	38.50±0.00	41.47±0.06	51.27±0.06	150
Lead	107.23±0.00	29.53±0.06	27.13±0.06	43.83±0.15	150
Zinc	141.37±0.02	385.09±0.06	226.53±0.12	253.12±0.12	500
Cadmium	0.08±0.01	1.40±0.00	1.10±0.00	2.30±0.00	3

*All values are means of three replicates with their standard errors. At level of significance equal to 0.05 all the parameters within treatments are statistically different. Standard values are limit values and were adapted from Kraus and Grammel (1992) German standards.

From Table 4.9, copper content was highest in the vermicompost, followed by the digestate, the turned windrow compost, and then the co-compost. Lead was highest in the digestate, followed by vermicompost, co-compost and turned windrow compost. The vermicompost contained the greatest cadmium content; however, it had the second highest content of zinc. Zinc was highest in the co-compost and lowest in the digestate. Lead and cadmium decreased after vermicomposting due to bioaccumulation of lead and organo-complex formation during composting (Ghyasvand *et al.,* 2008). Lead value recorded in this study was similar to what was reported by (Ghyasvand *et al.,* 2008). Cadmium increased in contrast with the report by Ghyasvand *et al.,* (2008).

Plants need small quantities of heavy metals like zinc and copper for their growth. However cadmium and lead are not essential for plant growth. These become accumulated in the plants when in large quantities and may hinder the metabolic activities of plants. They also affect the absorption of essential elements (Xu and Shi, 2000). Excess concentrations of some heavy metals in soils cause the disruption of natural aquatic and terrestrial ecosystems (Meagher, 2000). All composts produced had their copper, lead, zinc and cadmium contents within the limit values of 150 $mgkg^{-1}$ for copper and lead, 500 $mgkg^{-1}$ for zinc and 3 $mgkg^{-1}$ for cadmium as stated by Kraus and Grammel (1992). Using all the three composts for agriculture will not lead to the accumulation of heavy metals and hindering of metabolic activities in plants.

4.10 COD, BOD and BOD/COD Ratio

Table 4.10: COD, BOD and BOD/COD ratio within treatment

Treatments	COD (mg/l) ± SD	BOD (mg/l) ± SD	BOD/COD ± SD
Digestate	2080.30±0.00	680.67±0.00	0.33±0.00
Co-compost	2976.00±0.00	899.67±0.58	0.30±0.00
Turned windrow compost	3119.00±1.00	951.33±1.16	3.30±0.06
Vermicompost	2976.00±0.00	920.00±1.00	0.31±0.00

*All values are means of three replicates with their standard errors. At level of significance equal to 0.05 for all the parameters within treatments are statistically different.

From Table 4.9, COD was in the order turned windrow compost > co-compost > digestate > vermicompost. The least BOD was recorded in the digestate. In ascending order, this was followed by co-compost, vermicompost and turned windrow compost. The BOD/COD ratio was highest in the digestate, followed by the vermicompost. Co-compost and turned windrow compost had the same ratio.

4.11 Particle Sizes

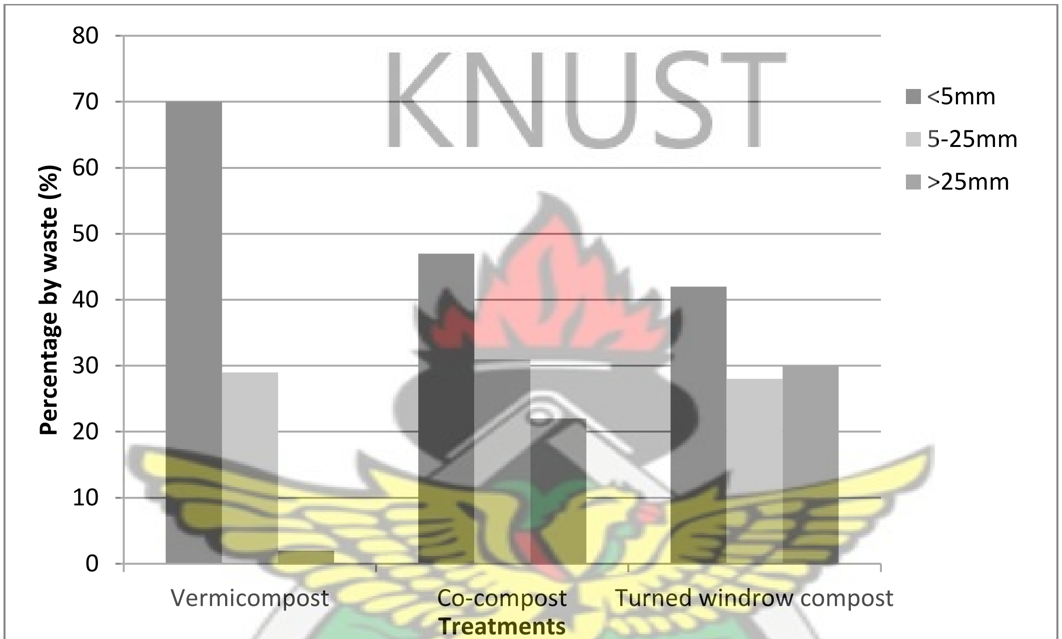

Fig 4.2: Particle size distribution

After composting the digestate, the vermicompost had smaller particles size than the co-compost and the turned windrow compost especially in the less than 5mm mesh size (Figure 4.2). The turned windrow compost had about 30% of the compost by weight falling outside the <25mm range stated by Fuchs *et al*. (2001) in the ASCP Guideline 2001 as standard particle sizes of compost.

4.12 Maturity and Stability

Curing was done for all treatment for a period of 28 days, which is greater than the minimum of 21days curing after which a self-heating test was done.

Self-Heating Test

After retaining compost in the insulated container for seven days, temperature rise for the vermicompost and co-compost ranged between 0-10°C above the ambient temperature, thus very stable and well-aged (Klindworth, 1994). This indicated that the composting process was completed. Rise in temperature above ambient temperature for the windrow compost ranged between 10-20°C. This indicated that the turned windrow compost was moderately stable hence still in the curing phase (Klindworth, 1994). The turned windrow compost could thus not be used immediately for agriculture.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The physicochemical parameters for digestate from a dry anaerobic digestion were analyzed. It was observed that the digestate had its organic matter content being greater than the 20% least value considered for direct application to agricultural land. This digestate therefore had high organic amendment property, thus would improve the physical attributes like permeability and water infiltration capacity of soil. It also had its heavy metal contents being within the standard limit values stipulated for digestate. The digestate, therefore when used would not have any adverse environmental effect.

Digestate should have a fertilizing effect on the soil. Of the nutrients content, only the nitrogen content was within the standard range required for digestate. Phosphorus and potassium were too low, and so was the C/N ratio. These are indications that the digestate when applied directly would hamper growth and reproduction as well as the plant's ability to retain water in their cells. Also, the pH of the digestate was too high. This digestate therefore when applied directly to the soil will modify the soil pH. The digestate had too much moisture and had large particle sizes. This would lead to anaerobic conditions when applied to farmlands. It was therefore necessary that the digestate had to be post-treated by composting.

The present study showed that composting can be used in post-treating digestate from anaerobic digestion plant. After a 58 day period of composting digestate with three different post-treatment methods: turned windrow composting, co-composting and vermicomposting, it was realized that composting had an effect on the digestate. pH, volatile solids, moisture content and lead quantities in the digestate decreased for all three treatments. However, copper, zinc and cadmium contents increased and were within the standard limit values designated for compost. The nutrient contents of all three composts were low, even though there were great increases in the phosphorus and potassium contents for all three methods of composting. Also, all three composts produced were dark brown to blackish-brown in colour, had earthy smell and felt greasy when squeezed between the fingers.

In general, vermicomposting was the best method of composting the digestate and yielded the best quality compost. With the exception of the nutrient contents that were generally low for all treatments, all its physicochemical parameters were within the standard limit value. Temperature rise above the ambient temperature after the self-heating test ranged between 0-10°C for the vermicompost, an indication that it was very stable. Vermicomposting did not require any extra hand since the earthworms in their movement and feeding activities aerated the system. This mode of composting was therefore not labour intensive. Most of the composts had their sizes being below 5mm, with only about 2% by weight being larger than the 25mm maximum standard size for compost, giving an indication that vermicompost can be an adequate composting method for reducing large sized organic waste into very small sized compost.

The turned windrow compost had some of its physicochemical parameters being within the standard values with others falling outside the standard values. After the self-heating test, rise in temperature above the ambient temperature for the turned windrow compost ranged between 10-20°C. This signified that the compost needed more time to stabilize.

The turned windrow composting was labour intensive. An extra hand had to be employed for the frequent turning of the piles for the circulation of air and the redistribution of temperature. The turned windrow compost had about 30% of the compost by weight being larger in size than the 25mm required as the maximum particle size for compost.

The co-compost produced the least quality compost. Even though it achieved the temperatures required for pathogen destruction, it had most of its physicochemical parameters falling outside the standard values required for quality compost. The co-compost had its rise in temperature above the ambient temperature ranging between 0°C-10°C after the self-heating test. This indicated that the compost was stable. However, this method of composting was labour intensive since an extra hand was employed for the frequent turning of the piles for the circulation of air and the redistribution of temperature. The co-compost had about 20% of the compost by weight being larger in size than the 25mm required as the maximum particle size for compost.

5.2 Recommendations

The digestate was too low in nutrient contents. This resulted in the composts produced also having low nutrient content, even though there was an increase during composting for all post-treatment methods. The feedstock for subsequent digestion should be worked on to improve the nutrients in the composts that will be produced.

Inoculants such as cow dung should be added to the digestates before composting to attain the high composting temperatures that will lead to total destruction of weeds and pathogens.

Source separation of waste should be included in municipal policy on waste management to enhance the quality of the feedstock used for subsequent digestion and composting

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