Evaluating quality of composts made from organic agro-wastes and their influence on maize yield and soil fauna in Western Kenya

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DECLARATION

This thesis is my original work and has not been presented for an award of a degree in any other university.

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DEDICATION

This work is dedicated to my mother, Keziah Mugure and my siblings; Monica, Simon, Samuel, Hannah and Joyce for their support and encouragement through the challenging times.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

LIST OF ABBREVIATIONS

AES – Atomic Emission Spectrophotometer

B/C ratio – benefit to cost ratio

C – carbon

°C – degrees centigrade

Ca – calcium

CEC – cation exchange capacity

cm – centimeters

cmol – centimoles

C:N ratio – carbon to nitrogen ratio

DCA – detrended correspondence analysis

g – grams

ha – hectares

ICP – Inductively Coupled Plasma

ISFM – Integrated Soil Fertility Management

K – potassium

kg – kilograms

km – kilometers

Lsd – least significant difference

m – meters

mg – milligrams

mm – millimeters

ml – milliliters

Mg – magnesium

N – nitrogen

Na – sodium

NH_4^+ – nitrate ions

NH_3 – ammonia gas

NO_3^- – nitrate ions

P – phosphorous

ppm – parts per million

P-value – probability value

r – correlation coefficient

RCBD – randomized complete block design

RDA – Redundancy Analysis

Sed – standard error of the difference

SOC – soil organic carbon

SOM – soil organic matter

SSA – sub-Saharan Africa

t – tonnes

ABSTRACT

Degradation of soils' physical, chemical and biological properties in arable lands of sub-Saharan Africa mostly results from little or no organic resource application coupled with sub-optimal fertilizer application. A study was conducted in Buyangu and Ivakale villages, Kakamega over three seasons from March 2010 to August 2011 to evaluate the potential of six locally available organic biomasses namely; cow manure, maize stover, *Tithonia diversifolia*, sugarcane straw, bagasse and filtermud for compost production and their effect on soil quality, soil fauna diversity and on maize yields. Treatments consisted of six composts made from the six organic biomasses, inorganic fertilizer treatment and a no-input control and these were replicated four times in randomized complete block design (RCBD). Soil samples were analyzed for chemical and biological properties. Earthworms were collected using soil monoliths while nematodes were sampled and extracted using steel core samplers and Baerman pan technique, respectively. Data obtained were subjected to analysis of variance using GENSTAT statistical software while treatment differences were evaluated using least significant difference (LSD) at 5 % level of significance. Strength and statistical significance of soil chemical properties with macrofauna abundance and taxonomic richness was conducted using the programme CANOCO 3.1.

There was no significant difference in chemical properties of the different composts types. Amending soils with composts significantly ($P < 0.001$) increased soils' N, C and P compared to no-input control plots. In these, C, N and P increased by 90, 21 and 2%, respectively upon addition of composts. The no-input control plots recorded a 37% increase in C, but a decline of 15% and 40% in N and P, respectively. Fertilizer treated soils recorded an increases of 92, 26 and 81% in C, N and P, respectively. Earthworm abundance and biomasses were significantly ($P < 0.001$) higher in compost amended soils (38 individuals m^{-2} and 1.2 g m^{-2}) compared to fertilizer and no-input control plots which had on average 10 individuals m^{-2} and a biomass of 0.3 g m^{-2}. The positive relationships between macrofauna abundance and soil chemical properties were highly significant ($P = 0.007$). Generally, plant-parasitic nematodes decreased with addition of composts, while bacteria-feeding nematodes increased with application of composts. Similar to macrofauna, the positive relationships between soil chemical properties and nematode density were also highly significant ($P = 0.001$). Maize yields over the three seasons were significantly ($P < 0.001$) highest in fertilizer treated plots (4.4 t ha^{-1}), followed by composts (2.8 t ha^{-1}) and lowest in no-input controls (1.4 t ha^{-1}). However, the benefit:cost ratio obtained from yields was highest on composts treated plots followed by fertilizer treated plots and lowest in control plots. The results of this study demonstrate the potential of composts in improving soil fertility and hence productivity.

CHAPTER ONE: INTRODUCTION

1.1 Background information

Rapid population growth in sub-Saharan Africa has been a major drawback towards realization of economic growth. This is due to slow rate of growth in agricultural sector, which is a major contributor to the developing countries' Gross Domestic Product (GDP). The slow rate of growth in agricultural sector may be due to subsistence production practices (Makokha *et al.*, 2001; Gichangi, 2003). Continuous farming on poor soils without replenishing lost nutrients has resulted in low agricultural productivity leading to food deficits (Twomlow and Bruneau, 2000; Bationo *et al.*, 2006) as well as impacting negatively on soil physical, chemical and biological properties (Savala, 2002). Soil fertility maintenance is essential in achieving and sustaining high crop yields (Bationo *et al.*, 2006). Persistent loss of nutrient from soils could have devastating effects on crop production and it may be difficult to reverse the process in the long run (Sanchez *et al.*, 1997). According to FAOSTAT (2004) and Rutunga *et al.* (2008), fertilizer use in sub-Saharan Africa has stagnated at less than 9 kg N ha^{-1} and 6 kg P ha^{-1}, producing a cereal yield that barely exceed 1.5 t ha^{-1} in most subsistence farms, compared to the global averages of 2.1 t ha^{-1} wheat, 3.0 t ha^{-1} rice and 3.5 t ha^{-1} maize.

Use of animal manure by farmers is a common practice in most parts of sub-Saharan Africa (SSA) and in the Kenyan highlands where animals are of major importance in the small-scale dairy and beef farming (Gichangi, 2003; Lekasi *et al.*, 1998; Makokha *et al.*, 2001). Livestock manure is a valuable source of soil nutrients such as N and therefore has successfully been used in improving fertility in tropical soils (Kihanda *et al.*, 2007). Manure is also an important soil conditioner (Gichangi *et al.*, 2007). Agro-industrial and farm derived wastes on the other hand have great potential in replenishing soil nutrients through proper utilization, conversion and recycling processes (Savala *et al.*, 2003). However, these organic biomasses are unable to meet crop nutrient requirements due to nutrient losses, especially nitrogen, which could be as a result of poor handling and storage practices on the farms (Gichangi *et al.*, 2007). Poor quality organic materials also reduce their significance as nutrient sources due to immobilization of available nutrients in soils when they are applied raw (Savala *et al.*, 2003). This may result from inadequate supportive policies that encourage recycling and utilization of industrial and other farm derived wastes to produce quality bio-fertilizers.

Co-composting of livestock manure and agro-wastes could be important in reducing losses of nutrients through volatilization and leaching during storage as well as increase their quantities (Gichangi *et al.* 2007). This leads to production of quality biofertilizers which contribute a lot not only to crop production but also in driving the ecosystem functions. Maeder *et al.* (2002) observed that efficient organic resource utilization could enhance soil floral and faunal diversity in sustainable farming systems which are features of a typical mature ecosystem. This is observed through stimulation of microfauna (fungi and bacteria), mesofauna (collembolans and tardigrades), and macrofauna (earthworms and termites) activities which contribute to decomposition of organic materials hence improving soils' physical, biological and chemical properties (Mando, 1997; Petersen, 2000; Karaca, 2011). Macrofauna such as earthworms and termites are important in formation of soil pores and stabilization of macroaggregates which improves soil-water relations such as transmission and retention capacities further improving the soil conditions as well as the overall ecosystem functions (Pulleman *et al.*, 2004). Livestock manure and composts have also been used to manage soil-borne diseases such as root knots caused by nematodes (Akhtar and Malik, 2000). However, the mode of action of organic amendments leading to plant disease control and stimulation of microorganisms is complex and dependent on the nature of the organic amendments (Akhtar and Malik, 2000).

1.2 Statement of the Problem

Due to high cost of fertilizers and other farm inputs, management of soil fertility is a major challenge to smallholder subsistence farmers in sub-Saharan Africa. Identification of alternative ways and means of addressing the challenge is thus very pertinent (FAOSTAT, 2004; Makokha *et al.*, 2001; Kimani *et al.*, 2007). In addition, little or no agricultural residues are ploughed back to farms as materials are either burned or utilized as fuel and animal feeds, especially in dry regions of sub-Saharan Africa (Karanja *et al.*, 2006; Achieng *et al.*, 2010). Burning and field disposal of organic biomass is a common practice during land preparation, but these practices results in loss of soil limiting nutrients such as N, S and C (Schöll and Nieuwenhuis, 2004). It is estimated that a loss of 20 to 40 kg N/ha and 5 to 10 kg S/ha could be expected every cropping cycle through such practices (Bationo *et al.*, 2006). This has resulted in decline of soil organic matter, a situation which compromises soils' physical, chemical and biological properties, and the overall reduction in crop productivity (Savala, 2002). Decline in soil organic matter has direct effects on soil-based constraints to crop productivity which includes water and nutrient availability and reduction in plant toxins (Woomer *et al.*, 1994; Karunditu *et al.*, 2007) as well as negative impact on soil flora and fauna ecosystem services such as, organic matter decomposition and soil structure stabilization (Kapkiyai, 1996; Moreira *et al.*, 2008). Besides, this has resulted in decline in soils' resistance to degrading forces as well as reduction in nutrient use efficiency further reducing crop yields. Utilization of agro-wastes from farms could have potential of addressing soil fertility problem hence improving productivity capacity of soils (Vanlauwe *et al.*, 2006). Lack of appropriate technologies to convert these agro-wastes to high quality bio-fertilizers limits their great effectiveness hence adoption by farmers.

Livestock rearing is a common practice among smallholder enterprises that serve to generate income, improve family nutrition and provide manure for crop production. Livestock manures are widely used in Kenya, with over 80 % of farmers using it to fertilize their soils (Lekasi *et al.*, 1998; Kihanda *et al.*, 2007; Okalebo *et al.*, 2007). The quality of manure determines its effectiveness in releasing nutrients to the soil and application of fresh dung, a common practice in Western Kenya could limit availability of nutrients to crops through immobilization. In addition, most of livestock manures from farmers' fields contain less than 1% N hence would not qualify as sole sources of nitrogen (Giller *et al.*, 1997; Kihanda and Wood 1996; Kihanda *et al.*, 2007). Poor handling and management of livestock manure by exposing it to extreme weather conditions could also limit availability of nutrients such as N due to losses through volatilization and leaching processes (Gichangi *et al.*, 2007). Estimates suggest that up to 60 % N and 10 % P could be lost through poor handling and management of manure stocks (Mafongoya *et al.*, 2003).

1.3 Justification

A major challenge in low input systems in sub-Saharan Africa is lack of effective technologies for converting available organic biomass such as agro-wastes and animal manure from farms and agro-industries into quality products that crops can benefit from. Recycling of these organic resources within the smallholder farming systems has great potential to reverse soil nutrient decline thereby contributing to sustained crop yields and building longterm soil fertility reserves

(Mafongoya *et al.*, 2003; Omotayo and Chukwuka, 2009; Munthali, 2007; Bationo *et al.*, 2006). Utilization of organic resources has gained importance in some parts of sub-Saharan Africa, especially in Kenya due to ease of availability of these materials (Gichangi, 2003). In many cases, wastes from the initial processing stage of agricultural raw materials presents a challenge in disposal due to high moisture content. These wastes include; coffee pulp and husks, sugarcane bagasse and filtermud and leftovers and rejects from packaging of fresh horticulture and floriculture produce. The potential sources of organic resources that could be utilized for the benefit of small-scale farmers are as a result wasted. The estimated production of crop residues such as maize stover and wheat straw ranges from 4 to 15 tonnes ha^{-1} in parts of Rift Valley and Western Provinces (Savala *et al.*, 2003), while bagasse and filtermud from sugar industries in Western and Nyanza Provinces are estimated at 1.6 million tonnes yr^{-1} and 150,000 tonnes yr^{-1} respectively (UNSD, 2007). The contents of bagasse on dry matter basis are 45 to 55% cellulose, 20 to 25% hemicellulose, 18 to 24% lignin and 1 to 5% ash and waxes (Convey *et al.*, 2006; Rainey, 2009). Filtermud on the other hand contains 5 to 30% fiber, 5 to 15% crude wax and fats, 10 to 20% ash including oxides of Si, Ca, P, Mg and K, 3.5% colloidal organic matter, 5 to 15% crude proteins and 5 to 15% sugars (Cheesman, 2004). Other materials such as maize stover contain 13.8 kg N t^{-1}, 1.3 kg P t^{-1}, 11.5 kg K t^{-1}, 2.2 kg Ca t^{-1}, 1.9 kg Mg t^{-1} and 129.0 kg lignin t^{-1}; sugarcane straw contains 3.9 kg N t^{-1}, 0.4 kg P t^{-1}, 7.0 kg K t^{-1}, 2.4 kg Ca t^{-1}, 0.4 kg Mg t^{-1} and 160.2 kg lignin t^{-1}; cow manure contains 9.8 kg N t^{-1}, 2.2 kg P t^{-1}, 8.5 kg K t^{-1}, 4.0 kg Ca t^{-1}, 2.3 kg Mg t^{-1} and 84.8 kg lignin t^{-1}; *T. diversifolia* leaves contains 38.4 kg N t^{-1}, 3.8 kg P t^{-1}, 45.5 kg K t^{-1}, 19.5 kg Ca t^{-1}, 4.1 kg Mg t^{-1} and 116.6 kg lignin t^{-1} (Sanginga and Woomer, 2009). Since most of these compounds are made up of carbon as the main element in the structure, a considerable amount of this element is lost through practices such as burning and field disposal.

Materials such as filtermud contains a high amount of other elements due to a higher amount of ash hence these could also be lost through these practices.

The quality of some of these organic biomasses may be low, making it difficult to rely solely on them to meet crops requirements. Addition of high quality materials such as green leaves and livestock manure or incorporation of inorganic sources such as rock phosphate during composting could produce high quality bio-fertilizers that may be of great importance in supplying soil nutrients and as soil conditioners (Njoroge, 1994; Lekasi *et al.,* 2003). Furthermore, composting of organic biomass is known to increase availability and solubility of nutrients and especially N and P (Savini, 1999). Increasing soil organic matter content in soil through application of composts and animal manure could improve soil biodiversity and generally encourage ecosystem functions such as organic matter decomposition, nutrient cycling and soil aggregate stabilization (Six *et al.,* 2002; Ayuke, 2010). For example, Kapkiyai (1996) stated that a greater microbial biomass occurs where crop residues are either retained or incorporated into soil compared to where residues were removed or burned. Sugiyarto (2009) also observed that application of maize residue as mulch enhanced a 44 and 73% increase in diversity index of surface and deep soil macroinvertebrates, respectively. Besides, long-term manure application in combination with other inorganic inputs results in higher earthworm biomass and diversity and therefore the associated effects of improved soil aggregation and stable soil structure (Kapkiyai, 1996; Ayuke 2010). Despite its limitations, utilization of organic resources remains one of the major viable options in soil fertility management in sub-Saharan Africa (Gichangi, 2003; Ayuke *et al.,* 2007).

1.4 Objectives

1.4.1 Broad objective

Production of high quantity and quality compost using locally available organic agro-wastes.

1.4.2 Specific objectives

1. Characterize selected locally available organic biomasses for use in composting.
2. Evaluate effect of compost types on soil quality and health.
3. Assess agronomic effectiveness of composts using maize as the test crop in farmers' fields.

1.5 Hypothesis

1. Quality of compost is not influenced by the type of organic biomass.
2. Soil chemical characteristics and soil fauna diversity is not affected by the type of composts made from different organic agro-wastes.
3. Use of composts as fertilizer will not improve maize yield.

CHAPTER TWO: LITERATURE REVIEW

2.1 Soil fertility management strategies

Nutrient management is a decision-making process with regard to control of nutrient flows in soils so as to combine an economically viable agricultural production with minimum nutrient losses (NRCS, 2006). In the past, crop production systems were based on shifting cultivation which allowed for the build up of nutrients lost. However, with the increasing pressure on arable land due to population growth, nutrient build up in soils is a challenging task in many cropping systems in tropical ecosystems. According to Sanchez *et al.* (1997), soil fertility reduction on the small-holder farms remains the central cause of decline in per capita food production in Africa, a situation which threatens food security. Price fluctuations on fertilizer and other farm inputs has led to decline in capacity of farmers in sub-Saharan Africa to put through necessary fertility measures (Van Straaten, 2002). This is aggravated by the rising rural poverty. Nutrient loses in soils is seen as a drawback towards achievement of food security. For variability of food systems in this region to be eliminated, then soil fertility decline must be addressed.

Integrated soil fertility management (ISFM), which is a strategy that maximizes fertilizer and organic resource use efficiency has been employed to address the challenge in attempt to improve crop productivity (Vanlauwe *et al.*, 2006; Munthali, 2007). Through adoption of appropriate rates of fertilizer application, use of available organic resources and improved germplasm, this strategy has been perceived to give satisfactory results (Vanlauwe, 2004). Application of fertilizer may not give the desired results of improved yields especially in less responsive soils due to low nutrient use efficiency. Nutrient use efficiency in organic materials applied alone is also low (Vanlauwe and Sanginga, 1995). The ISFM helps in overcoming a wide range of crop production related constraints including those not directly associated with soil nutrient supply such as improved soil structure, moisture content and soil organic matter (Kapkiyai, 1996; Munthali, 2007). Addressing the challenges facing agriculture in sub-Saharan Africa is critical given the changes in global climatic patterns that result in unequal distribution of food in the continent, sometimes leading to acute shortages. The technologies that are locally available for ISFM when properly utilized can provide desirable results (Vanlauwe *et al.*, 2006; Palm *et al.*, 2001). Almost all the soil fertility management interactions in ISFM are aimed at strategic application of commercial fertilizers, improving nutrient recycling within the farms, optimizing crop-livestock interaction and promoting intercropping and rotation programs such as cereal-legume based intercrops among other interventions. Improving availability of organic resources and efficiency in their utilization is important in increasing crop yields especially in areas where population density is very high (Omotayo and Chukwuka, 2009).

The success of ISFM has been achieved in some areas like Burkina Faso, Mali and Niger where fertilizer micro-dosing combined with institutional and market linkages known as 'warrantage' led to a 44 to 120% increase in yields of millet and sorghum hence increasing farmers' income by 52 to 134% (Tabo *et al.*, 2007). The ISFM through combined application of fertilizer with organic inputs facilitates in boosting efficiency in crop nutrient use and uptake when compared to the same materials applied separately (Vanlauwe and Sanginga, 1995; Vanlauwe *et al.*, 2001; Nziguheba *et al.*, 2004; Mugendi *et al.*, 2007). Geiger *et al.* (1992) concluded that combination of organic amendments with inorganic fertilizers resulted in greater enhancement of soil fertility properties than when the materials were used alone. This is a result of improved supply in both macro and micro nutrients. Jama *et al.* (1997) observed that application of high quality manure on a maize crop on two P-deficient sites gave comparable yield to application of Triple Super Phosphate (TSP) fertilizer. When an economic analysis was carried, it turned out that use of manure gave a higher benefit than use of TSP. Application of crop residues and manure in drier areas has also contributed to higher yield given that this practice improves soils' moisture retention capacity thereby ameliorating the effects of water deficit (Gichangi, 2003; Kimani *et al.*, 2007; Kihanda *et al.*, 2007; Mucheru-Muna, 2011). In Central Burkina Faso, integration of composts with fertilizer micro-dosing and water harvesting through formation of *zai* basins increased sorghum yield seven-fold from 200 to 1,700 kg ha^{-1} (Sanginga and Woomer, 2009). Sawadogo-Kaboré *et al.* (2008) also observed similar results where combination of water harvesting, fertilizer micro-dosing and use of organic matter led to a yield increase of between 25-40% in Burkina Faso and more than 50% in Ghana compared to the controls therefore increasing the value of their grain stocks by between 21-42%. From the sandy soil of Guinea Savanna of West Africa, localized application of urea fertilizer combined with organic inputs resulted in an additional 514 kg ha^{-1} maize yield compared to that mineral fertilizer or organic inputs applied separately (Vanlauwe *et al.*, 2001; Vanlauwe *et al.*, 2002). This yield increase was attributed to improved fertilizer use efficiency resulting from improved soil moisture storage. The practice has also been perceived to restore crusted and compacted soils through attracting beneficial macrofauna such as termites which open up voids on the sealed soil surface further increasing the benefits of an improved soil environment (Mando and van Rheenen, 1998).

Strategies such as Managing Better Interactions for Legume Intercrops (MBILI) have been tested by several farmers in Central and Western Kenya and were proven to not only increase yields and consequently increase profits but it has also been seen as the entry point to ISFM where the practice improves fertilizer use efficiency, increase biological nitrogen fixation among other benefits (Mucheru-Muna *et al.*, 2010; Woomer, 2007; Tungani *et al.*, 2003). Integrating green manure cover crops provides potential of improved soil productivity through increased soil organic matter content, soil microbial activities and ameliorating physical properties in soil (Kimani *et al.*, 2003). Establishment of on-farm biomass banks such as hedgerows and live fences has also been shown to be important sources of organic materials for improvement of maize yields (Palm, 1995; Palm *et al.*, 2001).

2.2 Management of organic resources towards improvement of soil fertility

In low-input systems, management of organic resources is a viable option for improving agricultural productivity and compensating for the nutrients lost from soils. This is relevant to farmers in sub-Saharan Africa where the soils are highly weathered and both socio-economic and environmental conditions limit them from accessing and/or using right quantities of chemical fertilizers (Mando and Brussaard, 1999; Van Straaten, 2002; Makokha *et al.*, 2001). Integrated Soil Fertility Management which involves integration of fertilizers and organic resources could also help in reversing nutrients loss and compensate farmers from the soaring cost of inorganic fertilizers (Kimani *et al.*, 2003; Vanlauwe *et al.*, 2006). In addition, ISFM helps in maintenance of soil organic matter stocks as well as increase water and nutrient use efficiency and therefore encourage persistence of soil fauna diversity, generally improving productivity of soils. Soil fauna in return affects soil organic matter dynamics through mineralization-immobilization processes. Soil biota is an essential component of soil health and constitutes key ecosystem functions such as material decomposition and nutrient cycling, soil structure modification and aggregate stabilization as well as biological control of soil borne pests and diseases (Woomer *et* *al*, 1994; Moreira *et al.*, 2008; Ayuke *et al.*, 2009). Soil health describes the capacity of any soil to meet performance standards relating to nutrient and water retention and release patterns, soil biota diversity and functions as well as soil structural stability (Moreira *et al.*, 2008). The interaction between soil fauna and soil organic matter affects crop productivity as it regulates soil nutrient release patterns of some elements such as nitrogen through processes like nitrification, nitrogen fixation, denitrification and volatilization. In environments with high leaching and denitrification potential, proper management of organic resources in combination with inorganic fertilizers may increase nutrient use efficiency by holding excess N through immobilization (Kimani *et al.*, 2003). This acts as a slow release fertilizer or split application of inorganic fertilizer as the nitrogen is released later in the season hence benefitting the crop during critical developmental stages since most small-scale farmers never top dress the crop.

The quality of organic resources has a great effect on composition and diversity of soil fauna and therefore influences the organic residue decomposition dynamics and nutrient release patterns in soils (Lavelle *et al.*, 1992; Lavelle, 1997; Tian *et al.*, 1997; Cadisch and Giller 1997; Vanlauwe *et al.*, 2005). Quality of organic resources, defined by the relative ratios of carbon, nitrogen, lignin and polyphenols, is an important fundamental determinant in controlling the rate of decomposition as well as nutrient release pattern of the end product of decomposition (Tian *et al.*, 1997; Mando and Brussaard, 1999; Ayuke *et al.*, 2007). Nevertheless, the relation of these quality properties to soil fauna composition and abundance is often complex and not well understood (Tian *et al.*, 1995). Composting is therefore a complex activity that involves multiple soil micro and macro-organisms to give a stable end product that can be used as a bio-fertilizer. Though the extent of solubilization of nutrients may vary with the kind of waste and the rate of decomposition, utilization of nutrients such as P by crops may be enhanced by addition of external sources of P such as rock phosphate during composting process (Ndung'u *et al.*, 2003).

2.3 Role of organic resource management in improving soil health

Management options in soils can have positive or negative effects on soil flora and fauna species composition and diversity, ranging from short-term to long-term (Ayuke, 2010). A significant change in soil organic matter content occurs when there is a change in management options; for example, conversion of forest to cultivated land due to losses of various elements through crop harvest, burning of residues and exposure of soil organic matter through tillage. Soil management practices such as use of organic inputs, crop rotation, mulching and cover cropping enhance macro-fauna diversity and functions through improvement of soil conditions as well as increasing supply of substrates (Ayuke, 2010). Systems like no-till and minimum tillage are encouraged due to their impacts in reducing losses of soil organic carbon, nitrogen and phosphorous in addition to enhancing symbiotic association such as mycorrhizae. Though relative losses in N and C from soil are related to the original content of these elements, tillage methods and cropping systems have significant effects on longterm content of the elements (Kapkiyai, 1996). Human-induced soil disturbance and land use intensification impacts negatively on soil structure leading to loss of soil biodiversity across most cropping systems and consequently reduction in provision of ecosystem services (Moreira *et al.*, 2008; Bationo *et al.*, 2006). Intensive tillage without application of necessary organic and inorganic inputs diminishes soil organic carbon and as a result a reduction in biogenic soil structural features and an overall reduction in crop performance (Bationo *et al.*, 2006).

Organic resources management could have profound effects on soil fauna activities such as earthworms and termites which consequently affect soil structure and its functions in water and aeration regulation (Mando *et al.,* 1999; Ayuke *et al.,* 2009). Anecic species of earthworms which form semi-permanent and permanent vertical burrows mix the top soil horizons with the deeper ones hence distribution of soil organic matter across soil horizons (Savala, 2002). The macro-channels created by macrofauna improve soil porosity enhancing aeration, water infiltration and root development (Lavelle *et al.,* 2001; Mando *et al.,* 1999; Karaca, 2011). Soil fauna induced decomposition of organic resources and redistribution of soil organic matter through excretions contributes to macro-aggregation of soil structural units. Structure stability of soil is important in affecting root distribution and water and nutrient availability as well as ease of uptake of these nutrients by plants. Though aggregation of soil is a complex activity that includes several factors such as soil management, biotic and abiotic processes, macrofauna can play crucial role in the overall stability of soil (Kavdir and İlay, 2011).

Earthworms and termites modify soil environment through ingestion of soil, creating organo-mineral structural units (Ayuke, 2010; Karaca, 2011). These units create a micro-habitat for other microorganisms to colonize such as actinomycetes which thrive well in presence of worm casts and the population is more than six times that in original soil (Mando *et al.,* 1999). The structural units are also resistant to erosion forces by increasing bonding strength between mineral constituents of the soil (Lavelle, 1999; Kavdir and İlay, 2011). In addition, earthworms promote nodulation, dispersal of mycorrhizae and disease suppression among other beneficial functions. Through mounding and nesting and transportation of plant biomass, termites influence physical properties of soil. Feeding by earthworms has a marked influence on formation and partitioning of both soil organic matter and aggregate formation while burrowing results in mixing of soil and formation of continuous void space leading to lower bulk density in soil and resultant ease in movement of water and air (Ayuke, 2010).

Earthworm activities turn over large amounts of organic matter in soils through breakdown of large particles into smaller ones and consequently mineralization of nutrients in worm casts (Savala, 2002). As a result, rate of decomposition of organic matter in form of wastes on soil increases, generally improving availability of crop nutrients (Swift *et al.,* 1996; Tian *et al.*, 1997). The excreta (castings) of the worms are rich in nitrates and available forms of P, K, Ca and Mg, compared to the ordinary humified soil organic matter. Ingestion of soil by earthworms increases water extractable inorganic P which encourages absorption by crops. Earthworms also inject ammonia directly into the soil through excretion from nephridia and when mixed with soil solution, it contributes to higher nitrate concentration (Savala, 2002). Excretions from soil organisms especially earthworms are important contributors to soil aggregation as these may contain cations that form bridges between mineral and organo-mineral particles hence increased stability of soil (Kavdir and İlay, 2011).

Combined with proper tillage and cropping systems such as conservation tillage, crop rotation programs and cereal-legume intercrops, organic resource management has the potential of improving soil environment through manipulation of soil physical, chemical and biological properties (Six *et al.,* 2002; Ayuke, 2010). Improving soil environment directly affects functioning of soil ecosystem through availability and release of nutrients with consequent effects on sustainability of agricultural production. However, the quality and quantity of organic resources applied determine community structure, abundance and composition of soil fauna and hence their impact on soil processes and ecosystem services (Lavelle *et al.,* 1994).

2.4 Challenges in management and utilization of organic resources

Improving soil fertility using organic biomasses in smallholder farming systems of sub-Saharan Africa has not achieved the desired results due to unequal distribution of these organic resources across various cropping systems. In dry areas, availability of organic resources in insufficient quantities poses a challenge to utilization of organic resources as a source of soil nutrients due to competition of available organic materials to various uses such as fuel and feed for animals (Gichangi, 2003; Bationo *et al.,* 2006; Gichangi *et al.*, 2007). On the contrary, high potential areas of Rift Valley and Western provinces such as Trans Nzoia and Uasin Gishu districts, production rate of crop residues such as maize stover and wheat straw is very high, ranging from 4 to 15 tonnes ha^{-1} year^{-1} (Savala *et al.*, 2003). Production of bagasse and filtermud from sugar industries in Western Kenya is estimated at 1.6 million ton year^{-1} and 150,000 ton year^{-1} respectively (UNSD, 2007). Some of the sugar industries such as Mumias Sugar and South Nyanza Sugar Company utilize part of bagasse produced in electricity generation. Annual reports from Nzoia Sugar Company estimate that over 24,000 ton ha^{-1} excess bagasse is produced per year (Nzoia Sugar Company, 2000; Kibwage *et al.*, 2003). In addition almost all filtermud is not utilized hence posing a challenge in disposal to most sugar industries due to lack of alternative means of utilization. Accumulation of agro-wastes within small-scale farms may become a challenge during land preparation and some farmers opt to burn them. According to Bationo (2008), this practice results in loss of volatile nutrients like N, S and.C and generally a reduction in soil organic matter. It is estimated that a loss of 20 to 40 kg N/ha and 5 to 10 kg S/ha could be expected every cropping cycle through such practices (Bationo *et al.*, 2006). An unaccounted C amount is also lost as CO_2 gas to the atmosphere. Bationo *et al.* (2006) and Bationo and Bürkert (2001) have documented that CEC of sandy loams of West Africa depend directly on the soil organic carbon (SOC) content than soil clay content and that a 1.0 g kg^{-1} difference in SOC resulted in a 0.25 cmol (+) kg^{-1} change in soils' CEC. Therefore a loss of such a small SOC margin could lead to high losses in major exchangeable cations and reduction in nutrient and water holding capacities, a situation which compromises crop performance.

Usefulness of organic resources as soil amendment depends on the quality of these materials, which in turn depends on the content of nutrient elements (C and N as well as trace elements) and other compounds, including and lignin and polyphenolic compounds (Vanlauwe *et al.*, 1996; Mando and Brussaard, 1999; Gichangi, 2003; Ayuke *et al.*, 2007). The quality of some of organic resources is very low, a situation which limits their relevance as soil amendments as they fix available nutrients. This could also slow the rate of decomposition of such materials. In addition, the quality of bio-fertilizers produced could be very low for such soil amendments to meet crops nutrient requirements (Omotayo and Chukwuka, 2009). Variation in quality of different organic biomasses leads to unequal release of nutrients in soil, some readily releasing while others taking time (Gachengo *et al.*, 2004; Okalebo *et al.*, 2007). For example, poultry manure readily mineralizes in comparison to low quality materials such as saw dust, maize stover, wheat straw or bagasse. This results in variation of the end product of decomposition of such materials which in turn reduces usefulness of organic resources as a source of crop nutrients (Gichangi, 2003). In addition, the amounts of such materials required to meet crop requirements could be high in order to justify the expected crop output. To stabilize and improve the quality of these high carbon content materials and therefore enhance release of nutrients, incorporation of inorganic compounds such as rock phosphate or higher quality materials such as green leaves through composting and vermicomposting is important (Ndung'u *et al.*, 2003; Rutunga *et al.*, 2008). Despite these limitations, utilization of organic resources remains one of the major options in soil fertility management in sub-Saharan Africa (Gichangi 2003; Ayuke *et al.*, 2007).

2.5 Composting as a means of stabilizing and improving quality of organic resources

Composting is the partial decomposition and stabilization of organic materials by provision of optimal moisture, temperature and aeration, and under the influence of multiple microbial populations (Cofie *et al.*, 2006; Inckel *et al.*, 2005). The end product of this process is a stable, nutrient rich material that can be used as a slow release fertilizer. Natural process of composting can be a very slow process and therefore to achieve quick results, right conditions must be provided. This involves several interventions ranging from regular to occasional turning of the compost heap. Control of the process can also be achieved through selection of materials to be used, moisture and aeration of heaps (Boland, 2005; Njoroge, 1994). The rate of decomposition can be speeded up by stacking materials to a height of about 1.0 to 1.5 m (Lekasi *et al.*, 2003). This enhances build up of correct temperature for decomposition to occur. However, due to increased activity during the initial stages of decomposition, regular turning is required to avoid overheating. It also helps to aerate the pile to eliminate accumulation of undesirable anaerobic by-products and production of malodor (Cofie *et al.*, 2006; Adam-Bradford, 2006). Decomposition reduces the mass and volume of original materials through losses of carbon dioxide and water. At the end of the composting process, a stable nutrient rich mixture, easy to handle and transport is formed (Gichangi, 2003).

Composting can be affected by physical, chemical and biological properties. The most important physical properties to composting are particle size and moisture content of materials to be composted (Lekasi *et al.*, 2003; Inckel *et al.*, 2005). Particle size not only affects movement of oxygen into and within the pile but also the rate of microbial and enzymatic access to substrates. Too fine particles restrict movement of air into and within the pile hence there is a need to mix fine materials with bulking agents such as wood chips. On the contrary, larger particles take long to be decomposed and therefore need to be shredded into smaller pieces. The most appropriate moisture content for composting lies between 40 to 60% (Lekasi *et al.*, 2003; Boland, 2005). High moisture contents interfere with oxygen accessibility, while low amounts reduce nutrient diffusion and microbial activity, thereby lowering the rate of decomposition (Lekasi *et al.*, 2003).

Chemical properties that affect the rate of decomposition include C:N ratio, lignin and poyphenols content as well as other micro- and macro-nutrients like P, Ca, Mn, Mg, and Mo which are important for microbial growth (Sanginga and Woomer, 2009). The C:N ratio, lignin and polyphenol content are measures of quality of a material (Tian *et al.*, 1995, 1997; Vanlauwe *et al.*, 2005). The relative quality and quantity of organic residues affect characteristics of the end product of composting. A high C:N (>40:1) ratio leads to immobilization of N, thereby slowing the rate of decomposition and may even cause N deficiency if such materials are applied to crops in the field. A narrow C:N ratio (<25:1) causes loss of N through ammonia (NH_3) volatilization. The correct ratios that lead to formation of stable compost lies in the range of 25-30:1 which enhances quick transformation of organic materials with high degree of efficiency in N-assimilation into microbial biomass (Njoroge, 1994, Cofie *et al.*, 2006; Adam-Bradford, 2006). Low quality materials can therefore be enriched by adding external sources of N and P such as rock phosphate or chicken manure, a process called compost fortification (Ndung'u *et al.*, 2003) or by mixing with high quality materials such as green leaves from legumes such as alfalfa. This process not only improves the quality of composts but also reduces losses of nitrogen through NH_3 volatilization. Biological properties that affect the process are classified as microbial, ranging from micro- to macrofauna. Macrofauna like earthworms, breakdown large materials and redistribute them hence increase the surface area for other organisms such as mesofauna (tardigrades and springtails) to colonize (Ayuke *et al.,* 2009). Microfauna such as fungi then take over, breaks large and complex molecules like lignin, cellulose and phenols into simpler ones. Bacteria then finalize the process, degrading them further into easily consumable products like lipids, glucose and amino-acids.

Composting process can be divided into mesophillic, thermophillic and curing stage (Njoroge, 1994; Inckel *et al.,* 2005). Mesophillic stage is the initial process which is characterized by rapid decomposition of readily available substrates. At the end of this stage, the temperature rises rapidly reaching about 65°C. In thermophillic stage the high temperature eliminate many of pathogens, including weed seeds and many parasitic eggs hence giving a pasteurization effect onto the compost (Lekasi *et al.,* 2003). Regular turning of the heap at this stage is important to ensure even heating, aeration and decomposition. The stage is followed by re-establishment of mesophillic state and the compost is colonized once again by the mesophiles. Curing is a relatively long stage where compost becomes stable and mature and fit to be applied to the field.

CHAPTER THREE: MATERIALS AND METHODS

3.1 Description of the study site

Figure 1 show the map of the area where the study was done. The study was conducted in Ivakale and Buyangu villages, Kakamega district in Western Kenya. The two sites are approximately 20 Km North of Kakamega town. The region lies between latitude 0° 10' N and 0° 21' N; Longitude: 34° 47' E and 34° 58' E, with an elevation of between 1500 and 1600 m above sea level (www.nationsonline.org). The area receives an annual precipitation of 2,080 mm; the rainfall is bimodal, with the highest amount occurring between April and May (Long rains), a slightly drier June and a second peak occurring between September and October (Short rains). January and February are the driest months. Temperatures are fairly constant throughout the year, with mean daily minimum and maximum of about 11 and 26°C, respectively, while mean annual temperature ranges between 18 to 27°C (Althof, 2005). The soils are predominantly luvisols and lixisols (FAO, 1987), showing moderately to slightly acidic conditions (pH 5.3 to 5.9). They have a relatively high moisture retention capacity but low inherent fertility as shown by low amounts of nitrogen, soil organic carbon and exchangeable bases.

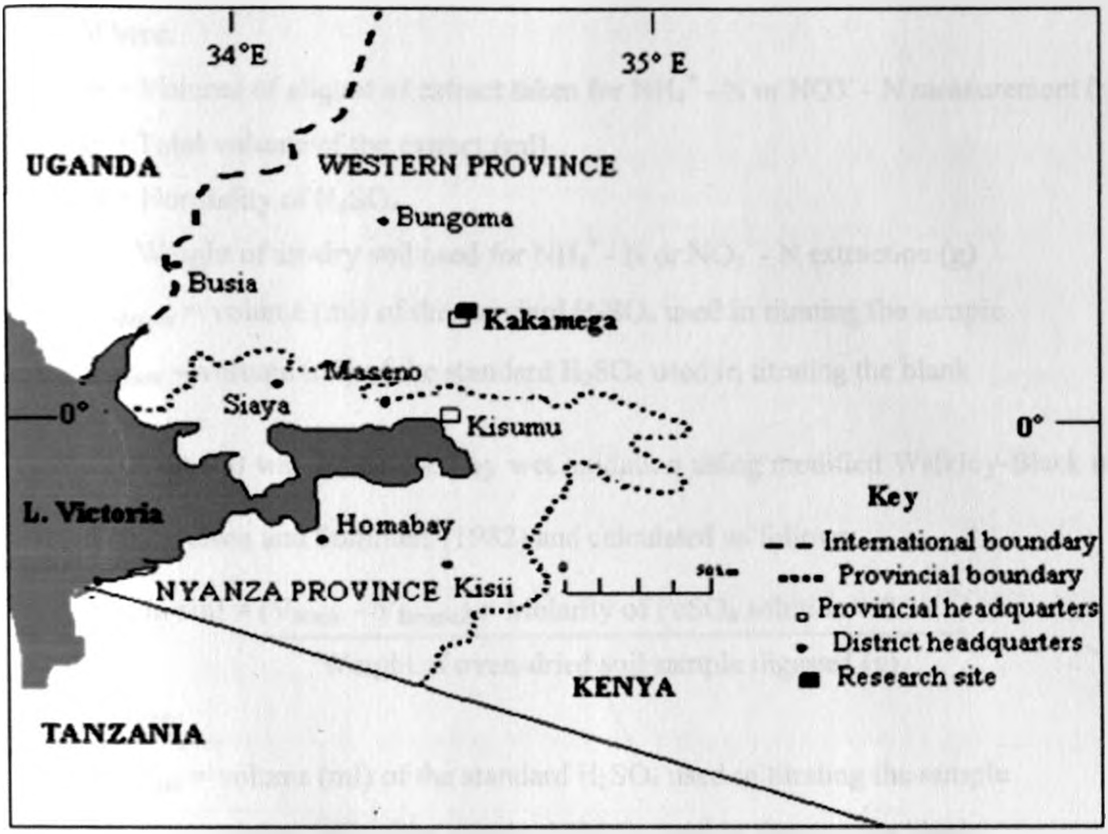

Figure 1: Map showing location of the research site. Adopted from Ayuke *et al.* 2006

3.2 Baseline soil chemical characterization

Soil sampling for baseline analysis was done before planting commenced. From each site, soil samples were taken randomly from each plot at a time then mixed thoroughly and two composite samples derived from them, labelled and transported to laboratory in cool boxes for analyses. The parameters measured included; Mineral N, total N, extractable Phosphorous, soil organic carbon, the bases (K, Na, Mg and Ca), CEC and pH. Mineral N was extracted using 2M potassium chloride (KCl) and determined using steam distillation method (Bremner and Keeney, 1965) and calculated as follows:

$$NH_4^+ - N \text{ or } NO_3^- - N \text{ (ppm)} = \frac{(V_{Sample} - V_{Blank}) \times N \times E \times 14 \times 1000}{S \times A}$$

Where:

A = Volume of aliquot of extract taken for NH_4^+ - N or $NO3^-$ - N measurement (ml)

E = Total volume of the extract (ml)

N = Normality of H_2SO_4

S = Weight of air-dry soil used for NH_4^+ - N or NO_3^- - N extraction (g)

V_{Sample} = volume (ml) of the standard H_2SO_4 used in titrating the sample

V_{Blank} = volume (ml) of the standard H_2SO_4 used in titrating the blank

Organic carbon (C) was determined by wet oxidation using modified Walkley-Black method as described by Nelson and Sommers (1982) and calculated as follows:

$$\%C \text{ in soil} = \frac{(V_{Blank} - V_{Sample}) \times \text{Molarity of } FeSO_4 \text{ solution} \times 0.39}{\text{Weight of oven-dried soil sample digested (g)}}$$

Where:

V_{Sample} = volume (ml) of the standard H_2SO_4 used in titrating the sample

V_{Blank} = volume (ml) of the standard H_2SO_4 used in titrating the blank

$0.39 = 3 \times 10^{-3} \times 1.3 \times 100$, where; 3 is the equivalent weight of C and 1.3 is a compensation factor for incomplete oxidation of organic carbon.

Total nitrogen (N) was determined by wet oxidation using Kjeldahl digestion and distillation procedures (Parkinson and Allen, 1975) and estimated using the formula below.

$$\%N \text{ in soil} = \frac{(V_{Sample} - V_{Blank}) \times \text{Molarity of standard } H_2SO_4 \times 1.401}{\text{Weight of oven-dried soil sample digested (g)}}$$

Where:

V_{Sample} = volume (ml) of the standard H_2SO_4 used in titrating the sample

V_{Blank} = volume (ml) of the standard H_2SO_4 used in titrating the blank

Phosphorus (P), potassium (K), sodium (Na) exchangeable calcium (Ca) and magnesium (Mg) were extracted by Mehlich-3 procedure (Mehlich, 1984) and then measured by automated colorimetry using an Inductively Coupled Plasma Atomic Emission Spectrophotometer (ICP-AES) (Kalra and Maynard, 1991). Analysis was done at the Crop Nutrition Laboratory, Nairobi.

3.3 Composting and chemical characterization of composts

3.3.1 Criteria for selection of materials

Six agro-organic wastes that are commonly found and used by farmers in the study area were collected and evaluated for their potential in making quality composts that can be used by local farmers to fertilize their soil. Selection criterion was based on availability of materials. These organic wastes included: *Tithonia diversifolia* trimmings, maize stover, bagasse, filtermud, sugarcane straw and cow manure. Cow manure was collected from the farmers' cattle sheds. Filtermud and bagasse were collected from West Kenya Sugar Company and transported to the two experimental sites of Ivakale and Buyangu. Maize stover and sugarcane straw, two of common crop residues on farms were collected from the respective farmers' field on each site. *Tithonia diversifolia* which is mainly grown as hedges or live fences around the farms was collected as fresh trimmings and used for composting.

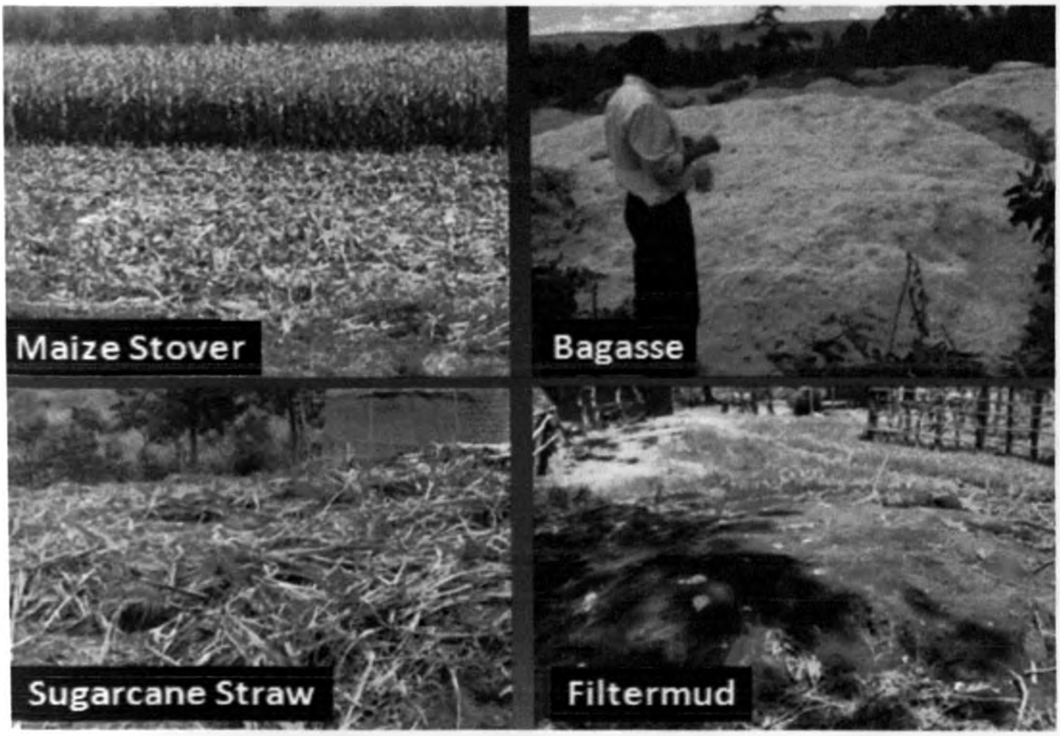

Plate 1: Some organic resources available as agro-industrial and farm derived wastes.

3.3.2 Chemical characterization of organic materials used for composting

Samples from selected organic resources namely: maize stover, sugarcane straw and *Tithonia diversifolia* were shredded to about 3 cm long pieces, placed in labeled sampling brown paper bags No 10 and then taken to laboratory for analysis. The other three remaining materials namely; filtermud, bagasse and cow manure were also sampled into labeled sampling bags and together taken to laboratory for analysis. The materials were air dried until a constant weight was obtained, after which they were ground and passed through 2 mm sieve and stored in plastic bags awaiting analysis. Maize stover, sugarcane straw, bagasse and *Tithonia diversifolia* samples were analyzed for macro-elements (N, P, K, Ca and Mg) and organic carbon. Organic carbon (C) was determined by wet oxidation using modified Walkley-Black method as described by Nelson and Sommers (1982); total nitrogen (N) by wet oxidation using Kjeldahl digestion and distillation procedures (Parkinson and Allen, 1975) while Phosphorus (P), potassium (K), sodium (Na) exchangeable calcium (Ca) and magnesium (Mg) were extracted using the dry ashing method and analyzed by an automated colorimetry using an ICP-AES (Kalra and Maynard, 1991). The analysis was done at the Crop Nutrition Laboratory, Nairobi.

3.3.3 Composting procedure

Composting was done at the farmers' field both at Ivakale and Buyangu using pit method (Njoroge, 1994; Inckel *et al.*, 2005). Pits measuring 2 m long by 1.5 m wide and 0.5 m deep were prepared (Plate 2a). Large, dry and bulky organic materials such as maize stover and sugarcane straw were shredded to 3 cm long pieces to enhance rate of decomposition. Material were placed in the pits in layers as follows; at the base was made of organic resource laid to a thickness of 15 cm followed by a thin layer of cow dung, about 2 cm thick to cover the organic material. A second layer of organic resource was added to thickness of 15 cm and wood ash sprinkled on this layer. About two liters of water was sprinkled onto this set-up to moisten it. This process was repeated in that order till there were about ten layers of alternating organic resource and cow dung to attain a height of about 1.5 m. The compost heaps were turned every two weeks to facilitate aerobic decomposition, for a duration of eight weeks with occasional sprinkling of about five liters of water to ensure that the material remained moist. The compost was cured for four weeks to allow stabilization of the bio-fertilizer before planting. The product was a dark mass of nutrient-rich material (Plate 2b).

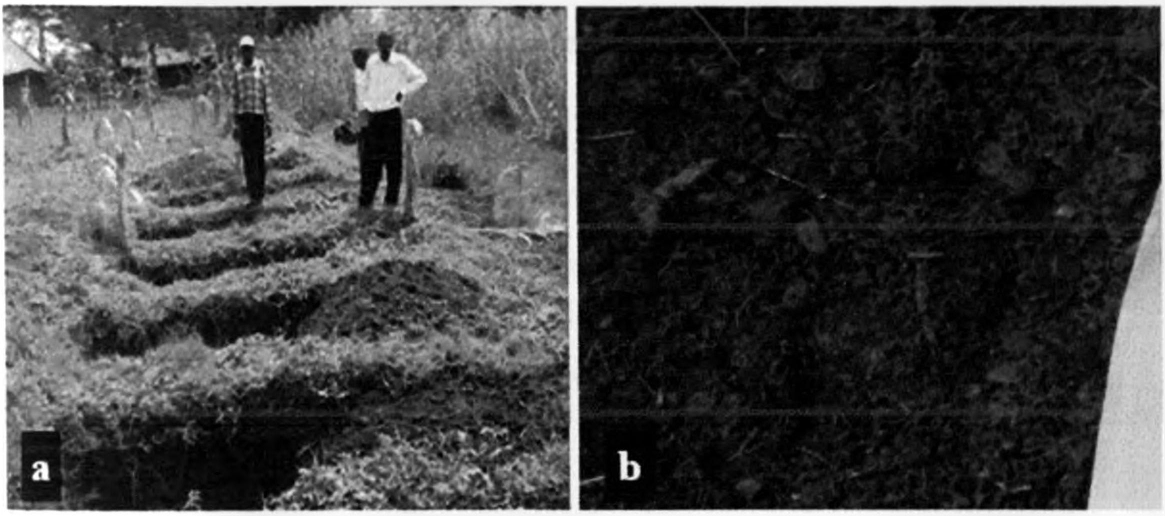

Plate 2: Composting process. (a) Pits used in composting of organic materials. (b) Compost high in humic substances hence dark colour.

3.3.4 Chemical characterization of composts

Compost samples were taken prior to planting and placed in brown paper bags No. 10 and taken to laboratory for analysis which was carried out at the Crop Nutrition Laboratory Services. The samples were prepared and analyzed for macro-elements (N, P, K, Ca and Mg), organic carbon and CEC following the procedure described in section 3.3.2

3.4 Evaluating effects of compost application on maize performance

3.4.1 Experimental design and treatment combinations

Field trials were conducted on two farms in Ivakale and Buyangu in Kakamega County, Western Kenya on 12th March 2010 at the onset of long rains. Plots measuring 5 m by 4 m were laid out in a randomized complete block design (RCBD). There were eight treatments that comprised of six composts made from six different organic biomasses: *Tithonia diversifolia* trimmings, maize stover, bagasse, filtermud, sugarcane straw and cow manure; a fertilizer treatment (Mavuno – 10% N, 26% P, and 4% MgO) and a control (neither fertilizer nor compost was applied). Each treatment was replicated four times. Composts were applied at a rate of 5 t ha^{-1} per season based on small-scale manure and compost application rates as recommended by Ncube *et al.* (2006) and Mapfumo and Giller (2001) while fertilizer at the recommended rate of 26 kg P ha^{-1} and 60 kg N ha^{-1} (Okalebo *et al.*, 2007). The treatment combinations were applied as shown on Table 1.

Table 1: Treatment combination and rate of application on the field trials.

Treatment code	Treatment description	Application rate
T1	Control	0
T2	Fertilizer (Mavuno)	
	Planting (10%N, 26%P & 4% MgO)	26 kg P ha^{-1}
	Topdress (26%N, 16%CaO & 5% S)	60 kg N ha^{-1}
T3	Cow Manure alone	5 t ha^{-1}
T4	Cow Manure + Maize stover	5 t ha^{-1}
T5	Cow Manure + Sugarcane straw	5 t ha^{-1}
T6	Cow Manure + Filter mud	5 t ha^{-1}
T7	Cow Manure + *Tithonia diversifolia*	5 t ha^{-1}
T8	Cow Manure + Bagasse	5 t ha^{-1}

3.4.2 Land preparation, planting, weeding and harvesting

Land preparation was done using an ox-plough in the first season. For the other consecutive seasons, hand hoeing was done for each plot at a time to retain the treatment effects as they were applied. Maize variety H-512 was planted on 12th March 2010 at the onset of long rain season. Planting was done on rows with treatments (composts or fertilizer) placed on furrows and mixed thoroughly with top soil before seeds were planted. This was done at a spacing of 75 cm between rows and 25 cm intra-row space with two seeds per hole after which thinning was done to one seedling two weeks after seedling emergence. Composts were applied at a rate of 5 t ha^{-1} while fertilizer (Mavuno – 10 % N, 26 % P and 4 % MgO) was applied at a rate of 60 kg N and 26 kg P ha^{-1}. Weeding was done twice, at four and eight weeks after sowing, respectively. For fertilizer treated plots, topdressing was carried out six weeks after sowing using Mavuno (26 % N, 16 % CaO and 5 % S) fertilizer. Maize was harvested at end of season after the cobs had dried. Stover was separated from cobs and total weight of maize on cobs and that of stover was recorded separately. Five sub-samples of both maize cobs and stalks from each plot were taken. Maize stalks were shredded into smaller pieces and placed in sampling brown paper bags No 10. The samples were air dried to constant weight. Maize grains were then separated from cobs by shelling and the total weight of grains recorded.

3.4.3 Determination of Benefit/Cost (B/C) ratio in maize yields

The B/C ratio was determined by dividing total benefits by total costs. Benefits were determined from direct sales of maize grains at farm gate prices. Total costs of production were calculated at the current market prices. Costs of production included: cost of purchasing organic materials or commercial fertilizers and the seeds, cost of transporting the materials, cost of composting and cost of land preparation, planting, weeding and crop harvesting.

3.4.4 Chemical characterization of soils treated with composts

Sampling for soil chemical analysis was done to a depth of 30 cm from each plot. The parameters measured were; the CEC, available N, total N, Phosphorous, organic carbon and the bases (K, Na, Mg and Ca). Analysis of these elements was done as explained on section 3.2.

3.5 Evaluating effects of compost application on soil fauna

3.5.1 Sampling for earthworms and other macrofauna

Collection of earthworms and other macrofauna was carried out eight weeks after sowing when they were active and mature for taxonomic identification. Two monoliths per plot, each measuring 25 cm long, 25 cm wide and 30 cm deep were randomly, excavated using shovels in three stratified layers of 10 cm depth from the surface; that is, 0 to 10 cm, 10 to 20 cm and 20 to 30 cm according to Moreira *et al.* (2008). The soil samples were placed in plastic trays and large clods were systematically broken-up to enable hand picking of earthworms and other macrofauna. Earthworms were placed in 75 % alcohol after which they were fixed with 4 % formaldehyde and stored in sealed and labeled vials. Insects and other arthropods were killed in 75 % alcohol, sealed in vials and labeled before being taken to laboratory for identification (Hall, 1996; Moreira *et al.*, 2008). Identification was done at the Department of Invertebrate Zoology of The National Museum of Kenya. The soil fauna abundance was calculated as number of individuals per square meters and biomass of individuals per square meters.

3.5.2 Sampling for nematodes

Figure 2 shows how sampling for nematodes was carried out. Sampling for nematodes was done in a grid system, with two circles of 1.5 m and 3 m radii marked out. Soil auger was used to make two equidistant samplings from the smaller inner circle and four from the larger outer circle. All samples were taken at 0 to 20 cm depth. The six cores were mixed thoroughly and a sub-sample derived from them. The soil was placed in soil sampling polythene bags, sealed and labeled for laboratory extraction and identification. This was done on each plot. Extraction of nematodes was done following Baerman pan technique (Hall, 1996; Carter and Gregorich, 2008). From well mixed sub-samples, 200 g of soil was taken and spread on a ½ mm nylon screen. The set up was placed on caker pans with enough water to saturate the soil and then covered with plastic covers. This was incubated for about three days, after which water in the pans was swirled and transferred into McCartney bottles and allowed to settle. The contents from the bottles were reduced to about five millilitres by siphoning excess water after which nematode identification process followed. Enumeration was done by pipetting two millilitres of the suspension into a counting slide (Hall, 1996; Carter and Gregorich, 2008).

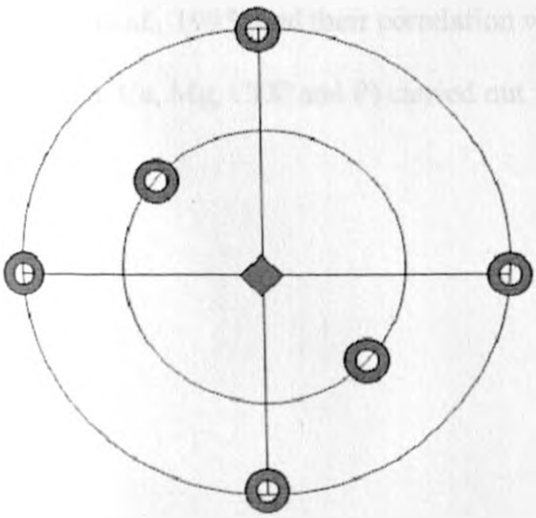

Figure 2: A sketch of the grid system used in sampling of nematodes

3.6 Statistical analysis and data management

The data obtained was entered into Excel Spreadsheets and subjected to analysis of variance (ANOVA) using Genstat statistical software (GENSTAT, 2009) and treatment differences evaluated using least significant difference ($LSD_{5\%}$). Due to non-homogeneity in macrofauna abundance data, the data was square root transformed $(x + 0.5)^{0.5}$. Multivariate analysis on macrofauna data was done using the programme CANOCO 3.1 (Ter Braak and Verdonschot, 1995; Ter Braak and Smilauer, 1998). A preliminary detrended correspondence analysis (DCA) was performed to determine the length of gradient of the first axis, and to decide on the ordination analysis to be used on the macrofauna abundance data. Since the length of gradient of the first axis determined by DCA was <4 in this study, linear ordination technique, Redundancy Analysis (RDA), was chosen to assess the correlation between soil chemical properties (soil pH, total N, Organic C, K, Na, Ca, Mg, CEC and P) and macrofauna abundance. The overall contribution of soil chemical characteristics to the variation in macrofauna data was assessed using Monte-Carlo test based on 999 random permutations under reduced model. Nematode families and genera were assigned to trophic groups; bacterivorous nematodes and plant parasites (Yeates *et al.*, 1993) and their correlation with soil chemical properties (soil pH, total N, Organic C, K, Na, Ca, Mg, CEC and P) carried out in a similar way as the macrofauna data.

CHAPTER FOUR: RESULTS

4.1 Chemical characteristics of soils from the two farms

Results of initial soil chemical characterization on selected parameters from the two sites are presented in Table 2. The soils were found to be moderately acidic with a pH range between 5.4 and 5.6. Exchangeable aluminium was high, being 1063 cmol (+) kg^{-1} in Buyangu and 1077 cmol (+) kg^{-1} Ivakale. Exchangeable bases were quite low except Ca which was relatively high in comparison to all other bases. Cation Exchange Capacity (CEC) of the soils was found to be 5.9 cmol (+) kg^{-1} in Buyangu and 4.2 cmol (+) kg^{-1} in Ivakale, which according to the rating by Landon (1984) was low. Total nitrogen and organic carbon were also low ranging between 0.13 to 0.14 % N and 1.40 to 1.64 % C. The ammonium form of available N was relatively higher compared to the nitrate form on both sites. Statistical analysis showed that there were no significant differences in most soil nutrients between the two farms.

Table 2: Soil chemical characteristics from the two sites

Characteristics	Site		summary of statistical analysis		
	Buyangu	Ivakale	Sed	Lsd$_{5\%}$	P-value
pH$_{(water)}$ (1 : 2.5)	5.40	5.60	0.02	0.08	0.010
Extractable P (mg kg^{-1})	10.95	9.57	0.79	3.40	0.709
Exchangeable K (g kg^{-1})	0.17	0.09	0.01	0.03	0.007
Exchangeable Na (g kg^{-1})	0.04	0.02	0.09	0.38	0.479
Exchangeable Ca (g kg^{-1})	0.93	0.63	0.09	0.38	0.043
Exchangeable Mg (g kg^{-1})	0.05	0.04	0.01	0.03	0.082
Base saturation (%)	20.0	19.0	0.81	0.43	0.070
CEC (cmol (+) kg^{-1})	5.96	4.20	0.04	0.17	<0.001
Exchangeable Al (cmol (+) kg^{-1})	1063	1077	9.19	39.55	0.848
Total N (%)	0.13	0.14	0.01	0.04	0.106
Organic C (%)	1.40	1.64	0.03	0.13	0.013
NO_3^- – N (mg kg^{-1})	1.36	1.67	0.05	0.19	0.031
NH_4^+ – N (mg kg^{-1})	8.05	4.51	0.54	2.34	0.016

4.2 Chemical characteristics of organic resources

The results of organic materials quality used in composting are given in Table 3. Filtermud and *T. diversifolia* had higher phosphorous values of 3.8 and 4.3 g kg^{-1}, respectively compared to other organic materials such as bagasse, sugarcane straw and maize.stover which had relatively low values of 0.1, 0.5 and 0.6 g kg^{-1}, respectively. Cow manure on the other hand had slightly higher amount of P (2.50 g kg^{-1}) than the three materials (bagasse, sugarcane straw and maize stover), but slightly lower than that of filtermud and *T. diversifolia*. The concentration of bases varied slightly across the organic resources. Of the six organic biomasses, *T. diversifolia* had the highest K value of 47.0 g kg^{-1} compared to other materials which were ranging between 0.7 and 6.7 g kg^{-1}. The concentration of calcium (12.7 g kg^{-1}) in *T. diversifolia* was also high compared to sugarcane straw, cow manure and filtermud which had values of 4.3, 6.1 and 7.2 g kg^{-1}, respectively. Maize stover and bagasse had the lowest calcium concentration of 2.4 and 1.1 g kg^{-1}, respectively. Sodium and magnesium concentrations were nearly the same in all the six organic materials. Bagasse showed a very high C:N ratio of 144:1 compared to other materials such as maize stover and sugarcane straw which had ratios of 65:1 and 80:1, respectively. *Tithonia diversifolia*, filtermud and cow manure had very low ratios of 12:1, 13:1 and 18:1, respectively. Although the total carbon content of the materials were within close range (between 46.3 to 53.1%), total N varied greatly leading to the sharp differences in C:N ratios. The highest N content was recorded in *T. diversifolia* and filtermud at 4.0 and 3.5% respectively. Cow manure had slightly higher N content of 1.4% than bagasse, sugarcane straw and maize stover which recorded the lowest values of 0.4, 0.6 and 0.8% N, respectively.

Table 3: Chemical characteristics of organic biomasses used in making composts.

Characteristics	Organic biomasses						summary of statistical analysis		
	CM	MS	SS	BG	FM	TD	Sed	$Lsd_{5\%}$	P-value
P (g kg^{-1})	2.50	0.60	0.50	0.10	3.80	4.30	0.24	0.57	<0.001
K (g kg^{-1})	1.50	6.70	1.20	0.70	1.00	47.0	0.64	1.56	<0.001
Na (g kg^{-1})	0.28	0.20	0.15	0.21	0.25	0.22	0.01	0.03	<0.001
Ca (g kg^{-1})	6.10	2.40	4.30	1.10	7.20	12.7	0.58	1.41	<0.001
Mg (g kg^{-1})	1.50	1.10	1.00	0.20	0.50	3.10	0.22	0.53	<0.001
% DM content	95.4	89.5	92.6	93.3	92.9	89.3	0.52	1.27	<0.001
C:N (ratio)	18.0	65.0	80.0	144	13.0	12.0	1.31	1.85	<0.001
Total N (%)	1.37	0.79	0.58	0.37	3.47	4.04	0.32	0.78	<0.001
Organic C (%)	25.2	51.6	46.4	53.1	46.3	46.8	1.79	4.38	<0.001

Key: BG = Bagasse, CM = Cow Manure, FM = Filtermud, MS = Maize Stover, SS = Sugarcane Straw and TD = *Tithonia diversifolia*.

4.3 Chemical characteristics of composts

Table 4 shows the chemical characteristics of composts in the two farms. All composts gave high pH which ranged from 6.9 to 7.3 in Buyangu and 6.8 to 7.1 in Ivakale. Composts made in Buyangu were superior in extractable P compared to those made in Ivakale. The highest extractable P of 979.0 mg kg^{-1} was observed in composts prepared from filtermud while it was lowest in bagasse composts (563.0 mg P kg^{-1}). Sugarcane straw, cow manure, maize stover and *T. diversifolia* composts had a range of 574.0 to 614.0 mg P kg^{-1}. In Ivakale, the highest extractable P was recorded in composts made from *T. diversifolia* (249.0 mg P kg^{-1}), while composts made from cow manure alone and sugarcane straw had the lowest values of 163.0 and 165.0 mg kg^{-1}, respectively. Bagasse, maize stover and filtermud composts had extractable P values ranging from 203.0 to 214.0 mg kg^{-1}. The exchangeable bases of all composts in both sites were within similar range. Generally, total N was slightly higher in composts made in Buyangu than in Ivakale. The highest value recorded in Buyangu was obtained from composts made from filtermud (0.99 % N). The rest of the composts were within similar ranges with a 0.1 % difference between the second highest (cow manure alone) (0.73 % N) and lowest (bagasse) (0.63 % N). In Ivakale, the highest value was also recorded from filtermud composts (0.70 % N). The lowest N content was obtained from compost made from cow manure alone (0.53 % N). The highest organic carbon content in Ivakale was recorded in composts made from sugarcane straw (8.41 % C) and maize stover (8.26 % C). Cow manure, bagasse, *T.diversifolia* and filtermud composts had a range of 6.73 to 7.94 % C. In Buyangu, maize stover produced composts with the highest carbon content of 8.01 % while filtermud composts gave the lowest C content of 6.18 %. However, all chemical characteristics of these compost amendments were not significantly different except CEC which was significantly different in both sites.

Table 4: Chemical characteristics of composts made from six organic biomasses.

Characteristics	Compost Type						Summary of statistical analysis		
				Buyangu site					
	T3	T4	T5	T6	T7	T8	Sed	$Lsd_{5\%}$	P-value
$pH_{(water)}$ (1 : 2.5)	7.28	7.19	7.11	7.05	7.28	6.87	0.129	0.289	0.660
Extr. P (mg kg^{-1})	574.0	610.0	571.0	979.0	614.0	563.0	127.2	283.2	0.054
Exc. K (g kg^{-1})	0.76	0.66	0.64	0.60	0.72	0.43	0.106	0.238	0.113
Exc. Na (g kg^{-1})	0.06	0.05	0.06	0.06	0.07	0.06	0.006	0.015	0.582
Exc. Ca (g kg^{-1})	3.82	3.79	4.40	3.55	3.78	4.87	0.614	1.369	0.338
Exc. Mg (g kg^{-1})	0.93	0.92	0.88	0.82	0.95	0.89	0.079	0.176	0.614
CEC (cmol kg^{-1})	38.72	35.38	32.49	33.41	34.51	44.21	0.924	2.058	< 0.001
C:N (ratio)	9.93	11.61	10.00	9.36	10.73	7.02	—	—	—
Total N (%)	0.73	0.69	0.70	0.99	0.66	0.63	0.116	0.258	0.101
Organic C (%)	7.25	8.01	7.00	6.18	6.76	6.95	0.949	2.114	0.573
				Ivakale site					
$pH_{(water)}$ (1 : 2.5)	7.06	6.99	7.01	6.80	6.87	7.00	0.205	0.456	0.801
Extr. P (mg kg^{-1})	163.0	219.0	165.0	219.0	249.0	203.0	65.10	146.0	0.752
Exc. K (g kg^{-1})	0.58	0.66	0.82	0.51	0.53	0.54	0.118	0.263	0.174
Exc. Na (g kg^{-1})	0.05	0.06	0.06	0.06	0.06	0.07	0.001	0.016	0.261
Exc. Ca (g kg^{-1})	3.16	3.15	3.11	3.75	3.07	3.62	0.251	0.559	0.081
Exc. Mg (g kg^{-1})	0.93	0.92	0.88	0.89	0.89	0.95	0.051	0.114	0.826
CEC (cmol kg^{-1})	27.96	26.98	27.47	30.48	26.25	31.33	1.346	2.999	0.020
C:N (ratio)	13.04	13.11	12.94	11.34	13.12	9.90	—	—	—
Total N (%)	0.53	0.63	0.65	0.70	0.59	0.68	0.075	0.167	0.332
Organic C (%)	6.91	8.26	8.41	7.94	7.74	6.73	1.030	2.300	0.505

Key: T3 = Cow manure alone, T4 = Cow manure + Maize stover, T5 = Cow manure + Sugarcane straw, T6 = Cow manure + Filtermud, T7 = Cow manure + *Tithonia diversifolia* and T8 = Cow manure + Bagasse. Extr. = extractable Exc. = exchangeable.

4.4 Effect of compost application on soil chemical properties

4.4.1 Nitrogen

Table 5 shows a sammury of the soil chemical characteristics of soils treated with composts in the two sites. Analysis of total N across different treatments on both sites showed that the results were highly significant ($P < 0.001$). In Buyangu, application of composts led to an increase in soil total N except where bagasse composts were applied where total N remained constant. Control plots recorded a 14% reduction in total N. Application of filtermud and cow manure composts resulted in a 69% and 54% increase in total N, respectively. The other three compost treatments; sugarcane straw, maize stover and *T. diversifolia* recorded a 46, 31 and 23% increase in soil N respectively. Fertilizer application also led to an increase in total N by 31%. In Ivakale, soils amended with bagasse composts recorded a 7% reduction in total N. Soils that received compost made from *T. diversifolia* gave a 29% increase in N which was the highest increase compared to all other treatments, followed by soils amended with inorganic fertilizer with a 21% increase. Soils amended with maize stover and sugarcane straw composts gave the least increments of 7% each while composts made from cow manure alone had no effect at all. Similarly, in Buyangu, control recorded a decline in total N of 14%. On average, composts amended soils recorded 6% increase in total N in Ivakale and 36% in Buyangu, and this was a 21% overall increase across the two sites.

Available N (NO_3^- and NH_4^+) showed the same trend as the total N in all the treatments in both farms and the results were statistically significant ($P = 0.004$). In Buyangu, the highest NH_4^+ value (37.5 mg kg^{-1}) was obtained from soils amended with filtermud compost. Soils amended with maize stover, sugarcane straw and cow manure alone had slightly lower values ranging between 32.4 and 34.7 mg kg^{-1}. Soils treated with fertilizer, *T. diversifolia* and bagasse had NH_4^+ values within similar range between 24.2 and 28.0 mg kg^{-1} while the control plots gave the lowest NH_4^+ of 18.8 mg kg^{-1}. In Ivakale, the highest values of 36.8, 34.8 and 31.1 mg kg^{-1} were obtained from soil amended with *T. diversifolia,* fertilizer and sugarcane straw, respectively. Filtermud, maize stover and cow manure composts and control treatments had their values within 25.3 to 29.6 mg kg^{-1} range. Bagasse composts recorded the lowest $NH4^+$ value of 18.6 mg kg^{-1} and this was lower than that observed in control plots.

Soil NO_3^- values were lower than those of NH_4^+ but tended to follow the same trend as total and ammonium N. The results of soil nitrates analysis showed that the NO_3^- content of soil receiving various soil amendments were significantly different ($P < 0.001$). The highest amounts were recovered from soils amended with cow manure, sugarcane straw and filtermud composts and inorganic fertilizer, recording values between 10.1 and 14.4 mg kg^{-1}. Maize stover, *T. diversifolia* and bagasse composts had values ranging from 5.2 to 8.8 mg kg^{-1} while control plots had the lowest NO_3^- value of 4.9 mg kg^{-1}. In Ivakale, soils amended with inorganic fertilizer recorded the highest NO_3^- value of 18.0 mg kg^{-1}. All compost treated soils and the control plots had NO_3^- values ranging from 4.4 to 8.2 mg kg^{-1}.

4.4.2 Organic carbon

The results of organic C in soils from both farms (Buyangu and Ivakale) were significantly different at $P < 0.001$ (Table 5). In Buyangu, all the treatments led to an increase in soil organic C including control plots. The highest value of 3.0 % C was obtained from soils amended with filtermud compost which was 116.4 % increase followed by fertilizer, maize stover, sugarcane straw and cow manure amended soil which had organic C values of between 2.8 and 2.9 % C representing a 102.8 to 108.6 % increase. Soil amended with composts made from bagasse and *T. diversifolia* had slightly lower values of 2.7 and 2.6 % C which was an equivalent of 94.3 and 90.0 % increase, respectively while control plots had a 52.1 % increase. In Ivakale, the highest organic C of 3.2 % was obtained from soils amended with composts made from sugarcane straw, which was a 96.3 % increase. Soils treated with filtermud, cow manure alone and maize stover composts and inorganic fertilizer recorded slightly lower values ranging from 2.9 to 3.0 % C which represented an increase of between 75.0 and 84.8 % while soils amended with bagasse and *T. diversifolia* recorded increases of 66.3 and 63.1 %, respectively. Control plots recorded the lowest amount (1.9 % C) which was an equivalent of 21.3 % increase from the baseline. The average increase in organic carbon on soils amended with composts was 76 % in Ivakale and 103 % in Buyangu; a 90 % overall increase in the two farms.

4.4.3 Phosphorus

Amending soils with different composts had significant ($P < 0.001$) effect on soil P content (Table 5). In Buyangu, all the treatments led to an increase in soil P except in control plots where an overall decline was recorded. However, only a marginal increase of P on soils amended with composts was observed. The highest P of 22.2 mg kg^{-1} was obtained on soils treated with fertilizer; a 102.7 % increase from the baseline. Soils treated with composts had their P values within similar range of 11.1 to 13.5 mg kg^{-1} which was a 1.4 to 23.3 % increase. Control plots recorded a 34.1 % reduction in soil P. In Ivakale, all the treatments recorded a decline in P except in fertilizer treated plots. The highest recorded P value of 14.8 mg kg^{-1} was obtained from soils treated with fertilizer and this was a 57.8 % increase from the baseline. The decline in soil P on soils treated with composts ranged from 34.8 % to 45.6 %. Control plots recorded the lowest P value of 3.2 mg kg^{-1}, a 66.2 % decline from the baseline value. The overall soil P content was higher in Buyangu than in Ivakale. On average, in Buyangu, soils amended with composts recorded 11 % increase in P but recorded a 40 % decline in Ivakale.

4.4.4 CEC and bases

The soil bases were within same range. In Buyangu, there was a reduction in content of all the bases except Mg which recorded a 25 % increase from the baseline. Application of different treatments had significant ($P < 0.001$) effect on K, Na and Ca but no significant ($P = 0.236$) effect on Mg (Table 5). There was an increase in CEC on all the compost and fertilizer amended soils, with values ranging from 6.01 (bagasse) to 6.99 cmol (+) kg^{-1} (filtermud). Control plots recorded a decline from 5.96 in baseline to 5.63 cmol (+) kg^{-1} at the end of the study. In Ivakale, there was a reduction in K and Ca on soils amended with composts while Na and Mg generally increased. There was an increase in CEC on all soil treatments including control plots, with the values ranging from 5.32 cmol (+) kg^{-1} (control) to 6.86 cmol (+) kg^{-1} (filtermud).

4.4.5 Soil pH

The pH of soil amended with different treatments was significantly different at $P < 0.001$ (Table 5). In Buyangu, application of composts led to a slight increase in soil pH from the baseline. The highest pH value recorded was 5.7 in soils treated with cow manure compost while *T. diversifolia* composts had the lowest soil value at 5.6. There was no change in pH on control plots while slight decrease from 5.4 in baseline to 5.3 in fertilizer treated plots was observed. In Ivakale, all the treatments led to a decrease in pH. However, soils amended with composts had higher pH values compared to fertilizer treated plots which recorded the lowest value of 5.3.

Table 5: Chemical characteristics of soils treated with composts over the three seasons.

Characteristics	Treatment type								Summary of statistical analysis		
					Buyangu Site						
	T1	T2	T3	T4	T5	T6	T7	T8	Sed	$Lsd_{5\%}$	P-value
$pH_{(water)}$ (1 : 2.5)	5.44	5.39	5.68	5.63	5.63	5.59	5.58	5.60	0.036	0.071	<0.001
Extr. P (mg kg^{-1})	7.23	22.17	11.33	12.49	11.73	13.53	12.76	11.12	1.543	3.037	<0.001
Exc. K (g kg^{-1})	0.05	0.04	0.06	0.06	0.06	0.05	0.05	0.06	0.002	0.004	<0.001
Exc. Na (g kg^{-1})	0.02	0.02	0.02	0.01	0.02	0.01	0.02	0.02	0.001	0.002	<0.001
Exc. Ca (g kg^{-1})	0.57	0.66	0.70	0.47	0.66	0.66	0.58	0.62	0.017	0.034	<0.001
Exc. Mg (g kg^{-1})	0.06	0.06	0.07	0.06	0.07	0.07	0.07	0.07	0.004	0.010	0.236
CEC (cmol kg^{-1})	5.63	6.11	6.88	6.20	6.27	6.99	6.69	6.01	0.144	0.284	<0.001
Total N (%)	0.11	0.17	0.20	0.17	0.19	0.22	0.16	0.13	0.013	0.025	<0.001
Organic C (%)	2.13	2.84	2.92	2.84	2.90	3.03	2.66	2.72	0.219	0.431	<0.001
NH_4^+ - N (mg kg^{-1})	18.75	24.23	34.69	32.36	33.75	37.45	24.42	27.95	3.358	6.629	0.004
NO_3^- - N (mg kg^{-1})	4.98	12.24	10.12	8.81	11.23	14.39	6.23	5.21	1.437	2.835	<0.001
					Ivakale Site						
$pH_{(water)}$ (1 : 2.5)	5.49	5.29	5.59	5.53	5.56	5.59	5.50	5.60	0.035	0.068	<0.001
Extr. P (mg kg^{-1})	3.23	14.81	5.21	5.84	5.32	6.15	6.24	5.92	1.472	2.897	<0.001
Exc. K (g kg^{-1})	0.04	0.04	0.04	0.05	0.05	0.05	0.03	0.05	0.002	0.004	<0.001
Exc. Na (g kg^{-1})	0.02	0.02	0.02	0.02	0.01	0.02	0.02	0.02	0.001	0.002	<0.001
Exc. Ca (g kg^{-1})	0.50	0.45	0.49	0.63	0.52	0.50	0.44	0.51	0.016	0.033	<0.001
Exc. Mg (g kg^{-1})	0.06	0.08	0.07	0.08	0.08	0.07	0.07	0.08	0.004	0.007	0.216
CEC (cmol kg^{-1})	5.32	5.41	5.66	6.14	6.16	6.86	5.57	5.69	0.140	0.275	<0.001
Total N (%)	0.12	0.17	0.14	0.15	0.15	0.16	0.18	0.13	0.012	0.024	<0.001
Organic C (%)	1.99	3.03	2.90	2.96	3.22	2.87	2.68	2.73	0.211	0.416	<0.001
NH_4^+ - N (mg kg^{-1})	25.32	34.81	26.98	29.08	31.05	29.64	36.80	18.63	3.277	6.469	0.003
NO_3^- - N (mg kg^{-1})	4.41	18.03	5.16	6.12	6.10	5.52	8.20	4.63	1.042	2.767	<0.001

Key: T1 = Control, T2 = Fertilizer, T3 = Cow manure alone, T4 = Cow manure + Maize stover, T5 = Cow manure + Sugarcane straw, T6 = Cow manure + Filtermud, T7 = Cow manure + *Tithonia diversifolia* and T8 = Cow manure + Bagasse, Extr. = extractable and Exc. = exchangeable.

4.5 Agronomic effectiveness of different compost types on maize performance

Table 6a shows maize grain yields over the three seasons in the two study sites. Addition of composts and inorganic fertilizer increased yields significantly ($P < 0.001$) compared to the control plots. Fertilizer treated plots produced the highest maize grain yields in both sites over the three seasons. In the first season, fertilizer treated plots recorded 5.9 t ha^{-1} of maize grain in Buyangu and 5.8 t ha^{-1} in Ivakale, which were 320 % and 350 %, respectively above the control plots. Compost treated plots recorded maize grain yields ranging from 2.1 to 2.7 t ha^{-1} in Buyangu and 2.3 to 2.6 t ha^{-1} in Ivakale, representing an increase ranging from 50 to 93 % in Buyangu and 77 to 100 % in Ivakale above the control treatments. In the second season, maize grain yields decreased due to inadequate rainfall. Yields were significantly ($P < 0.001$) highest in fertilizer treated plots at 1.0 t ha^{-1} in Buyangu and 1.1 t ha^{-1} in Ivakale which were 230 % and 270 % increase, respectively above control plots. Compost treated plots gave maize grain yields ranging from 0.6 to 0.7 t ha^{-1} in both sites, which was a 100 to 190 % increase above control plots. However, there were no significant yield differences ($P < 0.05$) in all the compost treated plots in the second season. During the third season, fertilizer treated plots gave the highest maize grain yields of 6.4 t ha^{-1} in both farms, an increase of 150 % in Buyangu and 140 % in Ivakale above control plots. Compost treated plots recorded maize grain yields ranging from 4.5 to 5.6 t ha^{-1} in Buyangu and 4.5 to 5.5 t ha^{-1} in Ivakale, a 75 to 115 % increase in Buyangu and 70 to 100 % in Ivakale relative to control plots.

Table 6a: Maize grain yield (t ha^{-1}) over the three seasons on the two study sites

Treatment	Yields (t ha^{-1})							
	April–July (2010)		Oct.–Dec.(2010)		April–July (2011)		3-Seasons Mean	
	Buyangu	Ivakale	Buyangu	Ivakale	Buyangu	Ivakale	Buyangu	Ivakale
T1	1.4	1.3	0.3	0.3	2.6	2.7	1.5	1.4
T2	5.9	5.8	1.0	1.1	6.4	6.4	4.6	4.5
T3	2.6	2.5	0.6	0.6	4.9	4.9	2.7	2.6
T4	2.4	2.3	0.6	0.6	5.0	4.6	2.7	2.5
T5	2.1	2.5	0.6	0.7	4.9	4.6	2.5	2.6
T6	2.7	2.5	0.7	0.7	5.6	5.5	3.0	2.9
T7	2.1	2.6	0.6	0.6	4.5	5.3	2.4	2.8
T8	2.2	2.6	0.7	0.7	5.0	4.5	2.6	2.6
Sed	0.158	0.233	0.054	0.061	0.428	0.412	0.816	0.795
$Lsd_{5\%}$	0.329	0.484	0.113	0.139	0.889	0.857	1.623	1.581
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.032	0.043

Key: T1 = Control, T2 = Fertilizer, T3 = Cow manure alone, T4 = Cow manure + Maize stover, T5 = Cow manure + Sugarcane straw, T6 = Cow manure + Filtermud, T7 = Cow manure + *Tithonia diversifolia* and T8 = Cow manure + Bagasse. Within a column, means followed by the same lowercase letters are not significantly different at $P < 0.05$

Table 6b shows the benefit/cost (B/C) ratio obtained over three seasons in the two study sites. The B/C ratio of all yields obtained from composts treated plots was higher than that obtained in fertilizer treated and control plots except in second season where all treatments recorded same ratios. Generally, within compost amendments, yields obtained from plots treated with cow manure, *Tithonia diversifolia*, maize stover and sugarcane straw recorded slightly higher B/C ratio than those treated with composts made from bagasse and filtermud.

Table 6b: Benefit/Cost ratio obtained over the three season yield averages

Treatment	Benefit/Cost ratio							
	April–July (2010)		Oct.–Dec.(2010)		April–July (2011)		3-Seasons Mean	
	Buyangu	Ivakale	Buyangu	Ivakale	Buyangu	Ivakale	Buyangu	Ivakale
T1	0.5	0.4	0.1	0.1	0.9	0.9	0.5	0.5
T2	1.0	1.0	0.2	0.2	1.1	1.1	0.8	0.8
T3	1.4	1.4	0.1	0.1	1.8	1.8	1.4	1.4
T4	1.4	1.4	0.1	0.1	1.8	1.8	1.4	1.4
T5	1.3	1.4	0.1	0.1	1.8	1.8	1.4	1.4
T6	1.2	1.2	0.1	0.1	1.6	1.5	1.4	1.4
T7	1.3	1.4	0.1	0.1	1.8	1.9	1.4	1.5
T8	1.2	1.3	0.1	0.1	1.6	1.6	1.4	1.4

Key: T1 = Control, T2 = Fertilizer, T3 = Cow manure alone, T4 = Cow manure + Maize stover, T5 = Cow manure + Sugarcane straw, T6 = Cow manure + Filtermud, T7 = Cow manure + *Tithonia diversifolia* and T8 = Cow manure + Bagasse.

4.6 Evaluating effects of compost application on soil fauna

4.6.1 Effect of compost on earthworms

The number of earthworms recorded in Buyangu before the start of experiment was 8 individuals m^{-2} and these were weighing an average of 0.26 g m^{-2} while in Ivakale, a population density of 12 individuals m^{-2} was recorded and the earthworms were weighing an average of 0.31 g m^{-2}. Table 7 shows earthworm number and weight recorded from the experimental sites. Application of different soil amendments had significant ($P < 0.001$) effect on earthworm abundance. In Buyangu, the highest number of earthworms (51 individuals m^{-2}) was recorded from soils amended with filtermud composts, which was almost double the number recorded from other types of composts. This was a 538% increase from the baseline of 8 individuals m^{-2}. Soils treated with bagasse and *T. diversifolia* composts had equal earthworm densities (36 individuals m^{-2}), a 350% increase from the baseline. Sugarcane straw, cow manure alone and maize stover composts recorded a fairly low densities than the other three composts; 26, 25 and 22 individuals m^{-2} which was a 225, 213 and 175% increase, respectively. Soils treated with fertilizer and the control plots recorded the lowest earthworm numbers (9 and 8 individuals m^{-2}), almost similar to the baseline number. In Ivakale, soils treated with filtermud composts recorded the highest earthworm density (70 individuals m^{-2}), a 483% increase from the baseline of 12 individuals m^{-2}. Maize stover, bagasse, sugarcane straw and *T. diversifolia* composts gave relatively higher number of 43, 40, 39 and 36 individuals m^{-2}, which was a 258, 233, 225 and 200% increase, respectively above the baseline. Of the six composts, cow manure alone gave the lowest density (29 individuals m^{-2}) that was 142% above the baseline. Fertilizer treated plots and the controls gave the lowest number (11 and 12 individuals m^{-2}, respectively), indicating no substantial change from the baseline. The biomass of earthworms followed the same trend as the abundance across all the treatments in both sites.

Table 7: Earthworm density and weight identified from the two farms under different treatments.

Treatment	Earthworm density (individuals m^{-2})		Earthworm weight (g m^{-2})	
	Buyangu	Ivakale	Buyangu	Ivakale
T1	8	12	0.31	0.37
T2	9	11	0.26	0.38
T3	25	29	0.57	0.87
T4	22	43	0.90	0.81
T5	26	39	0.72	0.75
T6	51	70	2.42	3.92
T7	36	36	0.67	1.20
T8	36	40	0.75	1.14
Sed	2.00	1.00	0.101	0.050
Lsd$_{5\%}$	3.00	5.00	0.203	0.102
P-value	<0.001	<0.001	<0.001	<0.001

Key: T1 = Control, T2 = Fertilizer, T3 = Cow manure alone, T4 = Cow manure + Maize stover, T5 = Cow manure + Sugarcane straw, T6 = Cow manure + Filtermud, T7 = Cow manure + *Tithonia diversifolia* and T8 = Cow manure + Bagasse.

4.6.2 Effect of compost on other macrofauna groups

Table 8a and 8b shows macrofauna diversity in Buyangu and Ivakale, respectively. A total of 26 macrofauna genera belonging to six classes were identified across the two sites. Class insecta dominated the macrofauna recorded from the two sites. Taxonomic richness varied across different treatments as well as between the two sites. In Buyangu, soils amended with bagasse composts had the highest taxonomic richness (20 taxa), followed by soils amended with composts made from sugarcane straw (16), cow manure (15) and filtermud (14). *Tithonia. diversifolia* composts had the lowest taxonomic richness with 12 taxa. In Ivakale, soils amended with filtermud composts were taxonomically the richest with 18 taxa, followed by bagasse composts (14 taxa). Soils treated with composts made from cow manure alone were among the treatments that recorded the lowest taxonomic richness (11 taxa) which was contrary to results obtained in Buyangu for the same treatment.

Table 8a: Macrofauna diversity and taxonomic richness across different treatments in Buyangu

Macrofauna description			Treatment								Summary of statistical analysis	
Macrofauna group	Family	Genera/Species	T1	T2	T3	T4	T5	T6	T7	T8	Total	% Total
Oligochaeta	Acathodrilidae	*Dichogaster bolaui*	0	0	1	1	0	8	0	0	10	0.9
		Dichogaster affinis	0	1	0	0	1	0	3	1	6	0.5
		Dichogaster saliens	0	0	0	0	2	2	0	1	5	0.4
	Ocnerodrilidae	*Nematogenia lacuum*	11	13	23	20	20	41	32	34	194	16.6
	Eudrilidae	*Eminoscolex violaceus*	0	0	0	0	0	0	0	0	0	0.0
Isoptera	Termitinae	*Microtermes pusillas*	13	2	28	39	11	51	29	95	268	22.9
		Macrotermes sp.	6	6	31	19	43	123	100	12	340	29.0
		Pseudacanthotermes sp.	0	0	0	0	0	0	0	0	0	0.0
Coleoptera	Staphylinidae	*Philonthus sp.*	2	4	4	3	1	1	0	3	18	1.5
		Leptocinus sp.	2	12	11	9	14	12	11	13	84	7.2
	Scarabidae	*Phillopertha sp.*	1	3	4	7	4	6	2	6	33	2.8
		Aphodius lvidus	0	0	0	1	0	0	0	0	1	0.1
	Carabidae	*Hyparpalus sp.*	3	1	0	1	1	0	4	6	16	1.4
Hymenoptera	Formicidae	*Anoma sp.*	1	7	4	11	5	11	6	3	48	4.1
		Euponera sp.	9	2	5	5	5	25	7	22	80	6.8
		Carebara sp.	0	0	0	0	1	2	0	0	3	0.3
		Bothroponera sp.	1	1	4	1	0	0	0	1	8	0.7
Orthoptera/Ensifera	Gryllidae	*Gryllus maculata*	0	0	1	0	1	1	0	1	4	0.3
		Gryllus bimaculata	0	0	5	0	2	2	2	1	12	1.0
Orthoptera/Califera	Acrididae	*Morphacris fasciata*	1	0	0	0	0	0	0	1	2	0.2
Diptera	Drosophilidae	*Drosophila sp*	1	0	0	0	0	0	0	0	1	0.1
Blattodea	Blattoidea	*Blatella sp.*	0	0	0	0	0	0	0	1	1	0.1
Scolopendromorpha	Scolopendridae	*Scolopendra sp.*	2	0	5	5	2	8	2	1	25	2.1
Diplopoda	?	?	0	1	0	0	0	0	0	1	2	0.2
Gastropoda	?	?	0	0	2	0	0	0	0	1	3	0.3
Araneae	?	?	0	2	1	0	1	0	2	2	8	0.7
Taxonomic richness (number of genera or species)			**13**	**13**	**15**	**13**	**16**	**14**	**12**	**20**	-	-

Key: T1 = Control, T2 = Fertilizer, T3 = Cow manure alone, T4 = Cow manure + Maize stover, T5 = Cow manure + Sugarcane straw, T6 = Cow manure + Filtermud, T7 = Cow manure + *Tithonia diversifolia* and T8 = Cow manure + Bagasse. Macrofauna groups represented by the symbol (?) could not be identified beyond the order level because they were too juvenile hence no identification key could be appropriately used.

Table 8b: Macrofauna diversity and taxonomic richness across different treatments in Ivakale

Macrofauna description			Treatment								Summary of statistical analysis	
Macrofauna group	Family	Genera/Species	T1	T2	T3	T4	T5	T6	T7	T8	Total	% Total
Oligochaeta	Acathodrilidae	*Dichogaster bolaui*	0	0	0	0	0	3	2	0	5	0.6
		Dichogaster affinis	0	1	0	0	0	0	0	0	1	0.1
		Dichogaster saliens	3	20	10	10	21	27	8	3	102	12.6
	Ocnerodrilidae	*Nematogenia lacuum*	8	21	19	26	20	26	28	9	157	19.4
	Eudrilidae	*Eminoscolex violaceus*	0	2	0	0	0	3	0	0	5	0.6
Isoptera	Termitinae	*Microtermes pusillas*	8	12	1	8	8	4	10	24	75	9.3
		Macrotermes sp.	0	5	1	27	33	57	2	36	161	19.9
		Pseudacanthotermes sp.	1	0	25	0	3	13	2	3	47	5.8
Coleoptera	Staphylinidae	*Philonthus sp.*	1	0	0	0	0	0	0	0	1	0.1
		Leptocinus sp.	3	2	8	1	2	1	1	4	22	2.7
	Scarabidae	*Phillopertha sp.*	0	2	3	5	2	3	1	2	18	2.2
		Aphodius lvidus	0	0	0	0	0	0	0	0	0	0.0
	Carabidae	*Hyparpalus sp.*	0	0	0	0	0	0	0	0	0	0.0
Hymenoptera	Formicidae	*Anoma sp.*	11	1	13	0	8	4	3	4	44	5.4
		Euponera sp.	8	4	6	6	2	2	8	4	40	5.0
		Carebara sp.	0	1	1	4	2	0	2	40	50	6.2
		Bothroponera sp.	1	0	0	1	0	2	45	0	49	6.1
Orthoptera/Ensifera	Gryllidae	*Gryllus maculata*	1	0	0	3	5	2	0	1	12	1.5
		Gryllus bimaculata	2	0	0	0	0	0	0	0	2	0.2
Orthoptera/Califera	Acrididae	*Morphacris fasciata*	0	0	0	0	0	1	0	0	1	0.1
Diptera	Drosophilidae	*Drosophila sp*	0	0	0	0	0	1	0	0	1	0.1
Blattodea	Blattoidea	*Blatella sp.*	0	0	0	0	0	1	0	0	1	0.1
Scolopendromorpha	Scolopendridae	*Scolopendra sp.*	0	0	0	0	0	1	0	0	1	0.1
Diplopoda	?	?	0	0	0	0	0	0	0	0	0	0.0
Gastropoda	?	?	0	0	0	0	0	0	0	0	0	0.0
Araneae	?	?	0	1	4	1	0	1	2	4	13	1.6
Taxonomic richness (number of genera or species)			**11**	**13**	**11**	**12**	**12**	**18**	**13**	**14**	-	-

Key: T1 = Control, T2 = Fertilizer, T3 = Cow manure alone, T4 = Cow manure + Maize stover, T5 = Cow manure + Sugarcane straw, T6 = Cow manure + Filtermud, T7 = Cow manure + *Tithonia diversifolia* and T8 = Cow manure + Bagasse. Macrofauna groups represented by the symbol (?) could not be identified beyond the order level because they were too juvenile hence no identification key could be appropriately used.

Table 8c shows the macrofauna abundance sampled across the two sites. Soil macrofauna sampled varied between the sites as well as within the site. Isopterans were the dominant group of the macrofauna sampled, constituting 56.5 % of the total in Buyangu and 40.7 % in Ivakale. They were followed by Oligochaeta, constituting 12 % in Buyangu and 22.9 % in Ivakale, and Hymenopterans constituting 9.7 % in Buyangu and 19.5 % in Ivakale. Other macrofauna groups such as Coleoptera, Orthoptera, Arenae, Diplopoda, Chilopoda, Diptera, Gastropoda and Blattelidae, each constituted less than 10 % of the total macrofauna. Within the Isopteran group, *Macrotermes sp.* dominated, representing 29.0 % of the total macrofauna in Buyangu and 19.9 % in Ivakale. *Pseudacanthotermes sp.* was observed only in Ivakale. Five genera of Oligochaeta group belonging to three families (Ocnerodrilidae, Acathodrilidae and Eudrilidae) were recorded from the two sites. *Nematogenia lacuum* of the family Ocnerodrilidae dominated the Oligochaeta group with an abundance of 16.6 % of the total macrofauna sampled in Buyangu and 19.4 % in Ivakale. However, *Dichogaster saliens* of Acathodrilidae family were also numerous in Ivakale constituting 12.6 % of the total macrofauna sampled. *D. affinis* and *D. bolaui* from the same family occurred in low numbers, recording a population below 1 % of the total macrofauna sampled from both sites. *Eminoscolex violaceus* from the Eudrilidae family were observed only in Ivakale, representing only 0.6 % of the total macrofauna sampled. Analysis of variance indicated no significant differences on all macrofauna groups except in Oligochaeta group (earthworms). Earthworm densities were significantly ($P < 0.001$) highest in soils amended with filtermud composts and lowest in soils amended with inorganic fertilizer and the control.

Table 8c: Soil Macrofauna abundance (number m^{-2}) identified across the two sites

Macrofauna group/order	Treatment type								Summary of statistical analysis				
	T1	T2	T3	T4	T5	T6	T7	T8	Total	% Total	Lsd$_{5\%}$	Sed	P -value
							Buyangu Site						
Oligochaeta	2	3	5	4	5	10	7	7	43	12.0	2	0.8	<0.001
Isoptera	6	3	20	19	18	58	43	36	203	56.5	24	5.7	0.096
Hymenoptera	3	3	3	4	3	10	3	6	35	9.7	7	3.6	0.391
Coleoptera	2	4	4	4	4	4	3	6	31	8.6	2	1.1	0.770
Diptera	1	0	0	0	0	0	0	0	1	0.3	1	0.4	0.561
Blattellidae	0	0	0	0	0	0	0	1	1	0.3	1	0.4	0.561
Orthoptera	1	0	2	0	1	1	1	1	7	1.9	1	0.6	0.428
Chilopoda	2	0	5	5	2	8	2	1	25	7.0	5	2.4	0.593
Arenae	0	2	1	0	1	0	2	2	8	2.2	2	1.3	0.630
Diplopoda	0	1	0	0	0	0	0	1	2	0.6	1	0.4	0.561
Gastropoda	0	0	2	0	0	0	0	1	3	0.8	1	0.4	0.080
Mean total	17	16	42	36	34	91	61	62	359	100	-	-	-
							Ivakale Site						
Oligochaeta	2	2	6	9	8	12	7	8	54	22.9	1	0.2	<0.001
Isoptera	3	2	9	6	15	25	12	5	96	40.7	10	2.9	0.083
Hymenoptera	5	1	5	1	3	2	3	15	46	19.5	5	0.5	0.243
Coleoptera	1	1	2	1	1	1	1	1	9	3.8	1	0.17	0.822
Diptera	0	0	0	0	0	1	0	0	1	0.4	1	0.1	0.369
Blattellidae	0	0	0	0	0	1	0	0	1	0.4	1	0.2	0.369
Orthoptera	1	1	0	0	2	1	1	0	6	2.5	2	0.2	0.388
Chilopoda	0	1	0	0	1	3	2	2	9	3.8	2	0.3	0.745
Arenae	0	4	4	1	0	1	2	2	14	5.9	1	1.0	0.544
Diplopoda	0	0	0	0	0	2	1	0	0	0.0	2	0.1	0.561
Gastropoda	0	0	0	0	0	0	0	0	0	0.0	1	0.1	0.080
Mean total	12	13	26	18	30	48	29	33	236	100	-	-	-

Key: T1 = Control, T2 = Fertilizer, T3 = Cow manure alone, T4 = Cow manure + Maize stover, T5 = Cow manure + Sugarcane straw, T6 = Cow manure + Filtermud, T7 = Cow manure + *Tithonia diversifolia* and T8 = Cow manure + Bagasse.

4.6.3 Effect compost application on soil nematodes

Table 9a shows the nematode genera identified from the two farms before start of the study. A total of 19 genera of nematodes belonging to three orders (Tylenchida, Dorylaimida and Rhabditida) were identified. These were further classified into two trophic groups; plant parasitic and bacterivorous groups. Of the plant feeders, three genera *Pratylenchus* (root-lesion nematodes), *Scutellonema* (spiral nematodes) and *Meloidogyne* (root-knot nematodes) dominated the soils in Ivakale and Buyangu. However, *Helicotylenchus* (spiral nematodes), *Tylenchorhynchus, Tylenchulus* and *Hemicriconemoides* also recorded high nematode densities compared to the other genera which occurred in very low numbers. Among the identified genera, *Criconema* (spine nematodes), *Heterodera* (cyst nematodes), *Hemicycliophora, Longidorus* (needle nematodes), *Paratrichodorous, Rotylenchus, Trichodorus* (stubby-root nematodes) and *Xiphinema* (dagger nematodes) were least dominant some recording a population of as low as 1 nematode/200cm^3. Only three bacterivore genera; *Acrobeles* and *Cephalobus* from Cephalobidae family and *Rhabditis* from Rhabditidae family were identified.

Table 9a: Nematode density (numbers 200 cm^{-3}) identified from the two sites before the experiment.

Nematode description				Site	
Trophic group	Order	Family	Genera	Buyangu	Ivakale
Plant parasitic	Tylenchida	Hoplolaimidae	*Helicotylenchus*	25	25
			Rotylenchus	6	5
			Scutellonema	52	50
		Criconematidae	*Criconema*	5	9
			Hemicriconemoides	13	14
			Hemicycliophora	2	2
		Heteroderidae	*Heterodera*	2	1
			Meloidogyne	37	31
		Pratylenchidae	*Pratylenchus*	66	68
		Belonolaimidae	*Tylenchorhynchus*	13	16
		Tylenchulidae	*Tylenchulus*	13	13
		Tylenchidae	*Tylenchus*	26	27
	Dorylaimida	Longidoridae	*Longidorus*	4	3
			Xiphinema	5	4
		Trichodoridae	*Paratrichodorous*	3	3
			Trichodorus	2	2
Bacterivores	Rhabditida	Cephalobidae	*Acrobeles*	4	5
			Cephalobus	4	4
		Rhabditidae	*Rhabditis*	4	4

Table 9b and 9c shows the nematode genera after application of various treatments across the two farms. Application of composts and other treatments had a significant ($P < 0.001$) effect on all nematode genera. Soils amended with fertilizer and the control plots were dominated by phytoparasitic nematodes. Amending soils with composts resulted in decline of phytoparasitic nematode densities compared to that of baseline. The most affected genera were *Pratylenchus, Scutellonema* and *Meloidogyne* which dominated the soil before application of treatments and their densities decreased by almost five fold. Bacterivore genera were low in control plots and those treated with inorganic fertilizer. However, when composts were applied, the population densities of these bacterivorous nematodes doubled.

Table 9b: Nematode density (numbers/200 cm^3) identified from Buyangu site under different treatments

Genera	Treatment type								Summary of statistical analysis		
	T1	T2	T3	T4	T5	T6	T7	T8	Sed	Lsd$_{5\%}$	P-value
Pratylenchus	70	61	26	32	21	23	23	25	2.69	5.33	<0.001
Scutellonema	54	56	18	17	13	13	16	17	2.09	4.15	<0.001
Meloidogyne	40	40	22	25	16	9	15	17	1.06	2.11	<0.001
Helicotylenchus	25	21	8	9	9	10	9	8	1.30	2.58	<0.001
Tylenchus	23	26	14	16	16	14	12	16	0.98	1.95	<0.001
Tylenchulus	13	15	6	7	5	7	5	6	0.66	1.31	<0.001
Hemicriconemoides	12	13	6	6	4	6	6	7	0.64	1.27	<0.001
Tylenchorhynchus	12	13	6	6	6	6	6	6	0.62	1.23	<0.001
Criconema	5	6	1	2	1	1	2	2	0.49	0.98	<0.001
Acrobeles	4	5	13	12	11	11	11	10	0.71	1.41	<0.001
Cephalobus	4	4	11	11	10	13	9	10	0.64	1.28	<0.001
Rhabditis	4	4	10	13	9	10	8	10	0.80	1.58	<0.001
Rotylenchus	4	7	4	2	8	5	6	6	0.77	1.53	<0.001
Trichodorus	4	4	1	1	1	1	1	1	0.29	0.58	<0.001
Xiphinema	4	4	2	4	2	7	4	7	0.65	1.28	<0.001
Paratrichodorous	3	2	1	1	2	1	1	1	0.27	0.53	<0.001
Hemicycliphora	2	2	1	1	1	1	1	1	0.29	0.57	<0.001
Heterodera	2	2	1	1	1	1	0	1	0.19	0.36	<0.001
Longidorus	1	8	3	5	3	1	7	1	0.66	0.13	<0.001

Key: T1 = Control, T2 = Fertilizer, T3 = Cow manure alone, T4 = Cow manure + Maize stover, T5 = Cow manure + Sugarcane straw, T6 = Cow manure + Filtermud, T7 = Cow manure + *Tithonia diversifolia* and T8 = Cow manure + Bagasse.

Table 9c: Nematode density (numbers/200 cm^3) identified from Ivakale site under different treatments

Genera	Treatment type								Summary of statistical analysis		
	T1	T2	T3	T4	T5	T6	T7	T8	Sed	$Lsd_{5\%}$	P-value
Pratylenchus	65	56	27	32	20	29	23	33	2.13	4.21	<0.001
Scutellonema	49	41	22	33	27	15	15	13	1.75	3.46	<0.001
Meloidogyne	35	39	24	25	7	13	11	11	1.14	2.25	<0.001
Tylenchus	26	24	12	12	9	14	15	12	0.86	1.69	<0.001
Helicotylenchus	24	26	9	8	9	9	8	8	1.02	2.02	<0.001
Tylenchulus	15	14	8	6	7	5	6	6	0.58	1.15	<0.001
Hemicriconemoides	14	13	6	5	5	7	4	7	0.62	1.22	<0.001
Tylenchorhynchus	12	14	5	6	7	6	6	7	0.61	1.20	<0.001
Criconema	6	5	1	1	1	2	1	2	0.44	0.87	<0.001
Acrobeles	4	4	11	12	11	12	12	10	0.64	1.26	<0.001
Cephalobus	4	4	11	10	10	11	11	9	0.65	1.28	<0.001
Rhabditis	4	5	11	17	15	9	14	11	0.74	1.47	<0.001
Hemicycliphora	3	3	1	1	1	1	1	1	0.39	0.62	<0.001
Paratrichodorous	3	3	1	1	2	1	1	1	0.60	1.18	<0.001
Rotylenchus	3	8	5	1	3	4	5	2	0.61	1.20	<0.001
Trichodorus	3	4	1	1	1	1	1	1	0.33	0.66	<0.001
Heterodera	2	3	1	1	1	1	1	1	0.22	0.44	<0.001
Longidorus	2	7	6	4	7	5	3	1	1.08	0.55	<0.001
Xiphinema	1	7	7	7	6	1	2	5	0.58	1.15	<0.001

Key: T1 = Control, T2 = Fertilizer, T3 = Cow manure alone, T4 = Cow manure + Maize stover, T5 = Cow manure + Sugarcane straw, T6 = Cow manure + Filtermud, T7 = Cow manure + *Tithonia diversifolia* and T8 = Cow manure + Bagasse.

4.6.4 Correlations of soil fauna abundance with soil chemical properties

Figure 3 shows the Redundancy Analysis (RDA) biplots between soil macrofauna and soil chemical properties. The eigenvalues of the first and second RDA axis constrained to the soil chemical properties were 0.165 and 0.032, respectively and the two axes explained 19.7 % of the observed variation in macrofauna abundance. The first axis was a potassium/total N gradient (r = 0.30 and -0.37, respectively) while axis 2 was a sodium/CEC/pH gradient (r = 0.30, 0.28 and -0.31, respectively). Macrofauna groups reacted differently towards soil chemical properties. Most of the macrofauna groups were found to be positively correlated with bases (Ca, Mg and

K), extractable P and pH, but negatively with total N and organic C along axis 2. Only Dipterans positively correlated with organic C. All other macrofauna groups weakly correlated with total N and organic C. Coleopterans strongly and positively correlated with K, while Araneae and Hymenoptera positively correlated with extractable P. The sum of all RDA canonical eigenvalues showed that soil chemical properties explained 25 % of the total variation observed in macrofauna abundance and the correlative relationships were highly significant (P = 0.007).

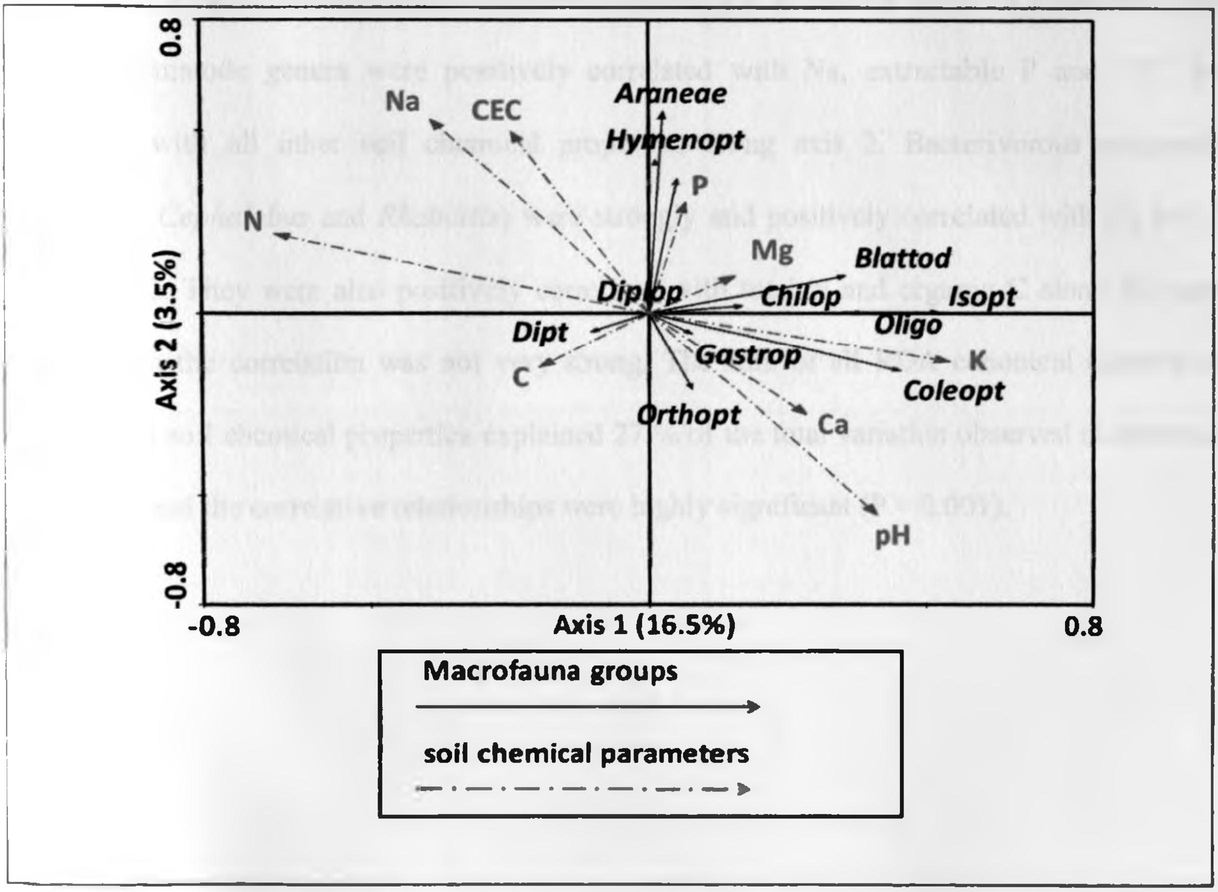

Figure 3: Redundancy Analysis (RDA) biplot showing correlation between soil macrofauna groups and soil chemical properties. Blattod = Blattodea, Cholop = Chilopoda, Coleopt = Coloeptera, Diplop = Doplopoda, Dipt = Diptera, Gatrop = Gastropoda, Hymenopt = Hymenoptera, Isopt = Isoptera, Oligo = Oligoptera and Orthopt = Orthoptera.

Figure 4 shows the Redundancy Analysis (RDA) biplots between soil nematodes and soil chemical properties. The eigenvalues of the first and second RDA axis constrained to the soil chemical properties were 0.247 and 0.009, respectively and the two axes explained 25.7 % of the observed variation in nematode abundance. The second axis separates plant-parasitic genera from bacterivorous nematodes. Bacterivorous nematodes dominated on soils with compost amendments while plant-parasitic nematodes dominated on soils treated with inorganic fertilizer and on control plots. Nematode genera reacted differently towards soil chemical properties. Plant parasitic nematode genera were positively correlated with Na, extractable P and CEC but negatively with all other soil chemical properties along axis 2. Bacterivorous nematodes (*Acrobeles, Cephalobus* and *Rhabditis*) were strongly and positively correlated with pH and K along axis 2. They were also positively correlated with total N and organic C along the same axis, though the correlation was not very strong. The sum of all RDA canonical eigenvalues showed that soil chemical properties explained 27 % of the total variation observed in nematode abundance and the correlative relationships were highly significant (P = 0.001).

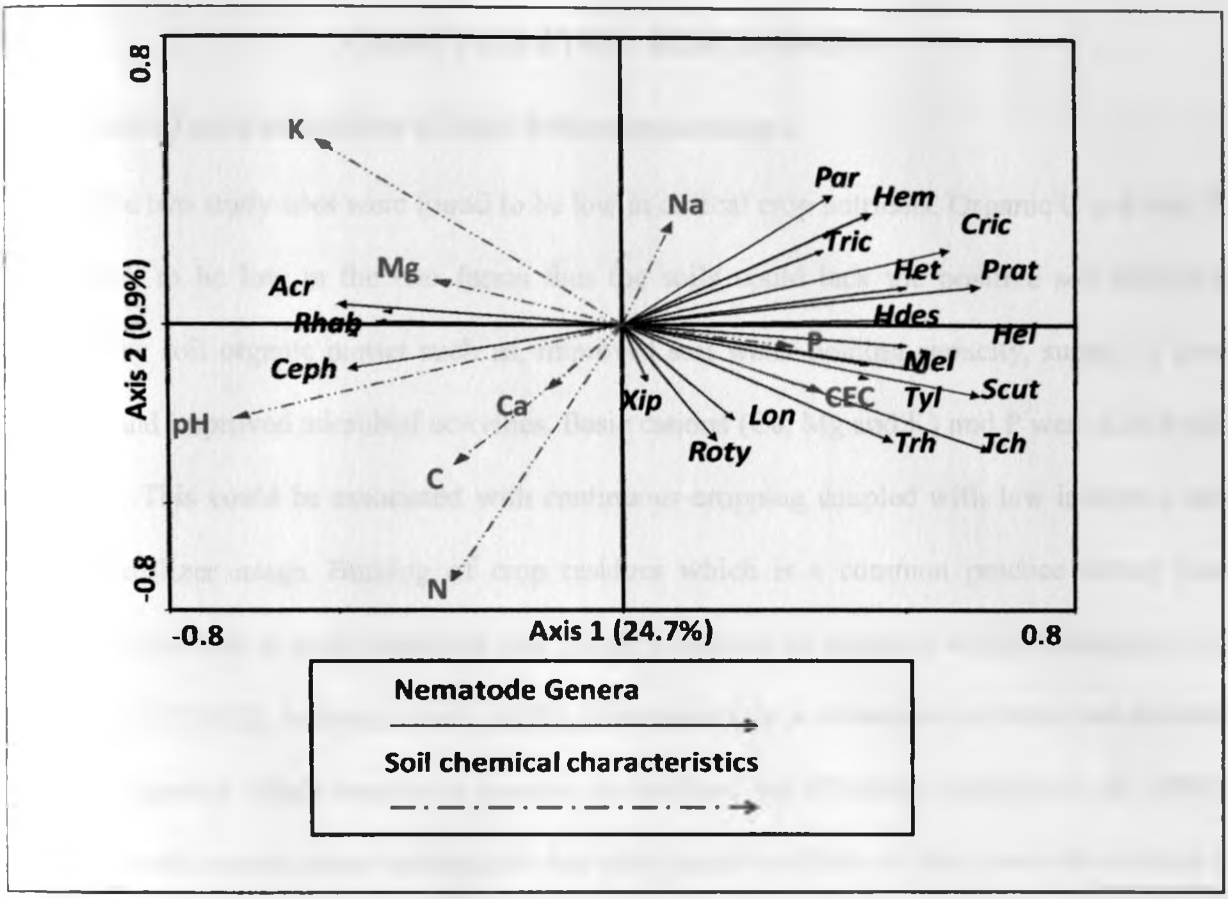

Figure 4: Redundancy Analysis (RDA) biplot showing correlation between soil nematodes and soil chemical properties. Acr = Acrobeles, Ceph = Cephalobus, Cric = Criconema, Hdes = *Hemicriconemoides*, Hel = *Helicotylenchus*, Hem = *Hemicycliophora*, Het = *Heterodera*, Long = *Longidorus*, Mel = *Meloidogyne*, Par = *Paratrichodorous*, Prat = *Pratylenchus*, Rhab = *Rhabditis*, Roty = *Rotylenchus*, Scut = *Scutellonema*, Tch = *Tylenchulus*, Trh = *Tylenchorhynchus*, Tric = *Trichodorus*, Tyl = *Tylenchus*, Xip = *Xiphinema*.

CHAPTER FIVE: DISCUSSION

5.1 Chemical characteristics of soils before experiment

Soils of the two study sites were found to be low in critical crop nutrients. Organic C and total N were found to be low in the two farms thus the soils could lack the positive soil attributes provided by soil organic matter such as, improved soil water holding capacity, supply of crop nutrients and improved microbial activities. Basic cations (Ca, Mg and K) and P were also found to be low. This could be associated with continuous cropping coupled with low inorganic and organic fertilizer usage. Burning of crop residues which is a common practice during land preparation reduces organic resources that should otherwise be returned to soil (Karanja *et al.*, 2006; Ayuke, 2010; Achieng *et al.*, 2010). This results in a reduction in water and nutrient retention capacity which negatively impacts on fertilizer use efficiency (Bationo *et al.*, 2006). Decline in soil organic matter content also has other negative effects on crop productivity since it plays other roles such as reduction in toxic substances that could render production of specific crops a challenge (Woomer *et al.*, 1994; Kapkiyai, 1996). The condition could be reversed by longterm application of organic and inorganic inputs (Bationo and Bürkert, 2001).

Soil P is one of the most limiting nutrients in the sub-Saharan region and deficiency in soil is often accompanied by very low yields (Jama *et al.*, 2000; Okalebo *et al.*, 2003, 2007; Achieng *et al.*, 2010). Gyaneshwar *et al.* (2002), Okalebo *et al.* (2003) and Khan *et al.* (2009) have documented that high aluminium content and acidity in soil could contribute to low amounts of macronutrients such as P through precipitation of the element into insoluble compounds hence rendering it unavailable to the crops. This could partly explain why the soil of the two farms was low in P because the aluminium content was high. Since application of small amounts of P has been shown to have significant responses in crops, applying recommended levels of this nutrient could increase yields by 50 to 180 % depending on the soil type and prevailing production constraints (Bationo, 2008). Furthermore, proper management of inorganic fertilizers, livestock manure and other organic resources could add to the gains accrued as well as improving nutrient use efficiencies (Palm *et al.,* 1997; Okalebo *et al.,* 2007).

5.2 Quality of organic resources used in composting

Within cereal-based cropping systems, the bulk of residues available at harvest are relatively low in nutrients but high in lignin and polyphenols and these may be classified as low quality materials. It was evident in this study that maize stover and sugarcane residues had considerably high C:N ratio compared to other organic biomasses such as *Tithonia diversifolia*, filtermud and cow manure. Since C:N ratio has been widely used as a measure of quality of organic resources (Tian *et al.,* 1997; Cadisch and Giller 1997; Vanlauwe *et al.*, 2005), the high C:N ratio observed on these materials could have had effects on the quality of composts produced.

Cow manure contained higher in extractable P content compared to maize stover and sugarcane residues except filtermud whose extractable P was exceptionally high which could have been as a result of higher amounts of bases in filtermud. Cow manure had low C:N ratio compared to other organic residues and this may account for the good quality composts obtained. *Tithonia diversifolia,* a perennial shrub has been recognized as effective source of crop nutrients due to high nutrient content in its green biomass. Jama *et al.* (2000) have reported that the green leaf biomass of *T. diversifolia* contained 3.5 % N, 0.37 % P and 4.1 % K on a dry matter basis which qualifies it as a potential source of crop nutrients. Analysis of *T. diversifolia* in our study showed that it contained high content of N, P and K as reported by Jama *et al.* (2000) and the content of these elements was higher than in the other organic residues used in composting, with exception of filtermud which contained almost equal P and N amounts. Returning organic residues in form of livestock manures and/or composts to soil could therefore be important in improving soil functions such as supplying crop nutrients, improving soil structure stability and hence increase soil moisture storage, increase soil microbial activities among other important soil functions (Barrios *et al.,* 1997; Nziguheba *et al.,* 2000; Fankem *et al.*,. 2008).

5.3 Quality of different composts

Organic resources used in composting influenced the quality of the composts as demonstrated by the chemical properties of individual composts. Incorporation of cow manure with other organic biomasses during composting resulted to better quality composts. This was manifested by the higher quantities of N, P and the bases (K, Ca and Mg) of most of the composts in which other materials namely; maize stover, sugarcane straw, filtermud, bagasse or *T. diversifolia*, were co-composted with cow manure, compared to the compost made from cow manure alone. Well prepared composts have been shown to contain high amounts of macronutrients which could in turn benefit the crops by supplying the important nutrient elements. Negassa *et al.* 2001 have reported that 5 t ha^{-1} could contribute upto 171 kg N, 41 kg P and 11 kg K ha^{-1} among other macro-nutrients. This confirms that composts could be used as quality biofertilizers by local farmers not only to raise crop production but also build soil nutrient reserves through improvement in SOM content.

5.4 Effect of compost on soil chemical properties

Application of compost increased soil macronutrients especially C and N across the two sites compared to fertilizer and control. This was in agreement with Hepperly *et al.* (2009) who observed that composts were superior in building levels of soil C and N compared to raw dairy manure and synthetic fertilizer treatments. Liu *et al.* (2010) showed that addition of organic amendments in Northwest China had the most beneficial effects on grain yield (maize and wheat) and soil chemical and biological properties compared to fertilizer and control treatments. Kihanda *et al.* (2007) also observed that application of goat manure for a period of four years in P-deficient soils of semi-arid Eastern Kenya resulted in residual effects on cereal yield (maize, sorghum and pearl millet), soil organic C and Olsen P, with the benefits lasting for 7 to 8 years.

The available N (NO_3^- and NH_4^+) also followed similar trend as total N. This could have resulted from release of NO_3^- and NH_4^+ upon mineralization of N in the composts. Soil organic matter regulates N content in soil as it holds 90 to 95 % of total N. Maintenance of high amounts of soil organic matter through return of crop residues as composts and other organic amendments is thus important if a steady supply of available N is to be realized (Karunditu *et al.*, 2007). This supports the importance of incorporating organic resources in soil nutrient fertility budgets. Soil pH and CEC tended to increase following application of composts which concurs with Adeniyan *et al.* (2011) who similarly observed an increase in CEC, exchangeable bases and soil pH on addition of composts and other types of organic manures.

5.5 Agronomic effectiveness of the composts on performance of maize in the field

The over 2 t ha^{-1} yield obtained from plots that were amended with compost was a reflection of the high quality value of their potential as fertilizers. Among the compost treated plots, the highest maize grain yields across the three seasons were obtained in plots where filtermud compost was applied. The higher N and P content recorded in filtermud composts could have contributed to the difference seen in maize grain yields compared to other compost types. The yield differences between fertilizer treated plots and the plots treated with composts decreased with time, with the least difference recorded in the third season. This could be attributed to residual effects of applying composts which contributes to longterm fertility by acting as a slow-release fertilizer. The nutrients retained in soil could therefore have contributed to the over 4.5 t ha^{-1} of maize yield recorded in plots treated with composts in the third season.

The Benefit/Cost ratio of maize grain yields on composts treated plots was higher than that obtained in fertilizer treated plots. This could have been attributed to the high cost of commercial fertilizer compared to the organic resources which are readily available to the farmers either for free or at a small fee. This concurs with Negassa *et al.* (2001) who observed that maize yield harvested on compost treated plots gave the highest marginal rate of returns to the farmers in Western Oromia, Ethiopia. However, the benefits obtained in plots treated with composts made from bagasse and filtermud were slightly lower than other compost types which could be attributed to the costs incurred during transportation of the materials to farmers' fields. Generally, organic amendments offers a potential and beneficial alternative to improving crop productivity where socio-economic conditions limit the farmers from accessing and using right quantities of chemical fertilizers (Van Straaten, 2002; Makokha *et al.*, 2001).

5.6 Effects of composts on soil fauna

5.6.1 Effect of composts on macrofauna

Application of composts led to increases in earthworm abundance compared to the control plots while application of inorganic fertilizer did not significantly affect the earthworm population. This concurs with Ayuke (2010) who observed that agricultural management options that resulted in high carbon storage led to significant increase in earthworm population. Fonte *et al.* (2009) also documented that cropping systems which received crop residues had significantly higher earthworm densities and biomass than those under bare fallow management. Riley *et al.* (2008) observed that incorporation of large amounts of organic matter led to higher earthworm biomass and density than the conventionally managed plots. The results demonstrate that organic matter inputs could have profound effects on earthworm density. Among the six composts types, plots treated with filtermud compost recorded the highest earthworm abundance. Plots treated with other compost amendments had earthworm abundances within similar range. Litter quality plays an important role in determining abundance and species diversity due to selective nature of some organisms (Rothwell *et al.*, 2011). The exceptionally high bases (Ca, Mg and K) and P content in filtermud could have contributed to a high quality soil amendment justifying the higher earthworm abundance that was recorded on plots treated with filtermud compost.

Taxonomic richness in soils amended with composts was higher compared to those amended with inorganic fertilizer and control treatments hence the variations in taxonomic richness and macrofauna abundance could be linked to the quality of composts. Increased soil organic C content coming from addition of composts could have given the macrofauna a conducive environment to thrive as documented by Karanja *et al.* (2009).

The canonical eigenvalues showed that soil chemical properties explained 25 % of the total variation observed in macrofauna abundance and the correlative relationships with selected soil chemical properties being highly significant. The results concurs with Karanja *et al.* (2009) and Ayuke *et al.* (2009) who observed strong and significant correlations between soil chemical properties with selected macrofauna groups under different land use systems in Taita and Embu, respectively. Soil tillage has been shown to negatively affect soil dwelling micro-organisms through destruction of nests and burrows and generally modification of soil microclimate within their habitat (Ayuke 2010; Ayuke *et al.* 2009; Karanja *et al.* 2009). This could therefore explain why despite addition of composts, some macrofauna groups such as Gastropoda and Diplopoda occurred in very low numbers.

5.6.2 Effect of composts on nematodes

Three genera of plant phytoparasitic nematodes namely; *Pratylenchus* (root-lesion nematodes), *Scutellonema* (spiral nematodes) and *Meloidogyne* (root-knot nematodes) were the most dominant which agrees with Chirchir *et al.* (2008) who observed these genera to be the most dominant in soils of four sugarcane growing zones in Kenya. However, the population of phytoparasitic nematodes declined upon addition of composts while no changes were observed in soils amended with inorganic fertilizer and in the control plots. This agrees with Briar (2007) and Tsiafouli *et al* (2007) who observed that the population of phytoparasitic nematodes was more abundant in conventionally managed soils than where organic inputs were applied. In another study, Kimenju *et al.* (2008) observed that *Tithonia diversifolia* was among the plants that were very effective in suppressing root knot nematodes (*Meloidogyne spp.*) by reducing their reproductive potential by up to 80 %. Many studies have shown that incorporation of organic inputs in soils negatively impacts on plant parasitic nematodes (Wang and McSorley, 2005; Briar, 2007; Karanja *et al.*, 2010). Decomposition of organic matter and consequently release of nutrients to soil attracts numerous micro-organisms some of which could be natural enemies to plant parasitic nematodes such as nematophagous fungi (*Arthrobotrys brochopaga* and *A. oligospora*), predatory nematodes (*Harposporium anguillulae* and *Catenaria sp.*), collembolans and tardigrades that feed on plant parasitic nematodes hence suppressing their population (Wang and McSorley, 2005; Akhtar and Malik, 2000).

The results also showed that application of composts also led to an increase in bacterivorous nematodes which agrees with Briar (2007) and Tsiafouli *et al.* (2007) who observed abundance of bacterivorous nematodes in soils amended with organic resources. Application of composts could have attracted numerous micro-organisms through provision of food substrate. This could have also led to an increase in predatory organisms such as bacterivourous nematodes. The significant correlation between the nematode abundances and soil chemical properties have demonstrated that soil fertility options adopted by the farmers could have profound effects in management of plant-parasitic nematodes. Therefore, incorporation of organic resources in soil fertility budgets may be important not only in supplying crop nutrients but could also act as biological control agent to phytoparasitic nematodes.

CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

6.1 CONCLUSIONS

1. Incorporation of composts into the soil had positive effect on contents of major nutrients namely; total N, organic C, extractable P, and the bases. They also increased earthworms and free-living nematodes while abundance of plant-parasitic nematodes decreased.
2. Addition of composts gave yield above 2 t ha^{-1} though inorganic fertilizers recorded the highest maize yields. Use of composts prepared on-farm was economical and supported higher returns to the maize farmers in Western Kenya.

6.2 RECOMMENDATIONS

Recycling crop residues through co-composting with available cow manure should be promoted to the farmers in Western Kenya. This ensures that sufficient high quality and cost effective materials are available to the farmers.

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