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EVALUATION OF FACTORS AFFECTING THE QUALITY OF COMPOST MADE BY SMALLHOLDER FARMERS IN MALAWI

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ABSTRACT

In Malawian agriculture, the use of compost as a soil amendment has received much attention over the last few decades. Despite this, little is known about the commonly practiced composting systems in Malawi and their potential in mitigating soil fertility problems experienced by smallholder farmers. This study characterized the Changu (turned and watered regularly) and Chimato (covered with mud and static) systems and investigated optimum conditions required for effective composting. It further investigated nutrient release characteristics of the composts from these systems and their impact on maize crop establishment.

Replicated compost heaps were formed from wheat (*Triticum aestivum*) straw and grass /clover (*Lolium perenne/Trifolium repens*) (in the UK) and maize (*Zea mays* L.) straw and green bean (*Phaseolus vulgaris* L.) residue (in Malawi) using the Changu and Chimato systems. Four initial C:N ratios of 20:1, 25:1, 30:1 and 60:1 were studied in the UK whereas two initial C:N ratios of 20:1 and 30:1, chopped into two lengths (5 or 10 cm) were used in Malawi. All the treatments were set in a randomized complete block design and the composting experiments ran for 112 days in the UK study and for 77 days in Malawi. Incubation-mineralization studies using the resultant composts were run for 42 days and 84 days for UK and Malawi respectively, followed by a maize establishment study run for 25 days.

The Changu systems had significantly longer mesophilic phases (19 days) and active composting periods (24 days) compared to the Chimato systems (14 and 22 days respectively). The temperature profiles for the two systems were similar in the glasshouse, but differed in the field due to reduced insulation in the Changu (uncovered) system. The composting processes in these systems contributed to the production of compost with as high as 1.1% total N. A higher concentration of NO_3-N (406 mg/kg dwt.) was produced in the Changu system *cf.* Chimato (359 mg/kg dwt.) whereas a higher concentration of NH_4-N (36 mg/kg dwt.) was produced in the Chimato system *cf.* Changu (34 mg/kg dwt.) for the Malawi compost. Similarly, Changu system resulted in greater

concentrations of TON (61 mg/kg dwt.) *cf.* Chimato (24 mg/kg dwt.) whilst Chimato contained high concentration of NH_4-N (61 mg/kg dwt.) *cf.* Changu (8 mg/kg dwt.) for the UK compost. No differences were observed in the concentration of extractable-P and extractable-K in the two systems for the UK studies whereas Changu treatments and those from initial C:N had more P in Malawi. Resultant compost pH ranged between 6.8 and 8.6 for the UK-based studies and between 7.2 and 8.9 for the Malawian-based study.

Incubation-mineralization studies indicated temporal differences when the resultant compost from the two systems (Changu and Chimato) was incubated in the soil with respect to nutrient release. Initial feedstock C:N ratio had a significant effect, treatments with C:N 20:1 mineralized nitrogen whilst those with initial C:N 30:1 and 60:1 immobilized nitrogen compared to the control for the UK experiments. No immobilization was observed for Malawi resultant compost. This was reflected in the maize establishment trials when compost from the two systems was used as a soil amendment. Treatment with materials from initial C:N 20:1 produced significantly larger plant stalks and high plant biomass (0.92 g/plant (dry basis)) than the other treatments. Varied differences were observed between UK and Malawi with respect to composting system on plant growth. The use of compost from this study increased CEC of the soil by 2.1 cmol/kg.

Efficient composting requires low C:N material and the required compost time and resultant quality is dependent upon the C:N ratio of the initial feedstock. The longer active composting time in the Changu systems appeared to influence production of TON compared to the Chimato. It is suggested that to optimise the compost quality there is a need to encourage the smallholder farmers to grow green leguminous crops which they can mix with the straw to reduce the initial C:N ratio to improve its compostability. It is also important to increase the number of aeration holes in the mud coat of the Chimato heap in order to improve the oxygenation process of the material and to use them for moisture adjustments. A cost benefit analysis conducted suggested that the lower the initial C:N ratio and the longer the chop length (≤ 10 cm), composting using the Changu system, the higher the net benefits which can be attained.

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LIST OF ACRONYMS

Al	Aluminium
ACB	Agricultural communications branch
ANOVA	Analysis of variance
BS	British standard
BS EN	British European standards
$BaCl_2$	Barium chloride
$BaCO_3$	Barium carbonate
C	Carbon
Ca	Calcium
CI	Confidence interval
CEC	Cation exchange capacity
^oC	Degree Celsius
CO_2	Carbon dioxide
Cd	Cadmium
CR	Chromium
CAN	Calcium ammonium nitrate
CIMMYT	The international maize and wheat improvement centre
DTPA	Diethylenetriaminepentaacetic acid
EDTA	Ethylenediaminetetraacetic acid
FAO	Food and agriculture organization
Fe	Iron
GDP	Gross domestic product
GoM	Government of Malawi
HCl	Hydrochloric acid
K	Potassium
KCl	Potassium chloride
LAI	Leaf area index
LSD	Least significant difference
M	Molar
Mn	Manganese
MAFF	Ministry of agriculture, fisheries and food
$MgSO_4$	Magnesium sulphate
MPTF	Maize productivity task force
N	Nitrogen
NH_4-N	Ammonium N
NO_3-N	Nitrate N
Ni	Nickel
NSRI	National soil resources institute
NaOH	Sodium hydroxide
NH_4OH	Ammonium hydroxide
ORD	Organic resource database
P	Phosphorus

pH	Power of hydrogen; a measure of acidity
Pb	Lead
PPI	Potash and phosphate institute
RCBD	Randomized complete block design
SOM	Soil organic matter
SOP	Standard operating procedure
TON	Total oxides of nitrogen
TCD	Thermal conductivity detector
t/ha	Tonne per hectare
UK	United Kingdom
UV-VIS	Ultraviolet-visible spectrophotometry

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CHAPTER ONE: Introduction, background and literature review

1.1 Introduction

Agricultural production remains a main-stay for poor countries and a source of hope and survival for the majority of inhabitants. It accounts for a significant proportion of the gross domestic product (GDP) for these countries. Evidence shows that creating enabling policies and access to markets triggers increased agricultural productivity, which consequently increases the incomes of farmers and creates employment. Agriculture supports as much as 45% of people in East and South East Asia, to 55% in South Asia and 64% in sub-Saharan Africa (FAOSTAT, 2004). The main threat to this scenario is the diminishing capacity of the soils in these regions to support increased crop production, coupled with low use of soil fertility enhancing technologies, to the extent that food insecurity is becoming a common phenomenon. Malawi, one of the poorest countries in the world, is hit by this decline in soil fertility, as the population increases, such that maize (*Zea mays* L.), the staple food, mainly produced by the smallholder farmers is becoming scarce (FAO, 2000).

The Maize Productivity Task Force (MPTF) of the Ministry of Agriculture in Malawi, constituted in 1995, was mandated to work on improving the national maize yield to attain national food security. The MPTF conducted research to mitigate soil fertility problems (MPTF, 2000). A number of traditional low-cost soil fertility management options common for smallholder farmers in most of sub-Saharan Africa were tried. This included intercropping maize with leguminous crops, rotation practices with leguminous crops, developing agro-forestry technologies, developing area-specific fertilizer recommendations and quality seed production. Promising options include utilisation of organic materials by incorporation of residues in rotation or intercropping systems (Waddington *et al.,* 2004; Kumwenda *et al.,* 1998). Composting and use of organic manure is currently being advocated as a viable option for improving soil fertility conditions for the poor farmers in Malawi.

This research aimed to develop techniques to optimise commonly used composting systems, and improve the production process and quality of compost for smallholder farmers. The improved quality compost would help to alleviate soil fertility problems and increase crop yields. This was accomplished by studying factors which affect the composting process including substrate and chop length of feedstock, aeration process, moisture and temperature conditions. The form and quality of substrate controls the decomposing microbial community and the attributes of the end product, while the chop length determines the effective surface area accessible to the micro-organisms to work on, thereby contributing to the duration it takes for the completion of composting process. The chopping process breaks the cell wall barrier to ease access of microbes to the substrate. The moisture of the feedstock is vital for the survival, mobility and assimilation of the substrate by the microbes. Any shortage or excess of it adversely affects the composting process. The temperature during composting affects the microbial community dominant in the composting process. Excessively low and high temperatures adversely affect microbial activities and hence the composting process. Controlled mineralization tests and plant growth tests were conducted using the resultant composts. Mineralization trials studied the nutrient release characteristics of the composts, while plant growth tests focused on the establishment characteristics of maize crop when the composts were applied into the soil. These processes are crucial in understanding the composting systems used and their impact on nutrient release and crop production. In these studies, the focus was specifically in the context appropriate to Malawi; to assess the potential of composting as a means of achieving food security.

1.2 Background

Africa’s declining food production phenomenon is no longer news. The continent’s per capita food production growth rates have consistently diminished over the past four decades. Statistics for the developing regions in the early 1990s highlight the contrast between per capita food production indices in China and sub-Saharan Africa (FAO, 1998). This report indicated China's 1992-94 average cereal yields of 4.5 t/ha to be the highest of the developing world, with Africa's average cereal yield of 1.0 t/ha as the lowest. Notably, most of sub-Saharan Africa countries have agro-based economies, which

are characterised by high population growth rates with up to 80 percent of their population living in rural areas. This makes increased agricultural production a major priority if these economies are to be sustained and food security attained.

Soil fertility degradation is one of the most important limitations to food security in sub-Saharan Africa (Sanchez, 2002; Waddington *et al.*, 2004). This is exacerbated by poverty levels of the rural communities (smallholder farmers) who are relied upon to grow food crops for their associated nations. Smallholder farmers have been bush-clearing for productive lands and then mining the soils of their nutrients for generations. The principal loss-pathway for nutrients is via exportation of crop residues from land for a variety of competing uses. The residues are commonly used as firewood or bedding and feed for livestock. The residues are also burned due to labour implications or cultural practices which make it impossible to incorporate dry residues into the soil. This is common in areas where land preparation is not done immediately after harvesting, making it harder to incorporate dry residues into the soil. This, combined with little or no replenishment of the soil with organic manure or fertilizers renders the soil quality poor. Sub-Saharan Africa is reported to have lost in excess of 22 kg of nitrogen (N), 2.5 kg of phosphorus (P) and 15 kg of potassium (K), per hectare of cultivated land each year in the last three decades through soil mining (Sanchez, 2002). As a specific example, over 30 kg/ha and 20 kg/ha of N *per annum* are reported to be depleted from Malawi and Zimbabwe respectively (Mughogho, 1992; Stoorvogel *et al.*, 1993; Smaling, 1998). Soil organic matter (SOM), which is central to the sustainability of soil fertility on smallholder farms, has also declined to low levels (Woomer *et al.*, 1994). Unfortunately, the opportunity for practising shifting cultivation, which subjected land to natural rejuvenation, is not tenable in the modern world due to an increased population and high demands for land for cultivation. The African population is currently growing at 2.4% and it is projected that about 490 million new habitants will be added between 1995 and 2020 alone representing an increase of 70% (Eilitta, 2006). This means alternative low cost soil fertility enhancing technologies need to be identified and employed to improve soil fertility.

In tropical arid, semiarid, and sub-humid areas, the prevalence of warm temperatures during times of the year when moisture is in abundance (*i.e.* rainy season), accelerates organic matter decomposition and loss. The soil organic matter (SOM) deficiency is an important cause of soil degradation in these areas, reflected in poor soil physical status, loss of favourable biology and occurrence of several nutrient deficiencies (Smaling, 1993). In addition to climatic effects, depletion of SOM is exacerbated by erosion in areas receiving high intensity rainfall. The situation is complicated further because of the increased use of marginal sloping land as land pressure increases, and farmers' reluctance and laggardish attitudes in employing science-based soil and water conservation technologies. The challenge is to find ways of replenishing and sustaining soil fertility, soil organic matter and food crop productivity within the existing low income resources and land and labour constraints of the smallholder farmers.

Malawi supports sub-humid tropical agro-ecosystems, which are characterised by a longer dry season with a unimodal rainfall pattern. Typically, rains commence in November and end in April. The beginning and cessation of main rainfall events varies from the north to the south of the country, with sporadic showers continuing through July in the southern part of the country. Soils are generally alfisols or ultisols, which are moderately fertile and deep (Young & Brown, 1962; Kanyama-Phiri *et al.*, 2000) but those under smallholder production generally have low levels of organic carbon (11 – 15 mg/kg) and are moderately acidic, typically pH 5.5 – pH 6.6 (Snapp, 1998). Since independence in 1964, to the late 1980's and early 1990's, crop production and soil fertility management in Malawi relied on heavily-subsidised inorganic fertilizers. When subsidies were removed, an increase in the relative cost of inorganic fertilizers resulted in significantly reduced usage by smallholder farmers. Inorganic fertilizers imported into Africa cost two to six times as much as those in Europe, North America or Asia (Sanchez, 2002) making it inaccessible to smallholder farmers.

The consequences of land pressure in Malawi are continuous cropping, overgrazing, poor soil management and expansion into marginal areas for cropping (NRI, 1996). These consequences have contributed to the decline in soil fertility, resulting in low crop yields

and they threaten sustainability of maize-based cropping systems in the country (Buresh *et al.*, 1997). Continuous cropping, due to the scarcity of land, has exerted considerable pressure on land resources. This, coupled with poor agronomic practices and exportation of crop biomass from the cropping land, has resulted in the depletion of SOM, rendering the soils vulnerable to erosion and with reduced exchangeable sites for nutrient ions (Blackie *et al.*, 1998). With reduced soil colloids and exchangeable sites for nutrients, crop production in these soils has become inefficient in response to low fertilizer applications.

A decline in SOM is known to promote an array of negative effects on crop production. Maintaining or improving its level is a prerequisite to ensuring soil quality and future agricultural productivity and sustainability (Katyal *et al.*, 2001). Despite SOM not being a nutrient *per se*, its concentration must be maintained, arguably above a critical level to enhancing soil properties and processes. In Malawi, the soils department at the national Chitedze Research Station uses a critical value for organic carbon of 0.90% (*i.e.* 1.58% SOM) to indicate a soil with low organic matter (Blackie *et al.*, 1998).

A potential remedy to the smallholder farmer's declining soil fertility status could be found in the strategic combination of organic sources, supplemented with small amounts of mineral fertilizer (Palm *et al.*, 1997*;* Mhango, 2002). This is expected to result in a substantial quality improvement of the applied low levels of organic materials. Little or no organic materials (especially crop residues) are incorporated into the soils, however, due to competing uses for the residues and delays in incorporation that commonly result in burning.

In contrast to temperate regions, where crop residues are mostly incorporated into the soil, in tropical, semi-arid and arid regions, the practice of returning residues to the soil is rare. This is because crop residues are either used as animal fodder, fuel, a roof thatching material or burning to ease land preparation. It is therefore essential to create a means of processing the crop residues to a state where they can be applied to the land, without a

significant increase in effort, or creating major problems in other aspects of life, if the promotion of SOM build up and enhanced soil fertility in these systems is to be realised.

Researchers are engaged in investigating alternatives to the use of inorganic fertilizers for smallholder farmers. In Malawi and elsewhere, agro-forestry systems of hedgerow intercropping with perennial species and maize proved successful under research station conditions. When these were extended to actual systems over the past decade, they failed due to high labour demand and competed with food crops for use of land on-farm (Snapp *et al.,* 1997). Intercropping 'green manure' annual legume crops with maize and incorporating the residues is thought to be a more promising technology. This has a potential to increase maize yield by about 30% compared to a maize mono-crop (Kumwenda *et al.,* 1996). Leguminous crops suited for this system includes pigeon pea (*Cajanus cajan*), velvet bean (*Mucuna pruriens*) and fish poison bean (*Tephrosia vogeli),* but velvet bean is best grown in a rotation system rather than inter-crop to avoid overwhelming maize by its vigorous growth. Rotation is another potential technology, but this is rarely practised due to the limitation of available land. Use of animal manure is another potential source of nutrients but it is limited by the low livestock numbers in most rural areas. Currently, it is observed that SOM inputs from leguminous plants, crop residues, animal manures and composts are insufficient to maintain SOM levels in most smallholder soils. Furthermore, in low-rainfall marginal areas, it is not possible to grow enough biomass to maintain SOM (Waddington *et al.,* 2004).

Whilst composting is conceived as a viable means of returning SOM and nutrients to the soil (Ouédraogo *et al.,* 2001), and is currently being promoted to Malawian farmers (Waddington *et al.,* 2004), most of the crop residues are either incorporated straight into the soil during re-ridging, exported from land or burned. Commonly, it is the low quality plant residues which remain and this result in poor quality composts (Waddington *et al.,* 2004).

1.3 Literature review

1.3.1 Importance of organic matter in crop production

Organic matter is heterogeneous material consisting of basic chemical building blocks. It comprises compounds such as carbohydrates and sugars, proteins, fats, hemicelluloses, cellulose, and lignin. Principally, organic matter has been described as identifiable high-molecular weight compounds such as polysaccharides and proteins or simpler substances such as sugars, amino acids and other small molecules or humic substances (MacCarthy *et al.*, 1990).

In the past, land was not so scarce, and the early man practised shifting cultivation as well as bush fallow rotation. Land was allowed to revert to bush fallow for a number of years, soils were self-rejuvenated and soil fertility restored, with long fallow periods and full vegetation regeneration. This ecologically balanced system relied on the build-up of SOM, with its moderation capacity on the environment and capacity to retain plant nutrients. Today, there is high demand for cultivation land which has promoted continuous cultivation, and meant that the approach to build up, and benefit from SOM has changed markedly.

There is a general consensus that SOM is an important regulator to a number of constraints to crop production in tropical agricultural systems. Sanchez *et al.*, (1989) indicated that mineralization of decomposing residues is a major source of plant nutrients in highly weathered soils with little inherent mineral fertility. It is also recognized that the activities of micro-organisms and soil fauna serve to promote soil aggregation (Oades, 1984), thereby leading to reduced erosion (Lal, 1986) and greater moisture infiltration and return (Lavelle, 1988). Furthermore, there is complexion of toxic aluminium and manganese from the highly weathered tropical soils by the labile carbon compounds, creating a more productive rooting environment (Hargrove & Thomas, 1981; Hue *et al.*, 1986). The other important aspects of good maintenance of SOM include nutrient retention and storage (Russell, 1973; Woomer and Ingram, 1990), increased buffering

capacity of low activity clay soils (Swift & Sanchez, 1984) as well as an increase in water-holding capacity (Lal, 1986). SOM contains negative charges on many constituent surfaces which constitute the exchangeable site for cations. This retains essential nutrients which are later utilized by plants. Similarly, they are also associated with sequestration of elements and nutrients such as total carbon, nitrogen, phosphorus and sulphur (Feller *et al*., 2001).

The importance of organic matter management is not limited to tropical agriculture. Philipps (2001) worked on long term research in the United Kingdom, into the effects of all-arable organic rotations on soil organic matter levels and phosphorus and potassium status, when grassland is converted to an arable system and into organic farming. He observed significant decline in soil organic matter over a period of 11 years without the use of livestock residues. This prompted him to indicate that if stockless rotations are to be widely adopted within the organic farming sector, then longer periods of fertility building and the use of composted green waste would be necessary to prevent the decline in organic matter levels. However organic farming needs to review the potential impacts of organic management on soil fertility particularly under intensive all-arable and horticultural situations. Earlier, Wander *et al.,* (1994) reported that during the period of conversion to organic production there is a fall in soil organic matter levels and other soil nutrients.

As has been shown, efforts of maintaining and building up SOM, and improving soil fertility levels, vary from place to place and with the system of agricultural production being practised. Worldwide, it is recognized that effective management of post-harvest crop residues is an important issue in the grain production areas. In areas where intensive grain production is being practised, post-harvest crop residues are considered a waste product. However the disposal of crop residues is criticized for accelerating depletion of SOM and nutrients, as well as increasing C emissions and reducing soil microbial activity (Biederbeck *et al.* 1980; Rasmussen *et al.* 1980; Cookson *et al.* 1998). Residue incorporation is known to assist in minimizing these impacts, despite sometimes creating difficulties with cultivation (Dickey *et al.,* 1994) and introducing residue borne diseases

of crops (Cook & Haglund, 1991; Jenkyn *et al.,* 1995). Incorporation of crop residues can also result in temporary nutrient limitations due to microbial immobilization (Jenkinson, 1985; Addiscott & Dexter, 1994).

In a Malawian context, the improvement of soil fertility status through the use of organic matter applications has been demonstrated by a number of researchers (*e.g*. Sakala, 1998; Nalivata, 1998; Mwato *et al.,* 1999; Mhango, 2002; Nkhuzenje, 2003; Kumwenda & Gilbert, 1998; Mughogho *et al.,* 1996). These researchers have worked on different interventions, which include the addition of plant residues from plant materials such as pigeon pea, fish poison bean, velvet bean, bambara groundnuts (*Vigna subterrenia*) and soybean (*Glycine max*). The list comprises some of the plant materials that are available, are readily decomposable, and mineralize quickly to enhance soil fertility. Once incorporated into the soil, these plant materials improve the nutrient availability to the plants.

Palm *et al.* (1997), indicated that the availability of the nutrients from the added organic material is as a result of the total nutrients that are added by the organic materials, control of the net mineralization-immobilization patterns, the extent to which the material acts as a source of C and energy to drive microbial activities and as a precursor to SOM fractions within the soil. The general problem with some of the technologies such as use of *Mucuna pruriens* (velvet bean) is that it focuses on residual fertility, whereby the main crop (*e.g.* maize), comes a year after *Mucuna pruriens* was grown and incorporated into the soil. This results in a 12 month break in maize supply from that field and with problems of scarce land its adoption could be limited in areas where land availability is a major problem.

Carbon, the main constituent of SOM, is transferred in many forms between the biosphere, atmosphere, oceans and geosphere within a biogeochemical cycle. This involves various sinks or stores of carbon and processes by which C is exchanged between the various sinks. Plants absorb CO_2 from the atmosphere during photosynthesis, and release CO_2 back into the atmosphere during respiration. Another major exchange of

CO_2 occurs between the oceans and the atmosphere. The dissolved CO_2 in the oceans is used by marine biota in photosynthesis. Two other important processes are fossil fuel burning and changing land use. Of interest in the use of organic sources of nutrients is the mineralization of the organic materials by the soil microbial community where the carbon cycle and the nitrogen cycle interact. The micro-organisms require nitrogen for their growth and in the process break down the organic materials and release the locked nutrients. This process involves immobilization of nitrogen from the soil by the micro-organisms especially at the beginning.

Generally, incorporation of crop residues is perceived as a viable strategy to improve soil fertility and organic matter management (*i.e.* improving SOM levels) in low input farming practices, but this has associated problems such as reduced fertility due to nutrient immobilization and difficulties of land preparation resulting from slow rates of residue decay (Cookson *et al.*, 1998). Furthermore, in Malawi, the hoe, commonly used by the smallholder farmer for land preparation, is not suitable for the incorporation of crop residues. The hoe is labour intensive and hardly cuts the dry maize straw to facilitate incorporation. It is therefore necessary to develop crop residue management strategies that enhance residue breakdown. Composting is one such strategy which could provide organic material that is already (semi-)decomposed and suitable for soil amelioration.

1.3.2 An overview of composting process

Composting is the deliberate biological decomposition of organic matter under controlled, aerobic conditions into a humus-like stable product (Epstein, 1997). The compost product is an organic matter source and adds humus to soil. It acts to improve soil conditions and plant growth, and reduce the potential for erosion, runoff, and non-source pollution. The composting process is primarily concerned with the creation of a suitable environment in which aerobic micro-organisms that are responsible for breakdown of organic matter can be optimally active. Composting processes typically have three main stages:

1. a mesophilic growth stage, which is characterised by bacterial growth under temperatures of 25 - 40^{o}C;
2. a thermophilic stage, where bacteria, fungi and actinomycetes (first level consumers) functioning at temperatures of 50-60^{o}C, breakdown cellulose, lignin and other resistant materials (this thermophilic stage can go as high as 70^{o}C);
3. a maturation stage, where temperatures stabilise and some fermentation occurs, converting the organic materials to humus (this process commences when the temperature of the composting material reverts to the ambient temperature).

Composting is dependent on the factors related to the breakdown of organic solids and these include the C:N ratio, pH, temperature, water content, and availability of oxygen (Fig. 1.1).

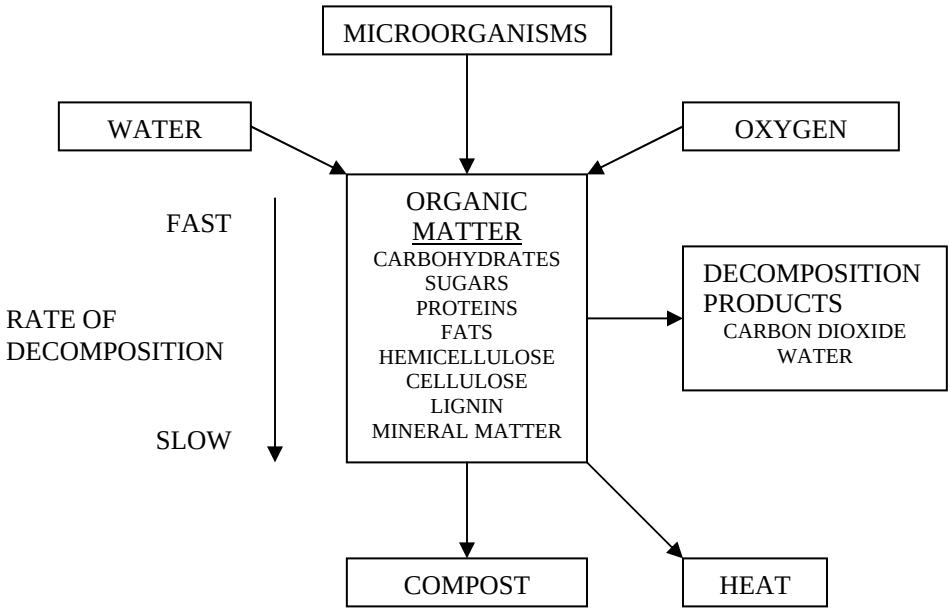

Figure 1.1 The composting process (adapted from Epstein, 1997)

1.3.3 Output quality and rate determining factors in the composting process

The rate at which composting will proceed and the final compost quality are determined by a number of factors. Optimization of these factors aims to promote the microbial activities that transform organic matter to compost. The following sections give an account of the factors and their influence.

1.3.3.1 Substrate (food)

Organic material is the substrate or food for the decomposing community (bacteria and other organisms). C and N are the two major elements contained in the organic matter and control the activities of the micro-organisms. Carbon is used as a source of energy by the organisms, which oxidize it, generating heat and CO_2. Nitrogen is the main source of protein needed for cell production and population growth (reproduction). C and N vary with each organic material or feedstock. It is recommended that a blend of organic material be made in such a way that their C:N ratio is < 35 (FAO, 1987), with a range of 20-30 ideal. When C:N rises above this level, heat production drops and the rate of composting slows down due to the limitation of nitrogen, falling short of microbial demand. On the other hand, when the ratio of C and N drops below 20, excess nitrogen is lost to the air as ammonia and there is a rise in pH level, which may be toxic to some micro-organisms.

As shown in Figure 1.1, the rate of composting is dependent not only on the environment for the process but also the nature of the input material (Stentiford, 1993). There is an order of decomposition rate for different fractions of the plant material: carbohydrates, sugars, proteins and fats decompose quickest, followed by hemicelluloses, cellulose and finally lignin. It is further indicated that composition of organic matter varies with source and consequently the organic constituents in compost also vary with their source (feedstock).

During the composting process, the C:N ratio of the initial feedstock typically declines because the C is oxidised and the N mineralized by the micro-organisms. A number of researchers have observed a significant reduction in C:N ratios when different sources of organic materials have been composted. For example, Thambirajah *et al.* (1995), observed a substantial reduction in C:N ratio when they composted empty fruit branches (with a relatively high lignin content) with manure added to the substrate. It is clear that C:N ratio is an indicator that the substrate has gone through the biochemical changes of composting, but more importantly is an indicator of compost maturity. A stable product that can be applied to a soil without significant immobilisation of soil mineral nitrogen is indicated by the final C:N of the product; for example, mature compost is indicated by a C:N ratio of 10:1 to 15:1 when the original material was 30:1 and 50:1.

1.3.3.2 Air exchange (oxygenation)

The metabolic process used by bacteria to produce energy requires a terminal electron acceptor to enzymatically oxidize the carbon source to carbon dioxide. Different classes of micro-organisms exist based on the carbon and terminal electron acceptor sources they use in metabolic processes. Bacteria that use reduced organic compounds (*e.g.* naturally occurring organics) as their source of carbon are termed heterotrophic; those that use inorganic carbon compounds (*e.g.* carbon dioxide) are autotrophic. Bacteria that use free oxygen as their terminal electron acceptor are aerobic; those that use a compound other than free oxygen (*e.g.* nitrate, sulfate) are anaerobic; and those that can utilize both oxygen and other compounds as terminal electron acceptor are described as facultative. An aerobic process is the most efficient form of metabolic activity (Section 1.3.2). Hence, oxygen is required for respiration by all aerobic organisms within the composting heap, making proper aeration a crucial factor in aerobic composting. Having sufficient oxygen, aerobic micro-organisms such as bacteria will be active and grow rapidly, consuming more organic material and in the process making nutrients available for plant growth. In the absence of oxygen, aerobic bacteria cannot thrive and anaerobic bacteria take over. These break down the organic material very slowly and often produce volatile compounds with unpleasant odours. This odour comes from sulphur compounds

(hydrogen sulphide, dimethyl sulphide, dimethyl disulfide), ammonia and volatile fatty acids (Epstein, 1997).

1.3.3.3 Moisture

Water is an essential compound for microbial metabolism and movement. A sufficient amount of water must be provided to coat the composting material. When moisture content is too low, microbial activities slow down considerably since this limits microbial mobility and when excess water is applied anaerobic conditions are created favouring anaerobic composting, as discussed above. For this reason, the recommended water level for composting is between 50-60% on a mass basis (Schultz, 1962), but the ideal percentage depends on the structure of the organic material. The optimum moisture content also varies with the composting technology used. The moisture content also affects temperature changes in compost (covered in Section 1.3.3.4). Water has a higher specific heat than most other materials, hence drier compost mixtures tend to heat up and cool down more quickly than wetter mixtures, provided adequate moisture levels for microbial growth are maintained.

1.3.3.4 Temperature

Biological systems typically operate over a limited range of temperature. At low temperatures microbes revert to resting state and at very high temperatures, essential proteins are denatured, killing them (Winkler *et al.,* 1996). Microbes can be classified based on their temperature tolerance. These include psychrophiles that grow at temperatures of less than 20^{o}C, mesophiles growing best between 15 and 45^{o}C, and thermopiles growing at temperatures greater than 45^{o}C. The compost heap temperature is a function of the accumulation of heat from metabolic processes and at the same time the temperature is a determinant of metabolic activity. The interaction between heat output and temperature determine the succession of microbial communities and metabolic rates during composting (MacGregor, 1981).

The temperature phases or composting phases (see Section 1.3.2) are therefore a result of the amount of heat being produced by microorganisms, balanced by how much is being lost through conduction, convection, and radiation (MacGregor, 1981). In heat loss by conduction, energy is transferred from atom to atom by direct contact; at the edges of a compost pile, conduction causes heat loss to the surrounding air molecules. Loss by convection indicates transfer of heat by movement of a fluid such as air or water. The warm air within compost system rises, creating convective currents which cause a steady but slow movement of heated air upwards through the compost and out the top. During this process, the energy is transferred in the form of latent heat, the energy required to evaporate water. Finally, heat is also lost from the compost heap through radiation. The heat generated in the compost pile radiates out into the cooler surrounding air. The smaller the bioreactor or compost pile, the greater is the surface area-to-volume ratio, and therefore the larger the degree of heat loss to conduction and radiation (Richard, 2005; Themelis, 2002). Insulation of small compost piles helps them to reduce excess heat losses.

The maintenance and residence of the high temperatures within the compost heap as compared to the outside, is controlled by the composting system, the nature of the feedstock, rate of microbial activity and external conditions (temperature and wind). Since there are interactions between the metabolic heat output and temperature, then outside temperature plays a role in controlling the rate of composting. The warmer external temperatures in the warmer regions stimulate microbial activities and speed composting while colder temperatures of the colder regions slow down the composting process.

In general, the literature indicates the optimum temperature range for fast decomposition is between 50 and 60^{o}C, but Epstein, (1997) gave a range of 65-70^{o}C as the temperature where maximum decomposition takes place for municipal solid wastes. This thermophilic stage is also important for destroying thermo-sensitive pathogens, fly larvae, and weed seeds. In outdoor systems, compost invertebrates survive the thermophilic stage by moving to the periphery of the pile or becoming dormant. To achieve a significant

reduction of pathogens during composting, the compost should be maintained at a minimum operating temperature of 40° C for five days, and with temperatures exceeding 55° C for at least four hours of this period. Most species of micro-organisms cannot survive at temperatures above 60-65°C, demanding cooling of the compost systems when temperatures get too high.

1.3.3.5 Surface area and particle size

Microbial activity mostly occurs on the surface of the organic particles. Smaller particles of organic material provide more surface area for microbes to attack and speed up composting (Haug, 1993). This is achieved by shredding and breaking down the organic materials into smaller pieces in order to expose a greater area for the microbes to work on and allowing ample air spaces thereby increasing the rate of decomposition. Apart from increasing surface area, the cutting of the feedstock also destroys the cell wall protective cover. The absence of the cell wall exposes the organic matrix for microbial attack. On the other hand, very small and compact particles hinder air circulation through the pile. Consequently, this reduces O_2 available to microorganisms within the pile and the microbial activities decreases (Haug, 1993).

1.3.3.6 Volume

Volume is the factor aimed at retaining heat of the compost. The more volume the more self-insulating it becomes in retaining the heat generated by the microbes (Richard, 2005). As indicated in Section 1.3.3.4, in relation to heat loss due to conduction and radiation, smaller compost piles are associated with greater surface area-to-volume ratios. This exposes the pile to a greater degree of heat loss (Themelis, 2002).

1.3.4 Maturity assessment

Duration of composting to maturity is determined as the time from initiation of the composting process to the moment maturity attributes have been identified in the composting material. These parameters include C:N ratio, germination indices, NH_4^+/NO_3^- ratio, NH_4-N concentration and CO_2 evolution.

Currently, there are no globally accepted criteria for compost maturity specification due to the fact that values of different parameters for mature compost depend on the material from which the compost was made (Bernal *et al.,* 1998; Mathur *et al.,* 1993; Warman, 1999). Nonetheless, the above mentioned parameters give a guide to maturation. A C:N ratio of less than 10 to 15 of composted material which had an initial C:N ratio of 30 to 50 indicates maturity. It is argued that in well humified field soils the C:N ratio is close to 10 and the addition of materials with C:N ratio below 15 may not alter microbiological equilibrium of the soil (Allison, 1973).

Other researchers indicate that a germination index of >50% of cress seed (*Lepidium sativum* L); NH_4^+/NO_3^- ratio of <0.16 and NH_4-N of <0.04% would indicate maturity (Bernal *et al.,* 1998; Pare *et al.,* 1997). Equally important is the assessment of the stability of the composted material using CO_2 evolution. It is suggested that evolution of CO_2 of < 1 mg CO_2-C $g[dw]^{-1}$ d^{-1} indicates stability (Thompson *et al.,* 2003; Wang *et al.,* 2004). Here, most of the substrate has been mineralized and microbial activities are low such that when the material is incorporated into the soil, it does not create a surge in microbial activities resulting in excess demand for nitrogen.

1.3.5 Why composting (and composts) for agricultural production?

The use of compost in agricultural production is associated with many benefits. These include physical improvement of the soil, and improvement of its biological and chemical status. The following sections illustrate the diversity of contribution attributed to compost utilization.

1.3.5.1 Soil structure

Soil structure arises from spatially arranged frameworks of aggregates of different sizes and shapes, establishing the pore space in the soil, which in turn facilitates movement of air and water into and through the soil. The soil structure influences soil temperature, air transport and mechanical impedance of soil to seedling emergence and root penetration.

Earlier research has long recognized composts as an effective means of improving soil structure and enhancing soil fertility (Follet *et al.*, 1981). Composts, when mixed with the soil, assist in the formation of better structural units with many voids and well developed aggregates or peds (Ouédraogo *et al.,* 2001). Structural units result from the different application of forces in the soils such as wetting and drying, root growth, tillage activities or burrowing activities of soil animals pushing individual particles together.

Humic compost, which is colloidal organic matter (and in that respect, similar to clay), adsorbs cations. If such cations include a high proportion of calcium (Ca^{2+}) and other divalent cations, the long polymer chains in the organic matter can form bonds with each other and with the mineral components of the solid phase. The humic organic matter also binds clay domains to quartz, which is the primary mineral component in silt and sand. In this way, a stable "clay-humus complex" is formed, resulting in aggregates.

Ouédraogo *et al.* (2001), associated improved soil structure due to compost application with better soil moisture retention of the soils, thereby improving efficiency of chemical fertilizer use by the crops. Soils with increased water holding capacity ensure extended periods of moisture availability in the root zone in times of dry spells.

1.3.5.2 Bulk density

The use of composts has been linked with the reduction of bulk density (Glover *et al.*, 2000). Measurement of the bulk density of the soil includes any air space and organic materials in the soil volume. Addition of composts to the soil builds up organic matter, reducing the bulk density of the soil, making it more suitable for crop production. Reduced bulk density from the use of compost has the following effects on the plant's root system:

a. Mechanical resistance to root penetration reduces, increasing the plant's ability to exploit its environment. Bulk densities above 1.75 g cm^{-3} for sands or 1.45 - 1.65 g cm^{-3} for silt and clays, cause hindrance to root penetration (Maurya & Lal, 1979).

b. The air-filled porosity of the soil increases, thus promoting the air supply to plant roots and increasing root respiration.

c. In general, hydraulic conductivity or permeability increases with lower densities, reducing water-logging effects on field crops.

Furthermore, it is worth noting that, on top of the increased amount of the organic matter affecting the soil bulk density, soils rich in organic matter are also easier to work with; they tend to be loose, friable and easily ploughed.

1.3.5.3 Source of plant macro and micro nutrients

As compost breaks down in the soil, it provides mineral forms of N, P, and K that are readily available for plant uptake. On top of the macro-nutrients and the build up of the organic matter in the soil, the compost adds micro-nutrients to the soil. Depending on the feedstock of the compost, a wide range of micro-nutrients may be added, including iron, copper, manganese, zinc and boron which are necessary for plant growth and not easily

obtained otherwise since most manufactured chemical fertilizers contain only macro-nutrients.

Earlier studies established that chemical fertilizers would not realize their full potential in the absence of composts and that better yields are obtained when a combination of composts and chemical fertilizers are used (FAO, 1987; Keeling *et al.,* 2001). The arguments behind these results can be explained mostly by the differences in the nutrients supplied, since the organic fraction will be likely to contain trace elements not found in chemical fertilizers and the nutrient retention capacity of the SOM as described below.

1.3.5.4 Reduces rate of nutrient release

Compost addition contributes to the improvement of the cation exchange capacity (CEC) of the soil (Ouédraogo *et al.,* 2001). CEC enables the soil to bind and retain nutrients on exchangeable sites so that they are available over a longer period of time for plant utilization. The nutrient binding capacity of compost is a very important aspect in the management of chemical fertilizers applied for crop production. Fertilizers applied to the soil are bound by the compost and prevented from leaching and running off in surface water during intense rain periods. Ouédraogo *et al.,* (2001) assessed the impact of compost made from crop residues, household refuse, ashes and animal manure on improving crop production and soil properties in West Africa (Burkina Faso). In their study, they found that compost gave three times higher yield of sorghum than where no compost was used and that the CEC of the soil increased from 4 to 6 cmol/kg. They also found that compost mitigated the effects of delay in sowing of the crop, such that no yield difference was observed even with a delay of one month, indicating strong attributes of the compost in retaining moisture.

In addition, compost is a long-term, slow release source of plant nutrients. Since compost is made of relatively stable organic matter, these nutrients are slowly made available for plant root uptake; an effective compost will release nutrients as the plant needs them.

1.3.5.5 Provision of carbon substrate

As an organic material, compost is a form of C substrate for soil organisms. This stimulates and increases microbial activity, which promotes root development and assists in the extraction of nutrients from the soil. Growth of earthworms and other soil fauna is encouraged in the presence of composts, promoting bio-turbation and tunnelling of the soils thereby increasing water infiltration and aeration.

1.3.5.6 Stabilizes soil pH

Compost buffers the soil to neutral pH, which facilitates more absorption of nutrients. Plant nutrients can be extracted within certain ranges of soil pH without which, plant growth will be hindered. Acidic soils can be dangerous to plants due to the greater solubility of aluminium and manganese which are toxic to root growth and lower solubility of phosphorus, calcium, magnesium, zinc, and copper which are very important to plants. In addition, there is a greater solubility of many trace elements (Cd, Cr, Pb, and Ni) which may be phytotoxic to plants and detrimental to animals/humans/micro-organisms when sufficient quantities of trace elements accumulate in plant tissue consumed by organisms. It follows that the pH of soils usually needs to be increased when its pH is low to alleviate the negative effects of acidic soils when easily accessible supplies of carbonate liming materials are not available.

1.3.5.7 Source of microbial diversity

Compost is biologically active. When this product is ploughed into the soil, it supplies a range of micro-organisms increasing soil's microbial diversity and populations (Barakan *et al.,* 1995) and microbial activity (Zink & Allen, 1998). With the increased level of activity of the microbes there is accelerated extraction of the nutrients from the soil and the organic materials, making them available for root up-take and plant development.

1.3.5.8 Suppression of soil-borne diseases and plant pathogens

Compost has some ability to combat some soil and plant diseases. The mechanisms are not fully understood but are linked to the microbial diversity and populations associated with the composts. Research on the basis for the control of soil-borne plant pathogens with composts by Hoitink and Fahy (1986) associated the effect of compost on micro-organisms (as described above) with their capability to suppress soil-borne plant diseases. Later, an association was linked to suppression of plant parasitic nematode populations and increased crop yields with micro-organisms (Johnston *et al.,* 1995). Bailey and Lazarovits (2003) looked at physico-chemical and biological factors associated with agricultural practices that influence organic matter levels, and the interaction between soil-borne plant pathogens and host crop systems, to understand the mode of action for their disease suppression ability. They associated organic amendments and composts with reduced soil-borne diseases through allelo-chemicals generated during product storage and subsequent microbial decomposition.

1.3.6 Composting in Malawi

Researchers in Malawi have investigated a number of different practices to improve soil fertility including use of animal manures and plant residues. Due to favourable conditions created during the post-independence period, the focus of the research was looking at efficient use of inorganic fertilizers and practices that require high input levels relative to smallholder farm resources. Composting never received as much attention compared to subsidised fertilizers, to the extent that use of compost on smallholder farms was largely a foreign technology brought in by non-indigenous technical services.

Loss of subsidies and continued degradation of soil fertility and food insecurity has seen a re-birth of composting as a potential fertilizer solution (GoM, 2002; Waddington *et al.,* 2004). Currently, research is being initiated in Malawi to assess the compost made by smallholder farmers and determine its suitability for crop production. This is done with little knowledge of the system processes and how they could be optimised.

A range of composting systems are used in Malawi including the box, pit, Changu (speed) and Chimato (coating). The Changu and Chimato systems are the most prevalent among the smallholder farmers in Malawi.

1.3.6.1 Changu system

This is a heap system and employs conical shaped piles of material. They are commonly made 1.5 m high, with a diameter base of 1.5 m. The feedstock used for this system ranges from maize residue, to dry grass and household waste. Additionally, manure from cattle, goats, or chickens and green grass is added to the mixture, where available. The Changu compost heap is constructed by piling layers on top of each other (Fig. 1.2).

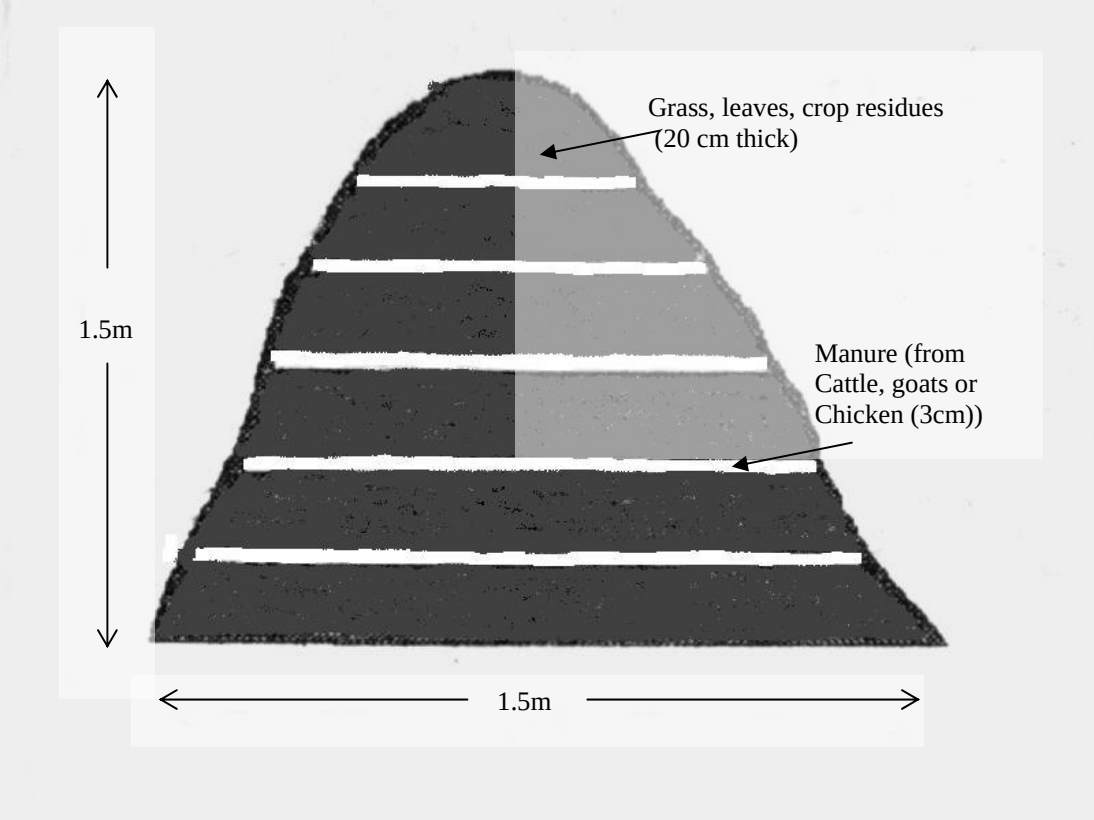

Figure1.2 A schematic cross-section of typical Changu compost heap when first constructed

The piles are aerated by natural convection. As hot air from the centre rises through the top of the pile, it creates a partial vacuum that draws cooler air in from the sides, thus circulating air through the pile. When temperature drops, aeration is achieved by manual

turning, thereby exposing new sites on the organic material for microbial attack. When substrate is still available, this will regenerate the heating process. Researchers elsewhere indicated that the optimum size and shape of the heap depended on particle size, moisture content, pore space, and decomposition rate, all of which affect the movement of oxygen toward the centre of the pile. Ideally, the heap should be sized so that the heat lost from the outer surfaces of the pile is balanced by heat generated by microbial decomposition within the pile. Once constructed, the only management task needed is turning or mixing of the piles to vent excess heat and moisture and to increase the porosity of the pile to improve airflow. When optimised, the Changu composting processes are typically complete in less than two months (ACB, 1994).

*1.3.6.2 Chimato (static and mud insulated system***)**

The Chimato is a static, insulated compost system. Compost heaps are made on a constructed base (made of wood or bricks) of 1.5 m length and 1.5 m width (Fig. 1.3). A stick is inserted in the middle during construction to create an air passage from the bottom to the top of the heap. The length of the compost heap can be extended to 6 m depending on the quantity of materials to be composted. The organic materials are piled in a pyramidal form. The feedstock used for this system is identical to Changu system. The shape of the constructed Chimato compost heap is shown in Fig. 1.4. Typically the composting process in this system will be completed after two months (ACB, 1994). The key contrasts with the Changu system are that the Chimato is insulated and is not turned; consequently there is a greater initial labour requirement in building the system, but less labour effort during the composting process.

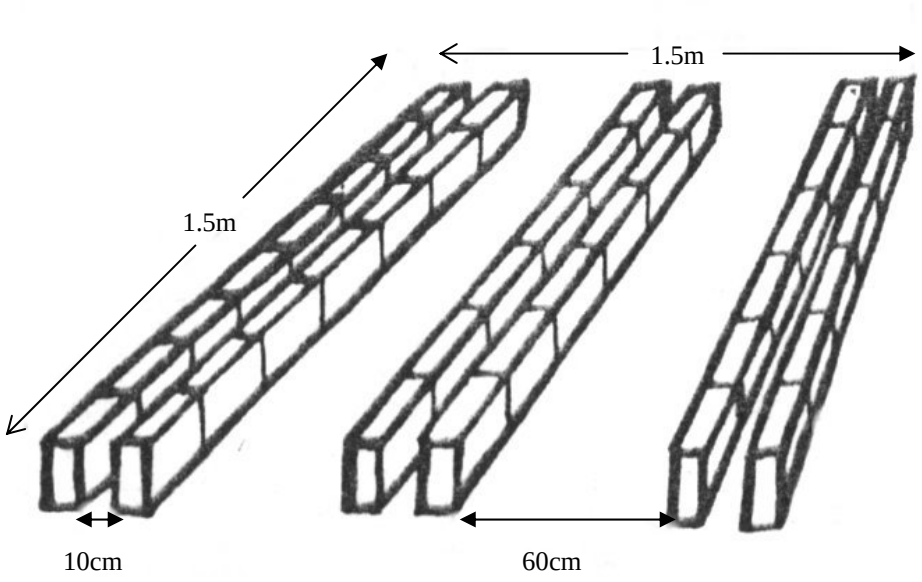

Figure 1.3 Constructed base of Chimato compost system

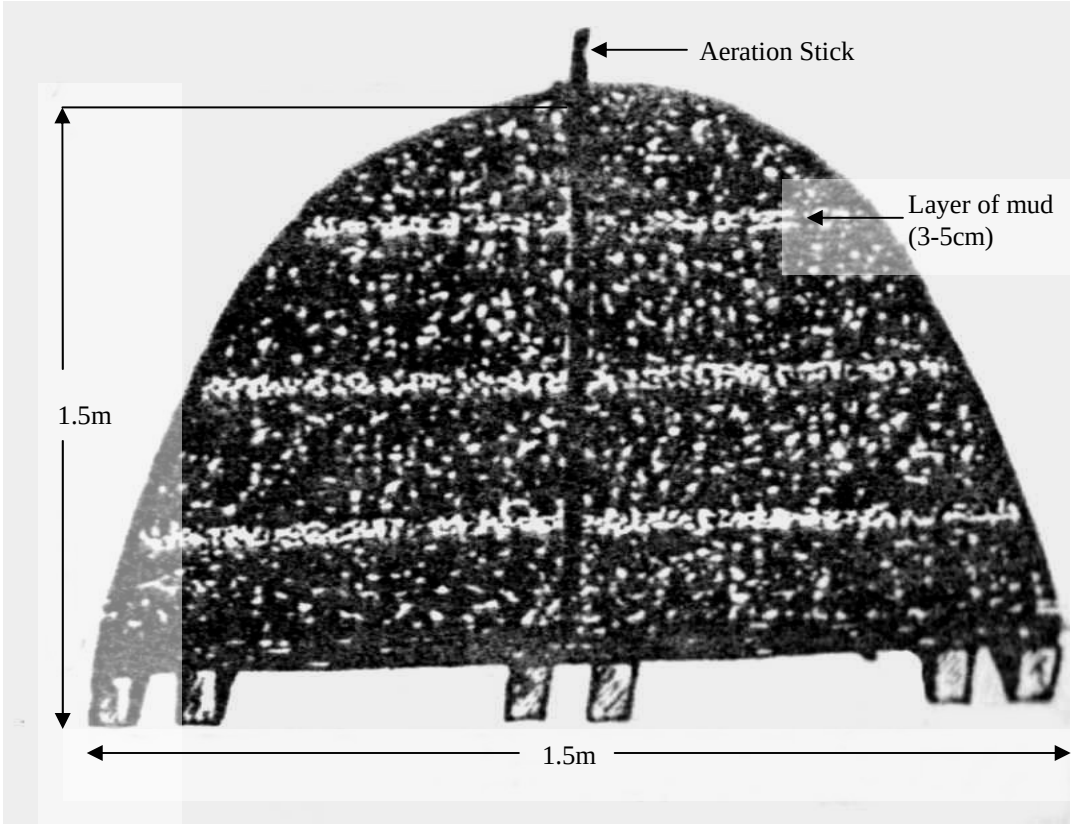

Figure 1.4 Cross-section of Chimato heap showing the compost heap on the base, the layer of mud for insulation and the aeration stick

1.3.6.3 Pit and Box systems

The Pit and Box systems are similar only that the Pit system requires a pit in the ground whereas the Box system is made on the soil surface going upwards. The pit is dug 1 m deep and has a length and width of 1.5 m. The Box system is made of similar dimensions going upwards. The box is constructed by wood on a flat soil surface. The formation of the compost layers is made as described in Section 1.3.6.1 and 1.3.6.2. For the Pit system, when the feedstock has filled the pit, the soil is piled on top of the feedstock to cover the pit completely. It is anticipated that the composting processes in the Pit and Box systems will be completed by the end of 1 month (ACB, 1994).

1.3.6.4 Optimising the Malawian composting process

In principle there are five critical factors for composting: 1) input feedstock (nutrient balance), 2) surface area, 3) moisture content, 4) oxygen concentration, and 5) temperature (as per the discussion in Section 1.3.3). Optimization of the composting processes requires adjustment of nutrient ratios, surface area, and moisture content in the pre-processing and initial mixing of materials. In addition, some systems include mixing as part of the composting process, which can help further blend ingredients, break up particles, and expose new surfaces to decomposition. Oxygen is supplied, and temperatures controlled, either by natural convection or forced aeration. Physical mixing of the material also helps to maintain optimum temperature and oxygen levels.

1.4 Justification and contribution of the study to knowledge

The apparent decline in soil fertility is widespread in Malawi and is threatening food security in the country. This is because the smallholder farmers cannot afford to use inorganic fertilizers due to very high fertilizer prices. This has triggered a new cycle of research geared towards developing low-cost nutrient enhancing technologies as alternatives for resource-poor farmers. Over the last decade, research has predominantly

concentrated on: crop residue management and its implications (Snapp 1998; Sakala 1998); development and evaluation of agro-forestry technologies (Itimu 1997; Saka *et. al.* 1994); maize-legume rotation practices; area-specific fertilizer recommendations and fertilizer management trials to promote efficient use of limited and scarce resources (Jones *et. al.* 1994; Kumwenda *et al.,* 1998). While there has been considerable research into the effects of straw incorporation, and its interaction with some leguminous residues, on soil N availability, and all the associated problems of nutrient immobilization and slow rates of decomposition (Cookson *et al.,* 1998; Sakala 1998; Garnier *et al.,* 2003), there have been few investigations of composting. No relationship has been established between the type of organic materials and compost quality, as well as management of the compost on the quality and crop production in a specifically Malawian context. The Government of the Republic of Malawi has recently embarked on a campaign to promote the use of composts and organic manure to improve soil nutrient status and raise crop yields on resource-poor farmers' fields in order to arrest famine and poverty among the smallholder farmers (Waddington *et al.,* 2004). Some smallholder farmers have started developing compost pits in an effort to recharge their soils for better crop production (Maliro *et al.,* 2002). There are no reliable guidelines and strategies on how best to utilize locally available organic materials to develop composts that could support maize production, and progress is hampered by limited scientific data, which could guide on how best to manage these composts and their impact on chemical, physical and biological properties of the soil. The research presented in this thesis aims to address some of these issues, specifically aiming to:

- Advance understanding of the mineralization and nutrient release properties of compost in soils in relation to composting systems used in Malawi
- Develop and optimise the composting systems for Malawian smallholder farmers adapted for local agro-ecological zones

Drawing from the literature reviewed, it is evident that there are serious soil fertility problems in Sub-Saharan African in general and Malawi in particular. This coupled with the rapid population growth as well as wide-spread poverty, has increased pressure on the land resources. With little use of inorganic fertilizers food shortages are experienced

continuously. This has opened a new wave of research in an attempt to find low-cost solutions to improve soil fertility and achieve the ultimate goal of food security. Use of compost is one of the methods which could mitigate these problems. In the Malawian context there are a number of questions which need to be addressed with regard to composting. These include:

- Is composting crop residues an effective way of recycling plant nutrients?
- How can the composting systems operating in Malawi be optimized?
- What will be the impact of this optimization on maize production?

1.5 Hypotheses of study

The following hypotheses were tested in this research:

1.5.1 Hypothesis 1

The type and quality of the feedstock determines the behaviour of the composting systems. Low C:N feedstocks and smaller particle sizes will result in faster decomposition, rapid heat build up and rapid loss of moisture, contrary to high C:N feedstocks in which case N will be in short supply limiting microbial growth and activity. The bigger particle sizes will reduce the exposed sites on which micro-organisms can operate on.

1.5.2 Hypothesis 2

Environmental conditions (ambient temperature, winds) influence the rate of composting processes for a particular composting system, the higher the ambient temperatures, the quicker the composting processes, and the shorter the composting duration.

1.5.3 Hypothesis 3

Systems differ in their influence on composting processes due to their capacities to promote air circulation, retain moisture content and heat, and hence the quality of the end product (type and amount of nutrients; absence of toxicity).

1.5.4 Hypothesis 4

The form and type of the nutrients in the compost produced are unique to a particular system and feedstock. The mineralization of the composts and their nutrient release when incorporated into soil is influenced by the amount and species of nitrogen and phosphorus available in the resultant composts.

1.5.5 Hypothesis 5

Plant establishment will be affected by the hypothesized different compost quality from the two systems, whereby the higher the compost quality, the more rapid the seedling establishment.

1.5.6 Hypothesis 6

The net benefit of the composting system is dependent upon the composting process affected by the capacity of the system in controlling the composting factors. The more favourable the composting factors, the more efficient the composting process, the higher the quality and quantity of the matured compost attained.

1.6 Research aim

The aim of the study was to develop techniques to optimise the composting systems and quality of compost produced by resource-poor farmers of Malawi for increased crop production.

1.7 Objectives of the study

The objectives of the research were:

1. To study and characterise two composting systems practised in Malawi using straw/green organic material feedstock under different agro-ecological zones.
2. To determine optimum conditions required for production of well matured and quality compost under these systems.
3. To investigate the nutrient release characteristics of composts in soils from different composting systems.
4. To determine the establishment pattern of maize seedlings in relation to different composting systems.
5. To evaluate the cost and benefit of the two composting systems with respect to the smallholder sector in Malawi.

1.8 Methodology outline (research approach)

To achieve the objectives of the research, the research methodology was structured into four parts: (i) composting experiments; (ii) controlled incubation post-compost mineralization tests; (iii) controlled incubation maize establishment studies and (iv) cost-benefit analysis. By combining research in both UK and Malawi, it was possible to investigate the composting processes operating in Malawi and link the composting systems to nutrient release mechanisms of the composts generated, and then to maize crop nutrient uptake and establishment. Finally, a cost-benefit analysis was carried out to look at the worthiness of choosing a particular system. The research approach is summarised in Fig. 1.5.

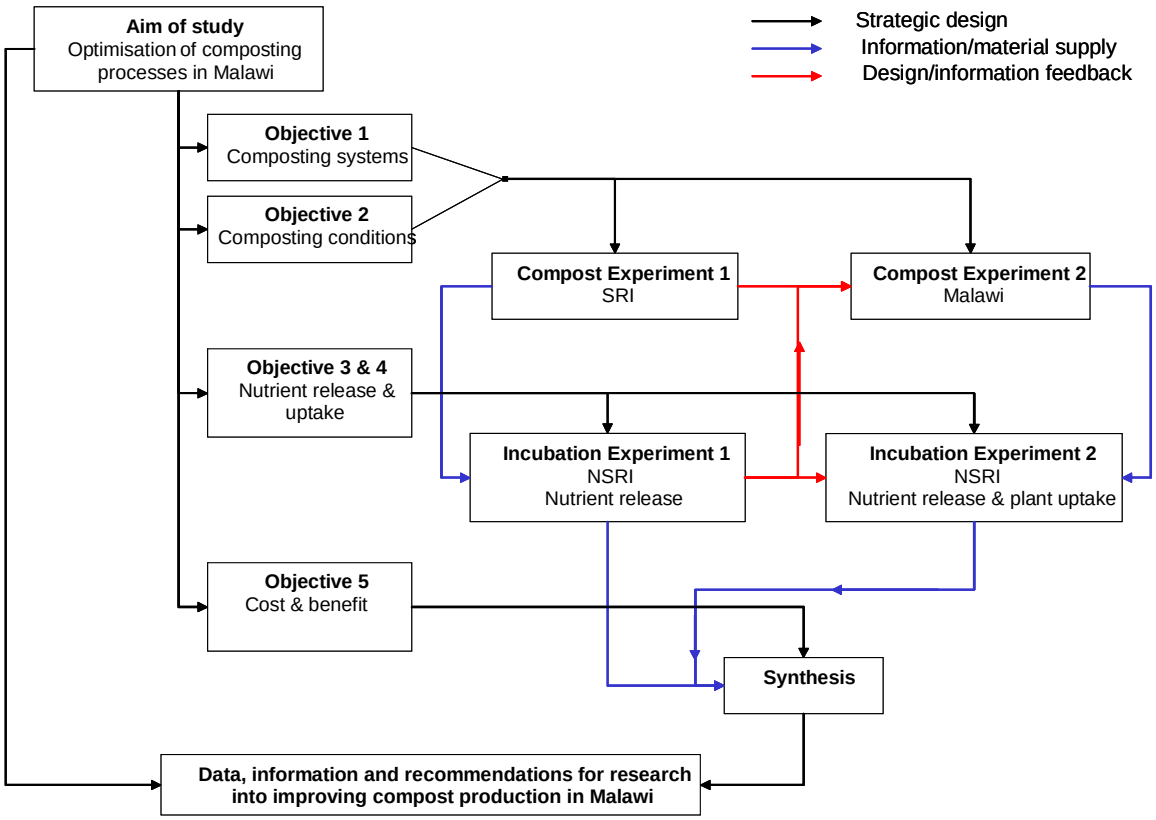

Figure 1.5 Summary of research approach in this study.

1.9 Thesis structure

The subsequent structure of this thesis is as follows:

Chapter 2 describes all the materials and methods used in this research. This articulates the choice of the methods, the principles behind them and as well as the procedures followed.

Chapter 3 reports all the results from the composting experiment, post-compost mineralization and maize establishment studies using Silsoe (UK) sourced material. This established the influence of the composting systems upon post-compost mineralization and plant development properties.

Chapter 4 reports all the experimental results for the composting, mineralization and maize establishment for Bunda (Malawi) sourced material so as to link the three experiments together in the context of this country.

Chapter 5 synthesizes all the experimental results from Silsoe and Bunda in order to understand the composting process of Changu and Chimato systems and establish how these can be optimized.

Chapter 6 draws the conclusions made from the research and makes recommendations for further studies.

CHAPTER TWO: Methodology

2.1 Introduction

This chapter draws together the research approach and all the experimental methods. It highlights the choice of methods, the principles behind them and problems encountered during conduct of the research.

In an effort to understand the most common composting systems (Changu & Chimato) used by smallholder farmers in Malawi and their influence on nutrient release characteristics and plant growth as expressed in the research aim and objectives (Chapter 1, Section 1.6 & 1.7), three sets of experiments were conducted followed by a cost-benefit analysis. The three sets of the experiments were:

1. composting experiments – which provided knowledge of the composting processes undertaken in the two composting systems and conditions which influenced them;
2. controlled incubation post-compost mineralization tests – which provided knowledge on the release pattern of nutrients from the resultant composts;
3. controlled incubation maize establishment studies – which provided knowledge on the influence of the compost yielded on plant growth (establishment)

This approach made it possible to investigate the composting processes operating in Malawi to link the composting systems to nutrient release mechanisms of the composts generated, and hence to maize crop nutrient uptake and establishment. The cost-benefit analysis (covered in Chapter 5) helped to assess the worthiness of making a particular choice of the composting system (see Chapter 1, Fig. 1.5, which illustrates the research approach).

The composting experiments were done in two localities, Silsoe, UK and Bunda College, Malawi to address the agro-ecological influence on the composting systems. To further understand the influence of chop length on the composting process of the two systems,

the Malawi composting experiments included chop length as an additional factor which was not included in the UK composting experiments (See this Chapter, Section 2.2.1.2 & 2.2.2.2). The controlled incubation experiments were all done in the UK to take advantage of the facilities available. During the 42-day period of the post-compost mineralization experiments with the UK resultant compost, immobilization was observed compared to the control (See Chapter 3, Section 3.3.1.1). This development influenced the extension of the duration of the incubated post-compost mineralization for the Malawi resultant compost to 84 days (see this Chapter, Section 2.3.1 & 2.3.2). This was aimed at establishing when the mineralization process was dominant, which is important in determining the timing of seeding after incorporation of the compost to avoid competition for N with micro-organisms. Similarly, an additional experiment was conducted during the maize establishment study for the Malawi compost with soil/compost pre-incubated before sowing maize seed (see this Chapter, Section 2.4.1 & 2.4.2). This was aimed at mitigating the immobilization problem experienced during the UK maize establishment as evidenced by the mineralization experiments.

A number of composting systems exist in Malawi including the box, pit, Changu and Chimato systems. The two latter systems were selected for study in this research for the following reasons:

1. the pit system requires digging of the pit which was not possible in the UK due to adverse conditions (winter) which limited the composting experiments to being conducted in the glasshouse
2. the box system is uncommon in Malawi and therefore it was not prioritised in this research
3. to control the size of the experimental units due to labour requirements

The compost made from the two systems both in the UK and Malawi were harvested and dried to arrest microbial activity and used for the controlled incubated mineralization and maize establishment studies which were all done in the UK. The soil for the controlled incubated experiments was collected from Silsoe (UK). This reduced the cost of importing soils from Malawi but served the need and purpose of the research.

2.2 Composting experiments

2.2.1 United Kingdom (Silsoe) experiments

2.2.1.1 Experiment location

Silsoe is situated 52.005^{o} N; - 0.428^{o} W at an altitude of 60 m above sea level. The composting experiments were done at Silsoe Research Institute between August and December of 2004 (see Appendices, Fig. A1.1). Due to the problems of rainfall and winter conditions, it was not possible to conduct composting experiments in the field. Consequently, the composting experiments at Silsoe were done in the glasshouse on a cemented floor. The other associated problems were the acquisition of maize residues and green beans which were not available during this period of the year. Wheat straw (*Triticum aestivum*) and grass/clover (*Lolium perenne/Trifolium repens*) were selected to replace maize (*Zea mays* L.) and green beans (*Phaseolus vulgaris* L.). Wheat has a similar C:N ratio as maize while grass/clover had a similar C:N ratio to the green bean. This made them a suitable replacement for the Malawi designated feedstock (maize & green bean). Compared with Malawi (Bunda College), ambient temperatures during composting at Silsoe (glasshouse) were lower. Silsoe had a mean of 19.3^{o}C (range of 11 – 35^{o}C measured in the glasshouse between August and December, 2004) while Bunda had a mean of 27.4^{o}C (range of 18 – 32^{o}C measured in the field).

2.2.1.2 Experimental design

The experiments were set up as a randomized complete block design (RCBD) with three replicates of each treatment assigned to the experimental plots using a randomization technique of sequence of appearance and ranking of the random numbers (Gomez and Gomez, 1984). A total of 8 treatments were developed combining wheat straw and grass/clover into different initial C:N ratios – compost-mix (*i.e.* 20:1; 25:1; 30:1 & 60:1) and compost systems (Changu & Chimato) (Table 2.1). The glasshouse layout is presented in Fig. 2.1.

Table 2. 1 Composting treatments set up at Sisloe, UK using a combination of wheat straw and grass/clover

ID	Combination	Description
A	CN_1M_1	Changu 20:1
B	CN_1M_2	Chimato 20:1
C	CN_2M_1	Changu 25:1
D	CN_2M_2	Chimato 25:1
E	CN_3M_1	Changu 30:1
F	CN_3M_2	Chimato 30:1
G	ZM_1	Changu 60:1
H	ZM_2	Chimato 60:1

Where: CN = C:N ratio; CN1 = 20:1; CN2 = 25:1; CN3 = 30:1; Z = Control (C:N 60:1); M = System

BLOCK 1	**BLOCK 2**	**BLOCK 3**
1 □ **B**	9 □ **H**	17 ○ **A**
2 ○ **C**	10 ○ **C**	18 □ **D**
3 ○ **G**	11 ○ **A**	19 □ **F**
4 □ **F**	12 ○ **E**	20 ○ **G**
5 ○ **A**	13 ○ **G**	21 ○ **E**
6 ○ **E**	14 □ **D**	22 ○ **C**
7 □ **H**	15 □ **B**	23 □ **B**
8 □ **D**	16 □ **F**	24 □ **H**

Figure 2.1 Silsoe glasshouse treatment randomization in each block; □ & ○ represent Chimato and Changu composting systems respectively; the treatments were assigned to the experimental plots using randomisation technique of sequence of appearance and ranking of the random numbers (Gomez & Gomez, 1984)

2.2.1.3 Compost heap formation

Wheat straw and grass/clover were used for compost heap formation. Prior to compost heap development, the wheat straw and grass/clover stocks were sampled to check the variability of the carbon, nitrogen contents and C:N ratios (Table 2.2 & 2.3). With consistency of supply determined, the carbon, nitrogen and C:N ratios of the straw and grass were analysed to be used for the determination of the compost recipes. The wheat straw had a C:N ratio of 60:1, the grass/clover 13:1 and the soil for inoculation 11:1. The initial C:N ratios of the compost feedstock mixes (C:N 20:1; 25:1 and 30:1) were developed using the method described by Dougherty (1999) (Appendix 2.1a). The straw was shredded to 5 ± 2 cm by the garden shredder (Fig.2.2). The feedstock mix ratios of wheat straw, grass/clover and inoculation soil in initial C:N 20:1 was 1.9:2.0:1 equivalent dwt./dwt, 2.9:1.7:1 equivalent dwt/dwt. for initial C:N 25:1, and 2.9:1.0:1 dwt./dwt. for initial C:N 30:1.

Table 2.2 Wheat straw total carbon and nitrogen and C:N ratio of the random samples from different position in the bales' pile prior to feedstock formulation

No.	C%	N%	C:N ratio	Position of bale (in the pile)
1	44.6	0.6	70.5	Outside the pile
2	44.5	0.7	62.2	Outside the pile
3	44.0	0.8	52.1	Outside the pile
4	45.1	0.7	62.5	Outside the pile
5	42.4	0.7	60.9	Outside the pile
6	43.4	0.8	52.5	Inside the pile
7	43.7	0.8	52.8	Inside the pile
8	43.3	0.7	58.1	Inside the pile
9	43.5	0.7	62.8	Inside the pile
10	42.5	0.7	62.8	Inside the pile
Mean	43.7	0.7	59.7	
Standard Error	0.28	0.04	1.34	

Table 2.3 Grass/clover total carbon and nitrogen and C:N ratio of the random samples from different fields (plots) prior to feedstock formulation

No.	C%	N%	C:N ratio	Source of sample
1	42.1	3.4	12.3	Field 1
2	42.0	3.5	12.1	Field 1
3	41.4	3.3	12.4	Field 1
4	43.3	3.3	13.0	Field 2
5	42.8	3.2	13.2	Field 2
Mean	42.3	3.34	12.6	
Standard Error	0.33	0.05	0.21	

Figure 2.2 The garden shredder used for shredding wheat straw

Changu compost heaps were formed on the glasshouse cement floor, whereas the Chimato compost heaps were constructed on a raised platform made of a wooden pallet, covered with galvanized steel chicken wire (Fig. 2.3).

The Chimato system comprised the formation of a pyramidal heap of repeated double layers of straw and grass/clover, piled in sequence, and with water added to each double layer before sandy loam soil was sprinkled on top as an inoculum. Each heap was made of 7 double layers of mean thickness of 18 cm (a range of 16 to 20 cm based on C:N ratio mix) resulting in heaps of 126 ± 5 cm high (Fig. 2.4). The soil was the main source of the micro-organisms for the compost heaps. Three thermistors (see Section 2.6.1) were placed in each compost heap, at: (1) 20 cm from the top of the heap; (2) in the middle of the heap; and (3) 20 cm from the bottom of the heap.

Figure 2.3 Chimato wooden pallet base (1 x 1 x 0.145 m) on which the compost was made. The mesh was used to prevent the feedstock from falling on the ground.

Figure 2.4 Chimato compost heap formation; layers of straw and grass/clover are formed into a pyramidal heap with a mud coat to prevent the heap from drying. The opening on the bottom promotes aeration which is conducted through the position where the central pole is fixed. Scale for the height is 1:36.

The Changu system employed a conical shaped heap formation with the feedstock, water and sandy loam soil applied the same way as in the Chimato system explained above. The compost was prepared directly on the cemented floor after sprinkling some sandy loam soil. The base of the heap had a diameter of 1 m and each heap was made of 7 double layers of mean height of 18 cm (a range of 16 to 20 cm based on C:N ratio mix) ending with heaps of 126 ± 5 cm high (Fig. 2.5). Three thermistors (see section 2.6.1) were placed in each compost heap, at: (1) 20 cm from the top of the heap; (2) in the middle of

the heap; and (3) 20 cm from the bottom of the heap as in the Chimato heaps. No mud coat was made for this type of system and it had no air passage created within the heap. Consequently, the heap was turned fortnightly to aerate it and water loss was compensated by watering the heaps to keep the moisture between 50 and 60% (mass basis).

Figure 2.5 Changu compost heap formation, layers of straw and grass/clover are formed into a conical heap. Scale for the height is 1:23.

2.2.2 Malawi (Bunda College) experiments

2.2.2.1 Experimental location

Bunda is situated 14^{o} S; 033^{o} E; and at an altitude of 1194 m above sea level. The composting experiments were done at Bunda Research Farm (see Appendices, Fig. A1.2). The experiments were conducted in the open field (Fig. 2.6) during the summer months of September, October and November, 2005. Maize straw (*Zea mays* L.) and green bean (*Phaseolus vulgaris* L.) residues were used for composting. Bunda had a mean temperature of 27.4^{o}C (range of 18 – 32^{o}C) during the composting experiments.

Figure 2.6 Field lay out of the composting treatments carried out in Malawi (Bunda)

2.2.2.2 Experimental design

The experimental design and the number of treatments and experimental plots were similar to the Silsoe set up (see Section 2.2.1.2). Unlike the Silsoe experiments, these experiments were conducted in the field. The treatments were developed combining maize straw and bean residues of different sizes into different initial C:N ratios – compost-mix (*i.e*. 20:1 & 30:1) and compost systems (Changu & Chimato). The maize straw and bean residues were cut into two groups of sizes - chop length (5 ± 2 cm and 10 ± 2 cm). The chop length was included for Bunda experiments to understand its influence on composting processes (Table 2.4). Randomisation of the treatments was as per the method in Section 2.2.1.2. The field layout is presented in Fig. 2.7.

Table 2.4 Composting treatments set up at Bunda College, Malawi using a combination of maize straw and green beans residues

ID	Combination	Description
A	$CN_1M_1S_1$	Changu 20:1; 5 cm
B	$CN_1M_2S_1$	Chimato 20:1; 5 cm
C	$CN_1M_1S_2$	Changu 20:1; 10 cm
D	$CN_1M_2S_2$	Chimato 20:1; 10 cm
E	$CN_2M_1S_1$	Changu 30:1; 5 cm
F	$CN_2M_2S_1$	Chimato 30:1; 5 cm
G	$CN_2M_1S_2$	Changu 30:1; 10 cm
H	$CN_2M_2S_2$	Chimato 30:1; 10 cm

Where: C:N = C:N ratio; CN_1 = 20:1; CN_2 = 30:1; S = Chop length; S_1 = 5 cm; S_2 = 10 cm; M = System

BLOCK 1	BLOCK 2	BLOCK 3
1 □ **D**	9 □ **H**	17 ○ **G**
2 □ **B**	10 ○ **G**	18 □ **F**
3 ○ **A**	11 □ **B**	19 □ **H**
4 ○ **C**	12 □ **D**	20 ○ **A**
5 □ **F**	13 ○ **C**	21 ○ **E**
6 □ **H**	14 ○ **A**	22 □ **B**
7 ○ **E**	15 □ **F**	23 ○ **C**
8 ○ **G**	16 ○ **E**	24 □ **D**

Figure 2.7 Bunda field treatment randomization in each block; □ & ○ represent Chimato and Changu composting systems respectively; the treatments were assigned to the experimental plots using randomisation technique of sequence of appearance and ranking of the random numbers (Gomez & Gomez, 1984).

2.2.2.3 Compost heap formation

The maize straw used in this experiment had a C:N ratio of 75:1; the bean residues had the C:N ratio of 12:1, while the soil had the C:N ratio of 15.:1 The initial C:N ratios of the compost recipes (C:N 20:1 and 30:1) were developed using the method described by Dougherty (1999) (Appendix 2.1a). The feedstock mix ratios for maize straw, bean and inoculation soil for initial C:N 20:1 was 1.7:1.8:1 equivalent dwt./dwt. and for initial C:N 30:1 was 3.4:1.3:1 equivalent dwt./dwt. The maize straw and bean residues were cut into two sizes of 5 ± 2 cm and 10 ± 2 cm by hand using panga knives, a traditional machete-like tool (Fig. 2.8). This is the common tool used for cutting plants and shrubs in Malawi;

in absence of the shredder, this tool conveniently mimicked the practice of the smallholder farmer.

Changu and Chimato compost heaps were made as described in Section 2.2.1.3. Changu compost heaps were made on the ground while the Chimato compost heaps were made on a raised platform made of a wood (Fig. 2.9). Each heap was formed by 6 double layers of mean thickness of 21 cm (a range of 19 to 22 cm based on C:N ratio mix) ending with heaps of 126 ± 5 cm high (Fig.2.10).

Figure 2.8 Panga knife used for cutting the maize and bean residues at Bunda (Scale: 1:15)

Figure 2.9 Chimato base made of locally available wood to create a raised platform and openings for aeration. Width = 1.5 m.

Figure 2.10 Changu and Chimato compost heap formation; layers of maize straw and bean residues made into conical and pyramidal shaped heaps.

2.2.3 Process management

Changu compost heaps were aerated by mixing the composting materials every fortnight for the Silsoe experiments and every week for the Bunda experiments. This was intended to evaluate the impact of turning frequency on the composting process. This allowed assessment of this management process between the two locations. Moisture content of the compost was adjusted during the turning procedures using a watering can. Samples of compost were taken at random to determine the moisture content of the compost prior to turning. The amount of water required was calculated based on the mass of compost in the heap in order to bring it to 60% moisture content. Lighter watering was applied on the surface of the compost heap at regular intervals to keep the surface of the compost moistened. Chimato compost heaps were not turned. Aeration in Chimato compost heaps was achieved through the base of the raised platform. The composting experiments were run for 112 days and 77 days for Silsoe and Bunda respectively. This duration was definitely by when the compost from the two locations were assessed to be mature, based on the maturity criteria (see this Chapter, Section 2.8).

2.2.4 Compost sampling

Sampling of the compost was done fortnightly for Silsoe, and weekly for Bunda experiments. Homogenisation of the compost samples was done at two levels. Samples for the compost respiration assays and those for mineralization and maize establishment studies were taken at 20 cm from the top, in the middle and 20 cm from the bottom of the heap. From each zone, four samples from different random positions within the zone were taken and homogenized. The homogenized samples from the different zones were further homogenised to be representative of the whole heap. These samples were then used for the laboratory analysis of carbon, nitrogen, potassium, phosphorus, pH and germination (*c.f.* cress seed). At the end of the composting experiments, the compost from each treatment was harvested, dried at 65^{o}C to arrest microbial activity and ground to < 1 mm to be used for the mineralization and maize establishment experiments.

2.3 Mineralization experiments

Mineralization experiments used compost harvested after completion of composting experiments. These experiments were conducted under controlled laboratory conditions. Soils from Silsoe, United Kingdom were used in all mineralization studies. The soils were air dried and passed through a 2 mm sieve to remove aggregation and stones.

2.3.1 United Kingdom sourced compost

Either 0.13 g or 0.40 g dry weight ground compost was mixed with 59.4 g dry weight (60 g air dry) sandy loam soil (Table 2.5) in 160 mL incubation bottles representing equivalent to 10 t/ha and 30 t/ha compost application rate respectively applied to 30 cm depth (see Appendix 2.1b). The incubation bottles were then incubated for 42 days at 30^{o}C and 60% moisture content in the dark (Hadas & Portnoy, 1994; Cambardella *et al*. 2003). The bottles were covered by perforated foil paper to reduce excess loss of moisture (See Fig. 2.11). The following parameters were measured during the incubation period from the soil compost mixtures:

- Total carbon
- Total nitrogen
- Mineral nitrogen (total oxides of nitrogen (TON) & ammonium-N (NH_4-N))
- Extractable potassium
- Extractable phosphorus
- pH
- Cation exchange capacity (CEC)

Sampling for analysis of the above parameters was carried out 0, 7, 14, 21, 28, 35 and 42 days after compost incorporation, except for CEC which was assessed on Day 0 and 42 only. The CEC was analysed only at the beginning and at the end of the incubation because it was used to establish if the use of compost had any influence on the CEC of the soil during the 42 day incubation period.

Table 2.5 Characteristics of sandy loam soil used for mineralization and maize establishment experiments

	Soil characteristics							
Material	Sand %	Silt %	Clay %	N %	C %	C:N	Extractable-P (mg/kg)	Extractable-K (mg/kg)
Sandy loam	71.8	15.8	12.4	0.068	0.65	9.6	35.46	201.81

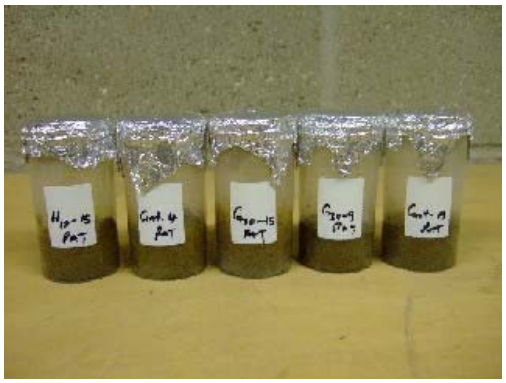

Figure 2.11 Mineralization incubation bottles covered with perforated foil paper to reduce excess loss of moisture.

The treatments were arranged in a 7 x 3 x 2 x 2 factorial design with incubation duration (0, 7, 14, 21, 28, 35 and 42 days), initial C:N ratio (the C:N ratio of the original mix, before composting, *i.e.* 20:1, 30:1, 60:1), composting systems (Chimato or Changu), and compost amendment rate (10 t/ha or 30 t/ha) as factors. A control was set where no compost was applied. The treatments were replicated 3 times; a total of 273 incubation bottles. The list of the treatments for soil/compost incubation mineralization studies are presented in Table 2.6.

Table 2.6 Mineralization and maize establishment treatments set up using compost made in the United Kingdom from wheat straw and grass/clover

No.	Composting system	Compost-mix (C:N ratio)	Compost application rate
1	Changu	20:1	10 t/ha
2	Chimato	20:1	10 t/ha
3	Changu	30:1	10 t/ha
4	Chimato	30:1	10 t/ha
5	Changu	60:1	10 t/ha
6	Chimato	60:1	10 t/ha
7	Changu	20:1	30 t/ha
8	Chimato	20:1	30 t/ha
9	Changu	30:1	30 t/ha
10	Chimato	30:1	30 t/ha
11	Changu	60:1	30 t/ha
12	Chimato	60:1	30 t/ha
13	Control (soil only)		

2.3.2 Malawi sourced compost

The dried and ground compost was exported to Cranfield University, Silsoe, UK for incubation and analysis under licence from HM Department for Environment, Food and Rural Affairs, UK. These experiments were formulated and incubated as described in Section 2.3.1. The soil compost mixtures were incubated for 84 days, twice the time for the UK experiments to establish when the treatments were mineralizing against the control (see this Chapter, Section 2.1). The same parameters as for the UK sourced compost mineralization (Section 2.3.1) were determined. Sampling for analysis of the parameters was done on day 0, 7, 14, 28, 42, 63 and 84 days except for CEC which was assessed on Day 0 and 84.

The treatments were arranged in a 7 x 2 x 2 x 2 x 2 factorial design with incubation duration (0, 7, 14, 28, 42, 63 and 84 days), C:N ratio (20:1, 30:1), composting system (Changu, Chimato), chop length (5 cm, 10 cm) and compost amendment rate (equivalent to 10 t/ha, 30 t/ha) as factors. A control (soil only) was set where no compost was added. The treatments were replicated 3 times and a total of 357 incubation bottles. The treatments are presented in Table 2.7.

Table 2.7 Mineralization and maize establishment treatments set up using compost made in Malawi from maize straw and green bean residues

No.	Composting system	Compost-mix (C:N ratio)	Chop length (cm)	Compost application rate
1	Changu	20:1	5	10 t/ha
2	Chimato	20:1	5	10 t/ha
3	Changu	30:1	5	10 t/ha
4	Chimato	30:1	5	10 t/ha
5	Changu	20:1	10	10 t/ha
6	Chimato	20:1	10	10 t/ha
7	Changu	30:1	10	10 t/ha
8	Chimato	30:1	10	10 t/ha
9	Changu	20:1	5	30 t/ha
10	Chimato	20:1	5	30 t/ha
11	Changu	30:1	5	30 t/ha
12	Chimato	30:1	5	30 t/ha
13	Changu	20:1	10	30 t/ha
14	Chimato	20:1	10	30 t/ha
15	Changu	30:1	10	30 t/ha
16	Chimato	30:1	10	30 t/ha
17	Control (soil only)			

2.4 Maize establishment experiments

Maize (*Zea mays*) is a major staple food for most Malawians (Ngwira *et al.* 1989). It occupies 70% of arable land with an estimated national average yield of 1.3 t/ha (CIMMYT, 1999). The yield of maize remains low due to a number of factors but the decline in soil fertility due to continuous cultivation and little addition of inputs is paramount. Poor crop stand resulting from low seedling establishment contributes to poor yields in maize production. On this basis, maize was selected for the crop establishment experiments.

2.4.1 United Kingdom sourced compost

Either 1.3 g or 4.0 g dry weight ground compost was mixed with 593.8 g dry weight (600 g air dry) sandy loam soil described above and put in the plant pots (Fig. 2.12) representing 10 t/ha and 30 t/ha compost application rate respectively (applied to 30 cm depth, see Appendix 2.1b). The pots were incubated in a growth cabinet (Snijders Scientific, NL) for 4 weeks with a 24^{o}C, 14 h day (light) and 22^{o}C, 10 h night (dark) cycle (as *per* Sowiński *et al.* 2005). Two maize seeds (hybrid variety Vernal Mesurol from Bayer, UK) were planted in the middle of each pot at 2.5 cm depth following watering of the soil. The growth pots were immediately put in the growth cabinets after planting. Thinning to 1 plant per pot was done 5 days after planting when germination was complete to reduce plants competition in a small soil volume. The thinned plants were retained for biomass analysis. The following parameters were measured during the incubation period:

1. Number of days taken to germinate
2. Germination %
3. Growth stage at end point
4. Plant height
5. Leaf length and breadth
6. Leaf area (end point)
7. Base stem diameter
8. Plant biomass
9. Root mass and root nutrient content
10. Plant nutrient content (total N, P and K)

Figure 2.12 Plant growth pot used for maize establishment; with a total volume of 545 cm^3 (scale for height is 1:3.3)

The treatments were arranged in a 3 x 2 x 2 factorial design with initial pre-compost C:N ratio (20:1, 30:1, 60:1), composting system (Changu, Chimato), and compost amendment rate (10 t/ha, 30 t/ha) as factors. A soil-only control with no compost was included. There were 4 replicates of each combination and the control *i.e.* a total of 52 pots. The list of the treatments is presented in Table 2.6.

2.4.2 Malawi sourced compost

The experiments were established *as per* Section 2.4.1., but following the results of the UK sourced compost establishment experiment, two separate experiments were developed:

1. A low fertility sand soil (Table 2.8) was used to determine the effect of the compost in low nutrient status soils typical of those found in Malawian agriculture
2. The same sandy loam soil used in the mineralization experiments above was used for a sub-set of experiments where pre-incubation of soil compost was done for 63 days prior to seeding to eliminate the immobilisation phase of the compost when first applied in the soil.

Table 2.8 Characteristics of sand and sandy loam soils used for maize establishment experiments with compost from Malawi

	Soil characteristics							
Material	Sand %	Silt %	Clay %	N %	C %	C:N	Extractable-P (mg/kg)	Extractable-K (mg/kg)
Sand	93.7	0.4	5.9	0.005	0.07	14	23.54	36.69
Sandy loam	71.8	15.8	12.4	0.068	0.65	9.6	35.46	201.81

In a further adaptation, 700 g of soil was used in each pot to fully support the plants so that they do not fall when they grew bigger. The same parameters as indicated in Section 2.4.1 were measured during the incubation period.

In the first experiment, the treatments were arranged in a 2 x 2 x 2 x 2 factorial design with initial pre-compost C:N ratio (20:1, 30:1), composting system (Changu, Chimato), chop length (5 cm, 10 cm) and compost amendment rate (10 t/ha, 30 t/ha) as factors. A soil only control with no compost was included. This was replicated 3 times *i.e.* a total of 51 pots.

In the second experiment, only the 5 cm chop length material and 10 t/ha amendment rates were used. An additional factor was included, incubation period (0 days, 63 days). This factor was included to investigate the consequences of mineralization/ immobilization dynamics on plant establishment. It is common practice in Malawi to plant immediately following application of compost to the soil. The results of the UK compost experiment indicated that immobilization immediately following compost amendment could result in adverse effects on plant establishment – (see Chapter 3, Section 3.3.1.1 & 3.4).

This experiment was arranged as a 2 x 2 x 2 factorial design with C:N ratio (20:1, 30:1), method of composting (Changu, Chimato) and incubation period (0 days, 63 days) as factors. A soil-only control with no compost was included. There were 3 replicates *i.e.* a total of 30 pots. The list of the treatments of experiment 1 and 2 are presented in Table 2.7 & 2.9.

Table 2.9 Maize establishment treatments for pre-incubated experiments set up using compost made in Malawi from maize straw and green bean residues

No.	Composting system	Compost-mix (C:N ratio)	Chop length (cm)	Compost application rate	Incubation status (days)
1	Changu	20:1	5	10 t/ha	63
2	Changu	20:1	5	10 t/ha	0
3	Chimato	20:1	5	10 t/ha	63
4	Chimato	20:1	5	10 t/ha	0
5	Changu	30:1	5	10 t/ha	63
6	Changu	30:1	5	10 t/ha	0
7	Chimato	30:1	5	10 t/ha	63
8	Chimato	30:1	5	10 t/ha	0
9	Control (soil only)				63
10	Control (soil only)				0

2.5 Chemical analytical methods

Several chemical parameters were measured during the three experimental phases of this research (composting, incubated post-compost mineralization and incubated maize establishment experiments; see Table 2.10). This measurement was focused on macro-nutrients required by plants in order to understand the impact of the compost on nutrition of the soil and plant growth.

Table 2.10 The chemical parameters measured during composting, mineralization and maize establishment experiments in the United Kingdom and Malawi

Element/compound	UK/Malawi	Extractable/Total	Material	Extractant	Determination
Carbon	UK	Total	a. Wheat straw b. Grass/clover c. Soil d. compost	Dry combustion (Dumas method)	TCD analyzer
	Malawi	Total	a. Maize straw b. Bean residue c. Soil d. compost	Potassium dichromate	Colorimetrically (at 600 nm)
Nitrogen	UK	Total	a. Wheat straw b. Grass/clover c. Soil d. compost	Dry combustion (Dumas method)	TCD analyzer
	Malawi	Total	a. Maize straw b. Bean residue c. Soil d. compost	Sulphuric acid/ Hydrogen peroxide in presence of selenium and lithium sulphate	Colorimentrically (at 655 nm)
Phosphorus	UK	Total	a. Wheat straw b. Grass/clover	Dry combustion	Atomic absorption spectrophotometer (at 400 nm)
		Extractable	a. Soil b. compost	Sodium bicarbonate (0.5 M) Calcium chloride/DTPA (CAT method)	Spectrophotometer (at 880 nm Automated ascorbic acid reduction method
	Malawi	Total Extractable	a. Maize straw b. Bean residue c. Soil d. compost	Sulphuric acid/ Hydrogen peroxide in presence of selenium and lithium sulphate Sodium Bicarbonate (0.5 M)	Spectrophotometer (880 nm) Spectrophotometer (880 nm)
Potassium	UK	Total	a. Wheat straw b. Grass/clover	Dry combustion/ Hydrochloric acid	Flame photometer
		Extractable	a. Soil b. Compost	Ammonium nitrate Calcium chloride/DTPA (CAT method)	Flame photometer
	Malawi	Extractable	compost	Mehlich 3	Spectrophotometry (at 766 nm
Total Oxides of Nitrogen (TON)	UK	_	a. Soil b. Compost	Potassium chloride (2 M) Calcium chloride/DTPA	Automated hydrazine reductio method
Ammonium-N	UK	_	a. Soil b. Compost	Potassium chloride Calcium chloride/DTPA (CAT method)	Automated phenate method
	Malawi	_	Compost	Potassium chloride (2 M)	Colorimetrically (at 655 nm)
Nitrate-N	Malawi	_	Compost	Potassium sulphate (0.5 M)	Colorimetrically (at 410 nm)
CEC	UK	_	Soil	Barium chloride/ Magnesium sulphate	Titration by EDTA
pH	UK/Malawi	_	a. Soil b. Compost	Water suspension	pH-meter

Total carbon and total nitrogen were determined to establish the C:N ratio of the different materials (plant residues, compost & soil) as this is described as an indicator of a soil's potential for organic matter decomposition (Bengtsson *et al.,* 2003). Similarly, total phosphorus and total potassium of the feedstock were determined to establish their contents and monitor their mineralization during composting and mineralization studies. The plant available forms of nitrogen (TON and NH_4-N) as well as plant extractable forms of phosphorus and potassium from different materials (compost & soil) were determined to establish the potential of the materials to support plant growth. The pH of compost and soil were measured to monitor the environment under which the microbial activities operated during composting and post-compost mineralization. Finally, the CEC of the soil was determined to establish the impact of the use of compost from this research on the capacity of the soil to retain nutrients for plant uptake.

Most of the methods used in this research were common for different parameters measured during composting, mineralization and maize establishment studies. Different methods were used during composting at Bunda (Malawi) where total carbon, total nitrogen, extractable phosphorus and extractable potassium used different methods from those used at Silsoe (UK). This was due to the fact that Bunda has different equipment from Silsoe.

2.5.1 Methods for total carbon of crop residues, soil and compost

The total C content of the wheat straw and grass/clover (from the UK experiments); and the composts and soils (from both experiments); was determined by the Dumas Method of total combustion (see Appendix 2.2a). Plant and compost samples were dried at 65^{o}C for 48 hrs, and soil samples air dried and ground to pass through a 2 mm sieve. Sub-samples from all the materials were finely ground (< 1 mm), homogenised and dried for two hrs at 105^{o}C. Aliquots of 50 ± 0.01 mg from the samples were placed in tin boats for analysis. Total carbon was determined using a thermo couple detector (TCD) array in an Elementar Vario EL II analyser (see Appendix 2.1c).

Determination of total C for maize residues, bean residues, compost and soil used in the Bunda experiments were done by wet-digestion using potassium dichromate ($K_2Cr_2O_7$) (Anderson & Ingram, 1993). The procedure used 1 ± 0.001 g of ground sample (< 1 mm) sample in a 100 mL digestion tube followed by addition of 10 mL $K_2Cr_2O_7$ solution (5%) and 5 mL H_2SO_4 (36 N) before digesting the material at 150^oC for 30 minutes. Standard solutions were prepared following the same procedure but with sucrose instead of organic residues (see Appendix 2.1d). After cooling, 50 mL of 0.4% $BaCl_2$ was added and left overnight before making absorbance measurements of the samples on a UV-VIS spectrophotometer (Spectomic 21D) at a wavelength of 600 nm. The quantity of C was determined from the standard curve after subtracting the mean value of absorbance for the blanks (see Appendix 2.1d).

2.5.2 Methods for total nitrogen of crop residues, soil and compost

Total nitrogen for the wheat straw, grass/clover, composts and soil was determined by combustion analysis (Dumas method) and samples were prepared and analysed as detailed in Section 2.5.1 for UK. For the Malawi experiment, 0.2 ± 0.001 g of ground maize straw, bean residues or compost samples (< 1 mm) were digested by 4.4 mL of digestion mixture (0.42 g selenium powder, 14 g lithium sulphate, 350 mL 30% hydrogen peroxide and 420 mL H_2SO_4) at 360^oC for 2 hrs to ensure that all the hydrogen peroxide was boiled off. The digest was allowed to cool, and then water was added volumetrically to make the solution up to 100 mL. Analysis of the ammonium-N was done colorimentrically at 655 nm (Anderson & Ingram, 1993). Standard curves were developed from the absorbance of the standard concentrations and the values for the samples were deduced from the graph after subtracting the absorbance from the blanks (see Appendix 2.1e & 2.2b).

2.5.3 Methods for total potassium of crop residues

Extraction for potassium from wheat straw and grass/clover was done using dry combustion, burning 2 ± 0.001 g of ground sample (< 1 mm) at 500^{o}C and dissolving the soluble minerals in the ash with 10 mL of 6 M hydrochloric acid (MAFF, 1986; NSRI/AL/SOP 14/Version 1). When the extraction process was complete (see Appendix 2.1f), the samples were diluted to 50 mL and filtered through a Whatman No. 4 filter paper. The concentration of potassium was determined by flame photometry (NSRI/AL/SOP 20/Version 1)(see Appendix 2.1g & 2.2c) .

2.5.4 Methods for extractable potassium of soil and compost

Potassium from soil (mineralization experiments) was extracted by 50 mL of 1M NH_4NO_3 (MAFF, 1986; NSRI/AL/SOP 14/Version 1; Faithfull, 2002). Ten grams of the air dried, 2 mm sieved soil sample was used for analysis. The solution was shaken for 30 minutes and filtered through a Whatman No. 2 filter paper. A blank was prepared with each batch of samples. The sample extracts and the blanks were measured by flame photometer after calibrating the machine with potassium standard solutions of a range of 0 – 50 mg/L potassium (see Appendix 2.1h). Compost extraction for potassium (in the United Kingdom) was done using $CaCl_2$/DTPA (CAT) method (BS EN 13651:2001). This was done in an extraction volume ratio of 1:5. The extracted samples were shaken for 1 hr, filtered through a Whatman No. 2 filter paper before determination of potassium. Analysis for potassium was done by flame photometry (NSRI/AL/SOP 20/Version 1). The full procedure is described in Appendix 2.1i.

In Malawi, a different method was employed for analysing extractable K due to differences in the analytical machines. Here 25 mL of Mehlich 3 extracting solution (0.2N CH_3COOH + 0.25N NH_4NO_3 + 0.013N HNO_3 + 0.015N NH_4F + 0.001M EDTA) was used to extract K from 2.5 ± 0.001 g compost sample (Mehlich, 1984). The solution was shaken for 5 minutes and left to stand for 10 minutes before being centrifuged. The samples were then filtered through a Whatman No. 2 filter paper. Potassium standards

were prepared (see Appendix 2.1j) and the blanks were prepared excluding the sample. The absorbance of the samples and blanks were determined by the atomic adsorption spectrophotometer at 766 nm and the concentration of the samples were derived from the standard curve after subtracting the mean value of the blanks (see Appendix 2.1j & 2.2d).

2.5.5 Methods for total phosphorus of crop residues

In the UK, the extraction procedure was similar to that of total potassium (section 2.5.3). Dry combustion was used to extract phosphorus from the wheat straw and grass/clover samples. Hydrochloric acid was used to dissolve the soluble minerals in the ash and later diluted to 50 mL before filtering through Whatman No. 4 filter paper (see Appendix 2.1f). 2 mL of the blank and each sample were mixed with 5 mL of 5 M hydrochloric acid and 5 mL of ammonium molybdate-ammonium metavanadate reagent before diluting to 50 mL with deionised water. This was left to stand for 30 minutes. Phosphorus was determined by atomic absorption spectrophotometer (NSRI/AL/SOP 19/Version 1) and the concentration was determined at 400 nm (NSRI/AL/SOP E4) (see Appendix 2.1k & 2.2e).

For Bunda, the extraction for phosphorus was done exactly as for total N (see Section 2.5.2). 1 mL of phosphorus standards and samples were used for this analysis. These were mixed with 4.0 mL ascorbic acid solution and 3.0 mL of molybdate reagents (made of ammonium molybdate, antimony sodium tartarate and sulphuric acid) and left to stand for 1 hr to fully develop colour (Anderson & Ingram, 1993). The absorbance of the standards and samples were measured colorimetrically at 880 nm and sample phosphorus concentration was determined from the standard curve (see Appendix 2.1l).

2.5.6 Methods for phosphate-P in the soil and compost

Fifty millilitres of sodium bicarbonate solution ($NaHCO_3$) was used to extract P from 2.5 g of air dried soil (< 2 mm). The samples were shaken for 30 minutes and filtered through a Whatman No. 2 filter paper (see Appendix 2.1m). The filtrate was used for the

determination of P spectrophotometrically at 880 nm (MAFF, 1986; NSRI/AL/SOP 15/Version 1). P extraction from compost was done using $CaCl_2$/DTPA (CAT) solution (BS EN 13651:2001). This was done in an extraction volume ratio of 1:5. The extracted samples were shaken for 1 hr, and filtered through a Whatman No.2 filter paper. Phosphate-P determination was done by an automated ascorbic acid reduction method. The full procedure is described in Appendix 2.1i & 2.2f.

$NaHCO_3$ (0.5 M) was used for extracting P from compost made in Malawi (Anderson & Ingram, 1993). 2.5 ± 0.01 g compost was extracted by 50 mL of extracting solution, shaken for 30 minutes, and filtered through a Whatman No. 42 filter paper and the absorbance was determined by spectrophotometry at 880 nm after colour development for 1 hr (Appendix 2.1n).

2.5.7 Methods for mineral nitrogen (TON, NH_4-N and NO_3-N) in the soil and compost

The compost samples for the mineral N were extracted immediately or refrigerated to arrest microbial activity (Cambardella *et al.,* 2003). $CaCl_2$/DTPA (CAT) solution was used to extract the compost for NH_4-N and TON for analysis (BS EN 13651:2001). Extraction was done in a volume ratio of 1:5. The extracted samples were shaken for 1 hr and then filtered through a Whatman No. 2 filter paper. NH_4-N was determined by an automated phenate method (NSRI/AL/SOP8) and TON was determined by an automated hydrazine reduction method (NSRI/AL/SOP7). The procedure is described in Appendix 2.1i and the principle in Appendix 2.2g.

For moist soil, 2 M KCl was used for extraction of TON and NH_4-N (Appendix 2.1p). Twenty grams of moist soil was mixed with 100 mL of 2 M KCl and shaken for 2 hrs before filtering through a Whatman No. 4 filter paper (MAFF, 1986; NSRI/AL/SOP 13/Version 1). Samples were stored in the refrigerator. Analysis for NH_4-N and TON was determined as described for compost.

In Malawi, K_2SO_4 (0.5 M) was used for extracting NO_3-N from compost. Fresh compost (10.00 ± 0.01 g) was shaken in 20 mL of extractant for 30 minutes and centrifuged. 0.5 mL of the sample and standards (see Appendix 2.1q) were mixed with 1.0 mL of salicylic acid ($C_6H_4(OH)CO_2H$) and left to stand for 30 minutes followed by the addition of 10.0 mL of NaOH before they were left to stand for 1 hr for colour development (Anderson & Ingram, 1993). The samples and standards were analysed colorimetrically at 410 nm. The concentration of NO_3-N was derived from the standard graphs after subtracting the blank mean values (Appendix 2.1q). For NH_4-N, 3.00 ± 0.01 g sample was put into a plastic centrifuge tube and 30 mL of 2 M KCl was added, and shaken for 30 minutes. The mixture was centrifuged before 0.5 mL of the sample was pipetted into vials for analysis. 5 mL of the standards N1 and 5 mL of N2 were added to the sample and left for the colour development before analysis at 655 nm (see Appendix 2.1e for details of N1 and N2 and analysis). Concentration of the samples was derived from a standard curve.

2.5.8 Methods for cation exchange capacity (CEC) of the soil

Five grams of air dry soil (< 2 mm) were treated with 200 mL buffered $BaCl_2$ reagent (triethanolamine and 2 N $BaCl_2$). The mixture was centrifuged, followed by removal of supernatant and additional of 200 mL of distilled water to break up the cake by shaking. 100 mL of $MgSO_4$ (0.05 N) was added, shaken for 2 hrs, centrifuged and decanted supernatant liquid into flask. 5 mL of this solution was taken, mixed with 6 drops of 2 N NH_4OH and 2 drops of the indicator. The excess magnesium in this was determined by titration using EDTA, and CEC was determined (see Appendix 2.1r & 2.2h).

2.5.9 Methods for pH of the soil and compost

The pH of the soil and compost was determined in an aqueous solution. For soil this was done on a soil/water ratio of 1:5 (m/m). The samples were shaken for 1 hr at room temperature and then allowed to settle for 5 to 10 minutes before taking measurements. For the compost samples, extraction was done in a ratio of 1:5 (v/v). The solution was shaken for 1 hr on the shaking machine at 22^{o}C ± 3^{o}C before determining the pH (BS EN

13037:2000). The pH of both soil and compost was read using a pH meter. (see Appendix 2.1s & 2.2i)

2.6 Physical methods

A number of physical parameters were measured during composting and setting up of the mineralization and maize establishment studies (Table 2.11). The temperature of the composting systems was monitored to understand the composting process in each system as microbial activity generates heat. The moisture of the compost and soil was monitored in order to be able to establish the need to water the compost or soil to desired moisture content ideal for microbial activities. The moisture content of the compost or soil was also important in computation of the mineral N of the material as well as the biomass of the maize plants. In order to classify the soil used for mineralization and maize establishment experiments, the soil particle size was determined (see Table 2.5 & 2.8). Other parameters such as plant base diameter, leaf length and breadth, leaf area, plant height, and plant biomass were determined so as to monitor and compare the maize plant growth characteristics.

Table 2.11 The physical parameters measured during composting, mineralization and maize establishment experiments in the United Kingdom and Malawi

Parameter	UK/Malawi	Material	Determination
Temperature	UK	Compost	Thermistors
	Malawi	Compost	Thermometer
Moisture	UK	a. Wheat straw	Gravimetrically
		b. Grass/clover	
		c. Soil	
		d. Compost	
	Malawi	a. Maize straw	Gravimetrically
		b. Bean residue	
		c. Soil	
		d. compost	
Soil particle size	UK	Soil	Pipette method
Plant biomass	UK	Maize plant	Gravimetrically
Base diameter	UK	Maize plant	Digital vernier caliper
Leaf length, breadth & plant height	UK	Maize plant	Metre rule
Leaf area	UK	Maize leaf	WinDIAS Software

2.6.1 Methods for measuring temperature of the compost

Temperature sensors were constructed to monitor the thermal regime of the different compost heaps (Appendix 2.2j). Type EC95 thermistors of 2.4 mm diameter (temperature range 0 to 70 ± 0.1^{o}C), were inserted into plastic tubes to insert them into the compost heaps in the UK experiments easily. Each sensor was calibrated individually against a laboratory calibrated temperature sensor before their insertion into the heaps. The probes were inserted at three positions in the compost heap, 20 cm from the top surface, in the middle of the heap and 20 cm from the bottom. The thermistors were logged at an hourly interval using a Delta-T data logger. Monitoring of temperature for the compost heaps at Bunda was logged manually using a commercially available T-Shaped thermometer (HANNA Instruments, UK) with a temperature range of -50 to 220 ± 0.3^{o}C. This was measured at similar positions as in the UK experiments.

2.6.2 Methods for measuring moisture content of the crop residue, soil and compost

Moisture values were determined gravimetrically. Moisture content of soil was measured by weighing 5 g moist soil into a metal container. The samples were left in the oven set at 105°C for 48 hrs (Rowell, 1994). The samples were allowed to cool in a dessicator before re-weighing. Plant samples were homogenised and dried in the oven at 105^{o}C for 24 hrs (Shaw *et al.* 1999). Similarly, the moisture content of the compost was determined gravimetrically, when dried for 48 hrs.

The difference in the mass of the samples before and after oven drying determined the water content. Results were recorded as a percentage of the dry solid mass.

2.6.3 Method for measuring plant biomass

The fresh plants were chopped into 2 ± 0.5 cm pieces and put in metal containers and their fresh weights recorded. The samples were dried in the oven at 105^{o}C for 24 hrs. The plant biomass on a dry basis was determined by subtracting the moisture content.

2.6.4 Method for measuring particle size analysis of the soil

Particle size analysis was determined using the pipette method (BS 1377:1990; Avery & Bascomb, 1982). The procedure used 10 g of air-dry soil (< 2 mm) where 10 mL of H_2O_2 was added to destroy organic matter. This was followed by heating at 90^{o}C for 1 hr, centrifuged for 15 minutes at 2000 rpm and dispersion of the soil particles by adding 20 mL of Calgon (Sodium hexametaphosphate). Wet sieving through a 63 μm sieve followed, after which the sieved contents were dried at 105^{o}C for 4 hrs and the dry sample sieved (through 600, 212, 63 μm and receiver) for 15 minutes on a sieve shaker representing the sand fractions *i.e.* coarse sand (CS), > 600 μm; medium sand (MS), 600-212 μm and fine sand (FS), 212-63 μm.

The residue on the receiver was made up to 500 mL by adding distilled water in a 500 mL cylinder and left in a water bath with a constant temperature of 25^{o}C until the equilibrium temperature was reached within the sample. A sample was collected at 10 cm depth using a 25 mL pipette after mixing thoroughly the solution by hand stirrer for 30 seconds. Based on the sedimentation theory, described by Stoke's law, the oven dried content of this sample represented the < 63 μm fraction. The remaining contents were mixed and allowed to sediment and a sample was withdrawn from the depth of 9 cm using 25 mL pipette after approximately 6 hrs. The oven dried contents of this sample represented fractions of < 2 μm. The Soil Survey of England and Wales textural triangle was used to determine the textural class of the soils (see Appendix 2.1t & 2.2k).

2.6.5 Method for measuring maize plant base diameter

The plant base diameter was measure by a digital vernier calliper (Sealey, UK). The measurements were made 1 cm above the soil surface in millimetres to ± 0.005 mm.

2.6.6 Methods used for measuring maize leaf length, leaf breadth and plant height

The leaf length, leaf breadth and plant height were all measured by the use of a meter rule to ± 0.5 mm. The length of the leaf was measured from the maize stalk (leaf attachment) to the tip of the leaf where as the leaf breadth was measured in the middle of the leaf. The plant height was measured from the soil surface to the position of the last fully developed leaf.

2.6.7 Method used for measuring maize leaf area

The area of the leaf was determined by the use of WinDIAS Software. A leaf was illuminated on a light-box. The image of the leaf was captured by a video camera (Delta-T Devices, UK). The values of the measurements were computed by the WinDIAS software (Delta-T Devices, UK). Calibration of the measurements was made using a ruler.

2.7 Biological methods

Two parameters were measured, cress seed germination and carbon dioxide evolution during composting (Table 2.12). CO_2 was measured to monitor the microbial activity, whilst cress seed germination was determined to assess the toxicity level of the composting material with time of composting.

Table 2.12 The biological parameters measured during composting and mineralization experiments in the United Kingdom and Malawi

Parameter	UK/Malawi	Material	Extractant	Determination
Carbon dioxide evolution	Malawi	Compost	Sodium hydroxide/Barium carbonate	Titration by HCl
Cress seed germination	UK/Malawi	Compost	Water	Direct sowing in compost

2.7.1 Method used for measuring carbon dioxide (CO_2) evolution from compost

The microbial activities of the compost heap and the depletion of carbon from the system marking the maturity and quality of the compost were assessed by CO_2 evolution assays (Appendix 2.2m). Basal respiration through a titration method was measured in Malawi where 10.0 ± 0.01 g moist compost samples were put in 50 mL beakers and the beakers were put in the 1 L plastic bottles which contained 20 mL of NaOH solution. The bottles were closed tightly and incubated for 4 hrs at 22^{o}C ± 3^{o}C. Two mL of barium chloride solution ($BaCl_2$) was added to the bottles to precipitate the absorbed CO_2 to barium carbonate ($BaCO_3$). At least 3-4 drops of indicator were added and titration was done on the remaining NaOH with HCl (Schinner *et al.,* 1996). A control was prepared without the compost. The respiration rate was derived from the amount of the HCl consumed during titration (see Appendix 2.1u). Since respiratory activities are influenced by soil water content (Wardle & Parkinson, 1990; Wilson & Griffin, 1975), the influence of

water on the respiration measurements was avoided by adjusting the moisture content of all samples to 60% of water holding capacity based on mass basis.

2.7.2 Method used for assessing cress seed germination

A direct seed test was used (Warman, 1999). Approximately 15 mL of compost was placed in a 9 cm diameter Petri dish and deionized water applied. A Whatman No. 4 filter paper was used in the control. Fifteen seeds of cress (*Lepidium sativum* L.) were placed directly into the compost or on the filter paper and were incubated at 20 ± 2^{o}C for 10 days with at least 8-10 hrs of light per day (Appendix 2.2n). Percentage germination was assessed by physically counting the seeds germinated in the control and the sample and the percentage was based on the total number of the seedlings germinated in the control. This assessement was done for the composting process on each sampling day to determine when the compost had less toxic substances.

2.8 Calculations and published critical values for compost maturity/stability assessment

2.8.1 Cress seed tests

Germination tests as an indicator of compost maturity were first proposed by Zucconi *et al*. 1981. Since then this has attracted a lot of controversy. Modifications have been made to the procedure due to problems of repeatability. Contrary to the compost solution extraction proposed by Zucconi *et al.,* 1981, other researchers have proposed seed soaks and direct seed sowing into the compost (Gajdos, 1997; Inbar *et al.,* 1993; Warman, 1999). Other plant species have also been proposed apart from the cress seed. These include ryegrass (*Lolieum perenne*) (Inbar *et al.,* 1993; Gajdos, 1997), Chinese cabbage (*Brassica rapa* L.) (Warman and Termeer, 1996) and barley (*Hordeum vulgare*) (Pascual *et al.,* 1997). Nonetheless, no single procedure is universally accepted since results vary with procedure and type of compost used. Values above ≥ 60% germination suggest fewer toxic compounds exist in the compost.

2.8.2 Carbon to nitrogen ratio (C:N ratio)

C:N ratio of the compost is derived by diving total carbon by total nitrogen both of which are determined as a percentage of the test material mass. This is an indicator of the substrate status of the material and its potential effect on the microbial community when it is incorporated into the soil. When compost of high C:N ratio is applied to the soil, it induces immobilization of N since micro-organisms use soil-N in order to mineralize the compost. A C:N ratio of less than 12 of composted material, which had initial C:N ratio of 30, indicates maturity. It is generally assumed that stable, mature compost should have a total C:N of less than 20 (Golueke, 1977). It is argued that in well humified field soils, the C:N ratio is close to 10 and the addition of materials with C:N ratio below 15 may not alter microbiological equilibrium of the soil (Allison, 1973).

2.8.3 NH_4-N to NO_3-N ratio

The ideal situation is to retain more NO_3-N in the compost as this is stable and preferred by the plants during their active growth stages. Earlier research established an NH_4^+/NO_3^- ratio of < 0.16 and an NH_4-N content of < 0.04% to represent mature compost (Bernal *et. al.,* 1998; Pare *et al.,* 1997). It is indicated that at these values, the compost is stable and not toxic to plant growth and would supply some nitrogen to the plant.

2.8.4 CO_2 evolution rates

An indication of compost stability can be achieved using CO_2 evolution. It is suggested that evolution of CO_2 of < 1 mg CO_2-C g^{-1} dwt. d^{-1} indicates stability (Thompson *et al.,* 2003; Wang *et al.,* 2004).

2.9 Statistical data analysis

The data from the different parameters measured in the composting, mineralization and maize establishment experiments were analysed by Genstat – Windows Software Package (Release 8.1). An exception to this was the TON and NH_4-N data (from the United Kingdom compost) which were analyzed using Statistica 7 (Windows Software). Analysis of variance (ANOVA) was used in these tests and the separation of means of the treatments was done by looking at the least significant difference (LSD) of the means at $p = 0.05$.

CHAPTER THREE: United Kingdom - Silsoe experimental results

3.1. Introduction

In Chapter 1, three sets of experiments were outlined as follows: i) Composting experiments – designed to investigate the Changu and Chimato composting processes and systems; ii) Post-compost mineralization experiments – investigating the release dynamics of the nutrients from the compost mixed with a standard soil; and iii) Maize establishment studies – investigating the influence of the resultant composts on establishment and plant growth. This chapter further explores the emerging issues from the first set of the experiments conducted in the United Kingdom.

Composting processes are governed by a number of factors (moisture, oxygenation, substrate, temperature, particle size as discussed in Chapter 1) and these are to an extent modulated by the composting system. Changu and Chimato systems are constructed and managed differently meaning that the above mentioned factors vary between them and consequently control the microbial decomposition rates and patterns differently. Understanding the composting processes undertaken by these two systems is a major step to devising an optimization strategy for these systems.

The principal aim in composting is to create a conducive environment for micro-organisms to mineralize the organic materials present in the feedstock. This can be achieved by deliberately mixing different organic materials to contain enough carbon and nitrogen required to support microbial activities, and controlling the moisture and oxygen is then vital to regulate microbial activity. Oxygenation of the material can be improved by controlling the particle size (based on substrate), turning the material frequently, creating air passages or forced aeration. For efficient composting it is necessary to avoid drying of the material or saturation conditions (which will induce anaerobic respiration). When all factors are properly controlled, composting will proceed, and at smallholder scale it can be monitored by the "feel" of the increase in compost temperature. Under composting, the work here attempted to test Hypothesis 1 (see Chapter 1) that the type

and quality of feedstock determines the behaviour of the composting system; and Hypothesis 3 (see Chapter 1) that systems differ in their influence on composting processes and the quality of end-products.

Composting for crop production aims at retaining more nutrients in the compost to potentially benefit the plant. This is associated with the feedstock and the composting process, prescribed by system. Therefore, post-compost mineralization characteristics relate to the composting systems. The desired situation is to create conditions for production of compost which can appropriately release nutrients for plant uptake. This chapter explores the mineralization of composts from Changu and Chimato systems and their nutrient release as influenced by the forms of nutrients as per Hypothesis 4 (in Chapter 1). It further tests the response of the plants to compost from the two systems based on Hypothesis 5 (see Chapter 1).

The methodology, treatments and sampling procedures for the three experiments are presented in Chapter 2. The data from different parameters measured during the experiments were analysed by Genstat Release 8.1 for Windows (software). The separation of the means of treatments was by LSD of the means at $p = 0.05$. Only TON and NH_4-N data from the composting experiments were analysed by Statistica 7 software due to the capacity of this software to handle transformed data. The results for different parameters measured during different experiments are covered in the following sections. Appendix 3 is presented in Annex on a CD-ROM.

3.2. Composting experiments

The feedstock used for the composting experiments comprised wheat straw and grass/clover (Table 3.1). The grass/clover contained higher amounts of N, total P and total K compared to the wheat straw, but had similar carbon contents. This indicates that grass/clover was the major contributor of the initial nutrients present in the composting material used in this study.

Table 3.1 Characteristics of the feedstock used for composting in the United Kingdom

Feedstock Characteristics				
Material	*N %*	*C %*	*Total P (mg/kg)*	*Total K (mg/kg)*
Wheat straw	0.74	43.7	251	8992
Grass/clover	3.37	42.4	2583	21321

3.2.1 Results and discussion

3.2.1.1 Temperature

Temperature data were converted into the length (in days) of three phases: 'mesophilic', 'thermophilic' and 'maturation', based on arbitrary minimum temperature values of 25^{o}C, 45^{o}C and ambient air temperature respectively before statistical analysis in order to make the results comparable with other researchers (after Miller, 1996; Epstein, 1997).

The temperature data obtained during the composting of straw and grass/clover using Changu and Chimato systems by thermistors (see Chapter 2, Section 2.6.1) showed typical temperature profiles for composting of this type (Fig. 3.1). Treatments with low initial C:N ratios reached the highest temperatures and longer active composting periods than those with high initial C:N ratios (Fig. 3.1) Treatments with C:N ratios 20:1; 25:1; and 30:1 attained temperatures of 60, 59 and 58^{o}C respectively, whereas the control only reached 43^{o}C. There was a big change of the ambient temperature from 30^{o}C to 10^{o}C within 100 day period in this experiment. This was due to the fact that the experiments run between August and December, 2004. This meant that the experiment was run partly in summer with higher temperatures, partly in autumn and partly in winter when temperatures were low hence the big change in the ambient temperatures obtained.

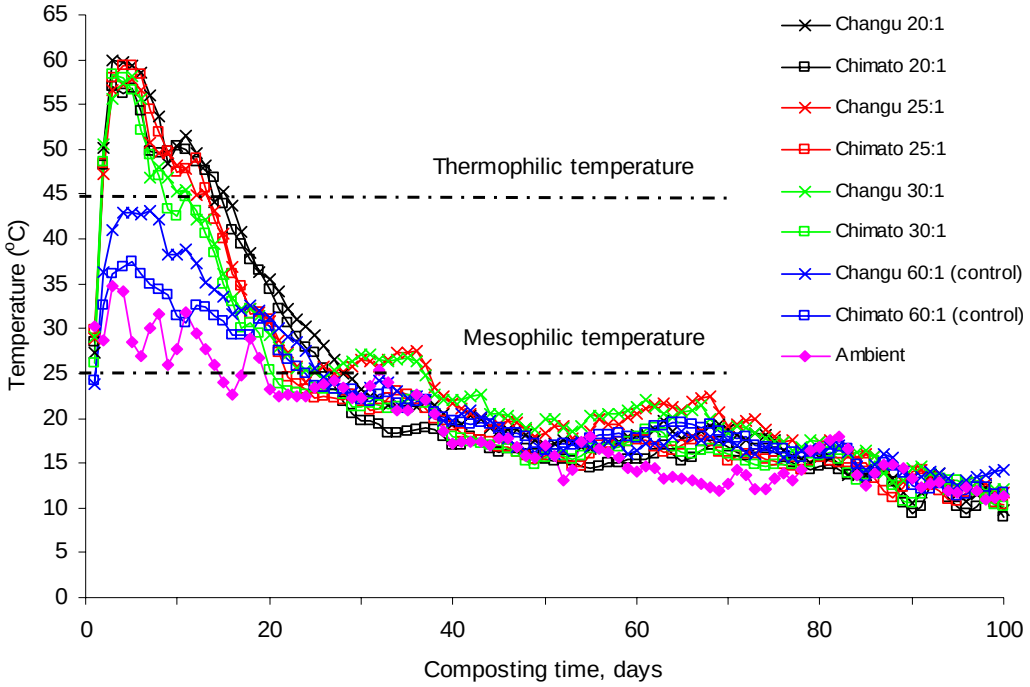

Figure 3.1 Mean temperature profiles for different initial C:N ratio treatments of compost during the composting period using Changu and Chimato systems. The temperature values are means of the temperature measured at three positions (depths) in the heap. Mesophilic phase represents any temperature between 25°C and 45°C and that is above ambient temperature while thermophilic phase represent those temperatures above 45°C. The compost process reached maturation phase when the temperatures reverted to ambient temperatures.

Mesophilic, thermophilic and maturation phases were observed in all the treatments except in the control where thermophilic phase was absent (Fig. 3.1 and Table 3.2). There was rapid increase of the microbial activity when the composting process was initiated. In all the treatments except the control, the mesophilic stage was attained within the first day of compost process initiation (second day in the control). The mesophilic stage lasted only 2 to 3 days before reaching thermophilic levels. The second phase of mesophilic temperature ranges were experienced by the treatments from Day 10 onwards for another 13 days before reverting to ambient temperatures.

Table 3.2 Length of mesophilic, thermophilic and maturation phases (in days, d) during the 112 day experimental period for four initial C:N ratios in the Changu and Chimato composting systems (UK experiment)

System	*Initial C:N*	*Mean length of phase, d*		
		Mesophilic	*Thermophilic*	*Maturation*
Changu	20:1	12.6	11.4	88.0
	25:1	15.8	9.6	86.6
	30:1	16.4	8.6	87.0
	60:1	22.6	0.0	89.4
Chimato	20:1	10.2	12.4	89.4
	25:1	12.4	10.7	88.9
	30:1	14.3	8.0	89.7
	60:1	20.4	0.0	91.6

The length of the maturation phase is the difference between the total 112 d period and the sum of the mean meso- and thermo-philic phases. Mesophilic phase represents any temperature between 25^{o}C and 45^{o}C and that is above ambient temperature while thermophilic phase represent those temperatures above 45^{o}C. The compost process reached maturation phase when the temperatures reverted to ambient temperatures. ANOVA determined that there was not a significant interaction between compost system and initial C:N for either of the mesophilic and thermophilic phase length variables.

Table 3.2 illustrates that as the C:N ratio of the substrate increased, the thermophilic phase length decreased while the mesophilic phase length increased. This is due to the increased amount of easily mineralizable substrate available at low C:N ratios which supports high microbial activities contrary to the high C:N ratios. But since the analysis of variance for thermophilic and mesophilic phases indicates that no significant interaction was obtained between compost system and initial C:N ratio (compost-mix), therefore the influence of C:N ratio on the composting temperature did not depend on the system used.

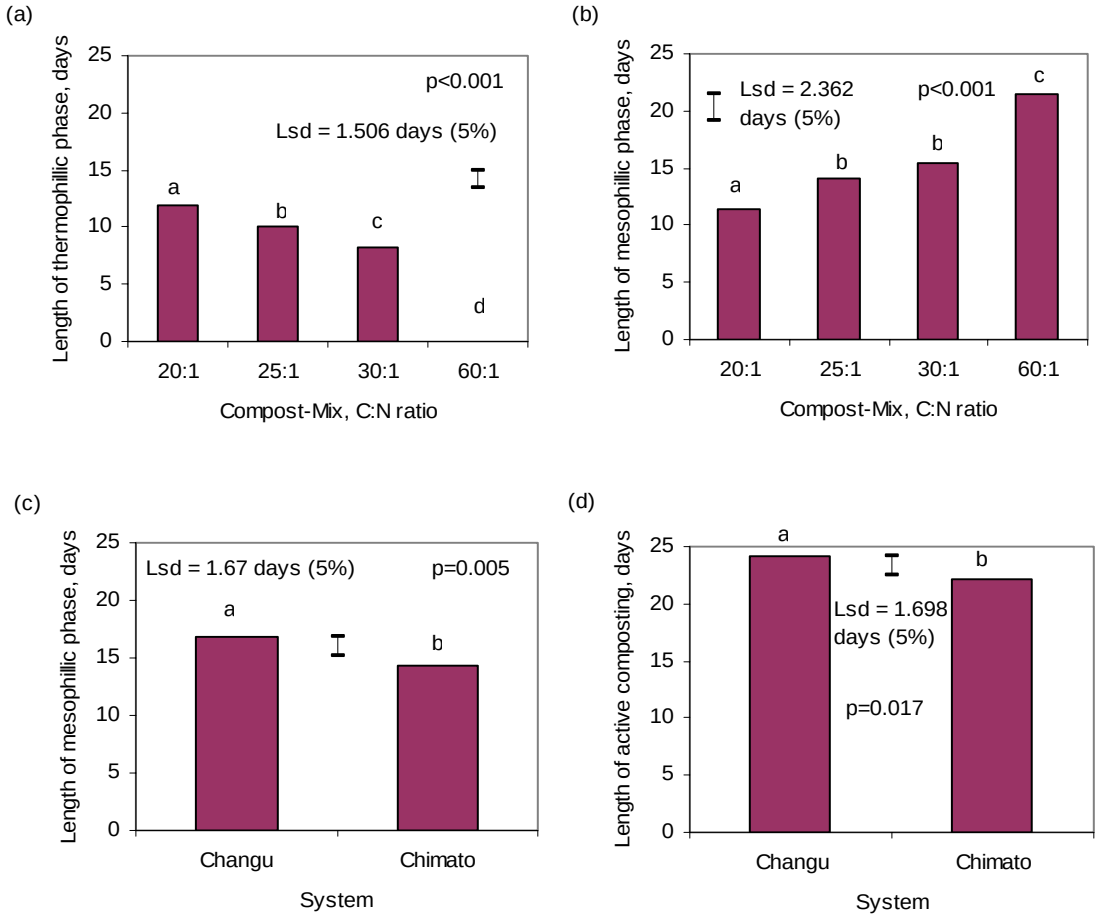

Figure 3.2 Effect of compost-mix, initial C:N ratio on the length of (a) thermophilic phase and (b) mesophilic phase of composting (n = 18) and effect of system on the length of (c) mesophilic phase and (d) active composting (n = 36); error bars represent LSD at 5%; same letter denotes that the means are not significantly different.

Significant differences were observed in the length of thermophilic phase among the initial compost mix ratios (Fig. 3.2a). The lower C:N ratios had the longest period compared to the higher C:N ratio treatments, due to the high levels of easily mineralizable substrates and presence of easily accessible N which supported and sustained the high microbial activities. The data partly supports the proposed Hypothesis 1 as stated in Chapter 1.

The opposite was true when the effect of compost-mix on the length of the mesophilic phase was analysed (Fig. 3.2b). The control (C:N 60:1) had significantly longer mesophilic phase than other treatments. The control had 22 days of mesophilic temperature while treatments with C:N 20:1 had 11 days. This was because there was no thermophilic phase in the control, consequently all the substrate present was used to support mesophiles, extending the period of mesophilic phase.

Analysing for the effect of composting system indicated that Changu systems had higher temperatures and longer mesophilic and active composting periods (Figure 3.2c & d). The Changu treatments had a significantly longer mesophilic phase and significantly longer active composting duration than Chimato treatments. The turning and watering of Changu systems improved the oxygen and moisture status of the heaps which increased the microbial activity especially where substrate was abundant and easily mineralizable *as per* Hypothesis 3 (Chapter 1).

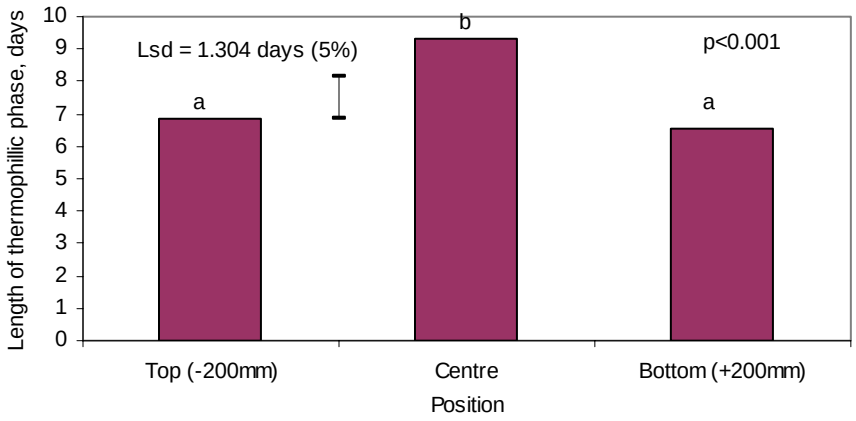

Figure 3.3 Effect of position within compost heap on the length of thermophilic phase; error bar represent LSD at 5%; same letter denotes that the means are not significantly different; n = 24.

With regard to position in the heap, the middle horizons of the compost heaps had significantly longer thermophilic temperatures than the upper or lower horizons, which had similar temperatures in the two composting systems (Fig. 3.3). The higher temperatures and longer thermophilic phase in the middle is likely to have arisen since

the middle is insulated by the feedstock mass from the top and the bottom promoting microbial activity.

3.2.1.2 C:N ratio

The carbon concentration of different treatments, expressed as a percentage, showed a declining tendency over time of composting. This decline was consistent in both composting systems. Comparison of the data obtained between Day 14 and Day 112 of composting indicates that carbon concentration changed from 16% and 16.2% to 11.2% and 10.1 % for Changu and Chimato systems respectively for treatments with initial C:N of 20:1 (Fig. 3.4a). This is a decline of 4.76% w/w and 6.11% w/w C over a period of 98 days. The decline was greater where treatments with high C:N ratio (controls) was considered. The control which had C:N ratio of 60:1 had a decline of 4.78% w/w C for Changu systems and 10.1% w/w C for Chimato systems.

Similarly, the amount of nitrogen in the compost declined over time (Fig. 3.4b). The decline was greater in the treatments with low initial C:N ratio than those with high initial C:N ratio. For Chimato, the decline ranged from 0.25% w/w N for treatments with initial C:N of 20:1 to 0.09% w/w N for treatments with initial C:N of 30:1. An increase of 0.08% w/w N was observed in the control (Chimato 60:1). In Changu, the treatment with the lowest initial C:N had the least decline of 0.04% w/w N, but the general trend observed was similar to that of Chimato (Fig. 3.4b). The Chimato systems showed a greater nitrogen decline than Changu systems. But the decline in C:N ratio as a reflection of the changes in carbon and nitrogen was relatively greater in Changu than Chimato treatments (Fig. 3.5). The declining trend of nitrogen concentration in this research contradicts findings by Dresbøll and Thorup-Kristensen (2005) who observed a tendency where nitrogen of their treatments increased with time during composting of wheat straw. Nonetheless, the differential decline of C and N were reflected in the reduced C:N ratios attained during composting.

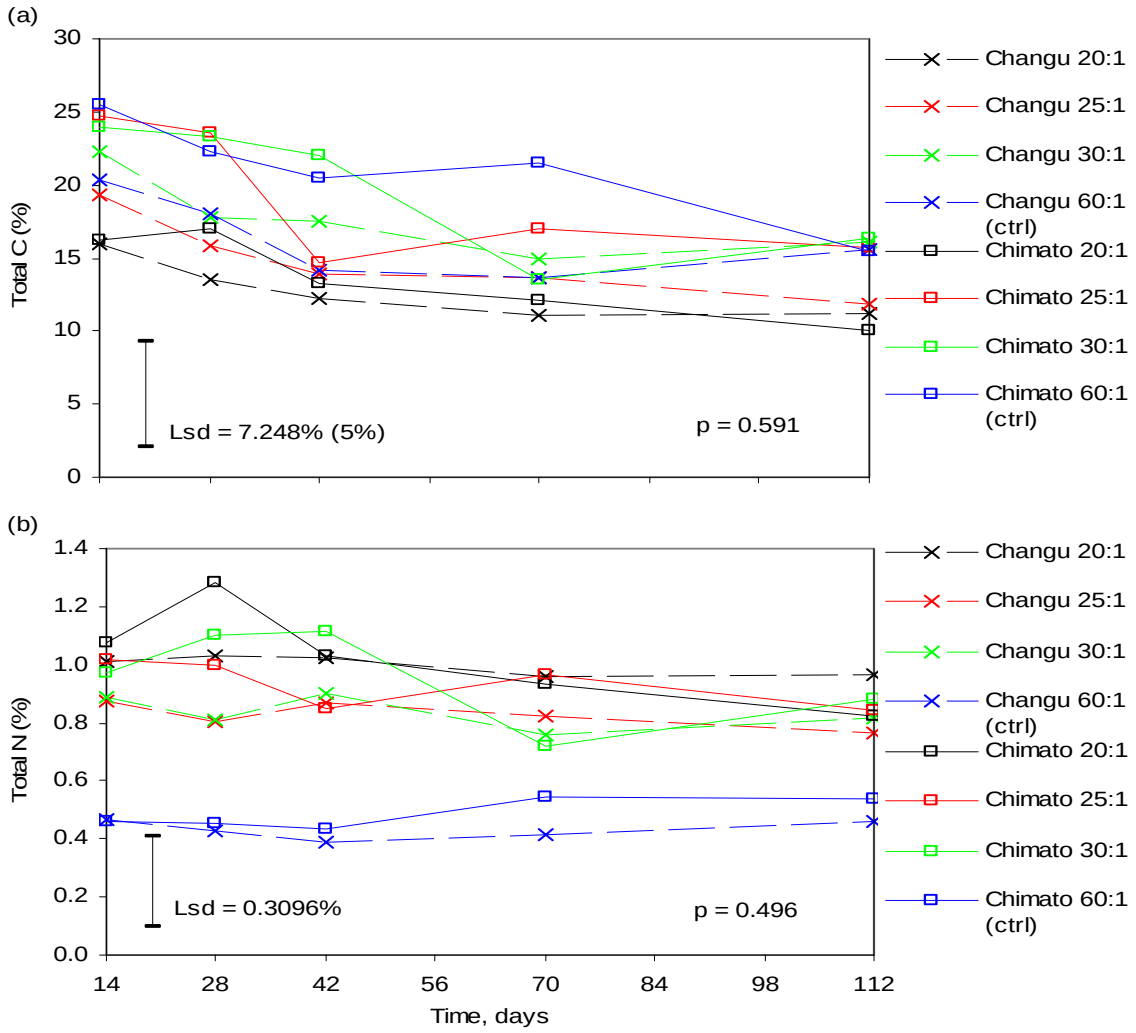

Figure 3.4 Changes of (a) total C (%) and (b) total N (%) for different treatments of initial C:N ratios in Changu and Chimato composting systems during composting of wheat straw and grass/clover; error bars represent LSD at 5%; ANOVA determined no significant interaction between compost system, initial C:N ratio and time for both total C and total N

Figure 3.5 shows a declining trend of C:N ratio with time across the treatments indicating that composting took place. The target for the C:N for different treatments was <15:1 to 20:1. The C:N ratio of the control remained much higher throughout the composting process than the other treatments. The lowest C:N ratio attained in the control over 112 days was 30:1 whereas for the other treatments, the lowest C:N ratio attained was 12:1. The decline in C:N ratio from Day 0 to Day 112 was greater in Changu than Chimato related treatments. There was a decline in C:N ratio of 41% for Changu 20:1 compared to

39% of a similar treatment under Chimato. Similarly, Changu 25:1 had a decline of 38% compared to 27% for Chimato 25:1. The exception to this scenario was Chimato 30:1 which indicated a higher C:N decline of 38% compared to 35% for Changu 30:1. The regular turning and watering procedures in Changu heaps, promoted increased microbial activities and organic matter breakdown hence the low C:N ratios obtained compared to Chimato systems.

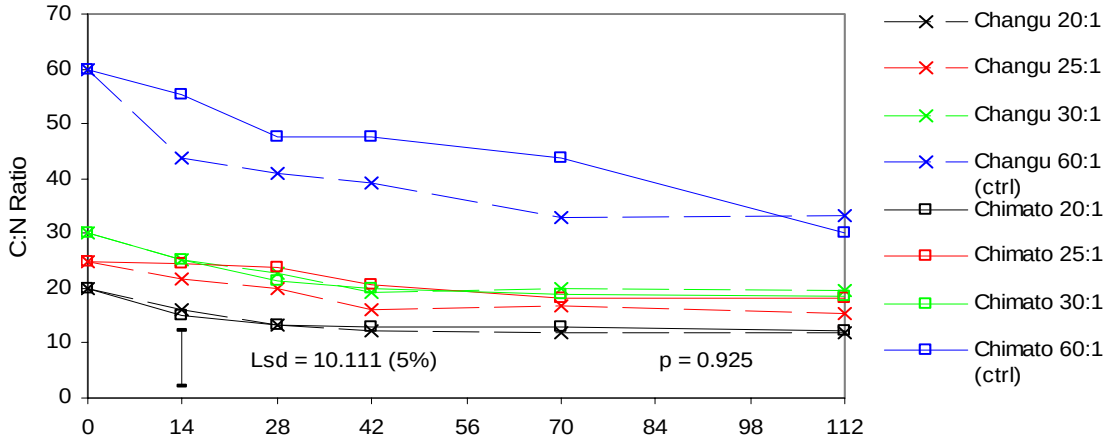

Figure 3.5 C:N ratio trends for different treatments of initial C:N ratios in Changu and Chimato composting systems during composting of wheat straw and grass/clover; error bar represent LSD at 5%; ANOVA established no significant interactions.

Comparably, the changes or decline in C:N ratio over time was greater in the control than the other treatments *i.e.* as high as 45% for Changu 60:1 and 50% for Chimato 60:1 (Fig. 3.5). This implies that the available carbon for microbial breakdown was rapidly used up during the first 28-42 days of the composting process in the main treatments compared to the control. The rate of C:N depletion slowed down in the main treatments due to limitation of mineralizable carbon which was not the case in the control. The rate of decomposition in the control was likely limited by the amount of nitrogen required for microbial multiplication and growth (see Fig. 3.4b). Significant differences were observed between initial C:N ratios where treatments with initial C:N 20:1 had lower final C:N ratio than those from initial C:N 25:1, 30:1 and 60:1 (Fig 3.6).

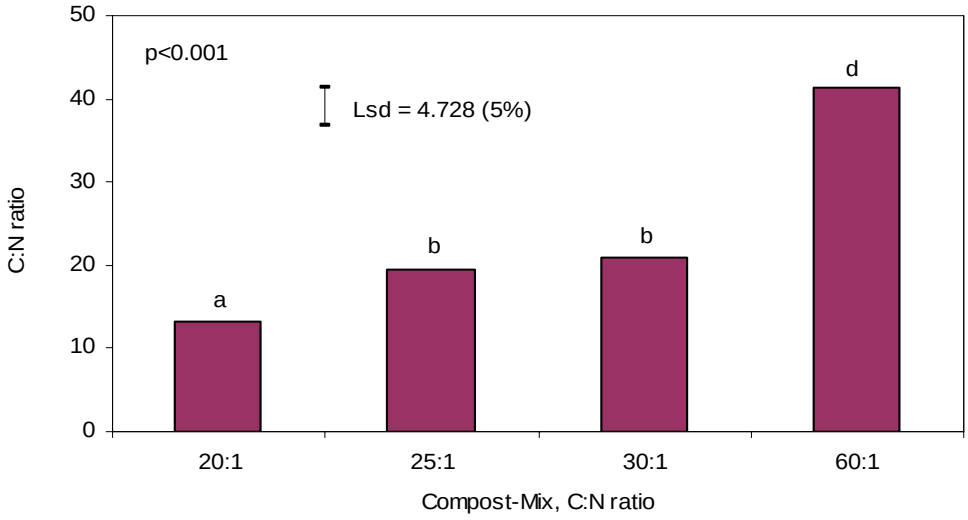

Figure 3.6 The final C:N ratio for initial C:N ratios of compost during the composting of wheat straw and grass/clover; error bar represent LSD at 5%; same letter denotes that the means are not significantly different; n = 60.

The resultant compost from treatments with initial C:N 60:1 (control) had a significantly greater C:N ratio than the other treatments despite experiencing the greater rate of composting, meaning that the initial C:N of 60:1 was too high for effective composting of substrates used in this experiment at smallholder scale. Thus, the lower the initial C:N, the lower the final C:N ratio attained, meaning that the final C:N of the compost depended on the initial C:N ratio. The low initial C:N ratios were associated with sufficient easily accessible substrate for microbes than the high C:N material which was limited by N contents. As for the system, the Changu system promoted the composting factors (oxygenation and moisture) which supported increased microbial activities compared to Chimato.

3.2.1.3 Mineral Nitrogen (N)

Mineral N was determined by measuring TON and NH_4-N. The data was normalized by applying a square-root transformation. The amount of TON in the compost ranged from as low as 0 mg/kg (undetectable) to as high as 819 mg/kg between Day 14 and 112 while

that of NH_4-N ranged from 0 to 901 mg/kg for the same period (Fig. 3.7a & b). Analysis for the interaction of system, compost-mix and time showed significant increase in TON with time in treatments with initial C:N ratio of 20:1; 25:1 and 30:1 in Changu while the differences were only observed in initial C:N ratio 20:1 and 25:1 in Chimato (Fig. 3.7a).

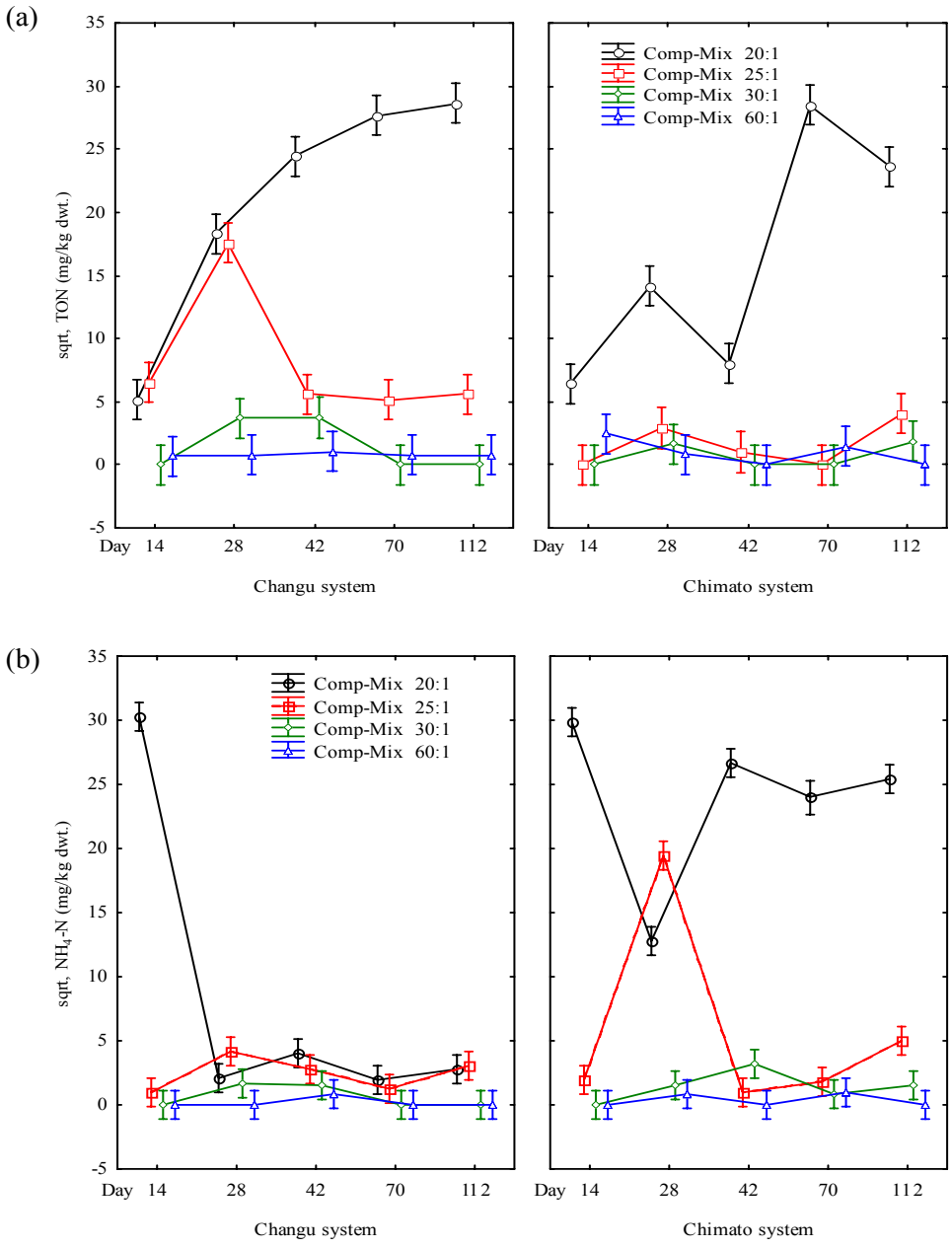

Figure 3.7 Amount of (a) TON and (b) NH_4-N in the two composting systems as influenced by the interaction of system, compost-mix (C:N ratio) and time of composting; error bars denote 95% confidence intervals (CI). The y-axis started at -5 to accommodate the error bars on low values.

Unlike TON, the concentrations of NH_4-N in the compost was consistently lower in Changu except on Day 14 for the treatment with initial C:N 20:1 when it had significantly higher concentrations of NH_4-N. On the other hand, in Chimato system, treatments with initial C:N ratio 20:1 and 25:1 had significantly higher concentrations of NH_4-N than the other treatments and the control (Fig. 3.7b). Treatment with initial C:N 20:1 consistently retained higher concentrations of NH_4-N throughout the duration of composting while treatments with initial C:N 25:1 had high NH_4-N on Days 28 and 112 only. The higher concentrations of TON and NH_4-N in the treatments with low initial C:N ratios could be due to high concentration of easily mineralizable N which promoted the mineralization process in the two systems.

It was observed that, the lower initial C:N ratio treatments were associated with higher concentrations of TON in both Changu (*i.e.* 20:1 & 25:1) and Chimato (*i.e.* 20:1) and higher concentrations of NH_4-N in Changu (*i.e.* 20:1) and Chimato *(i.e.* 20:1 & 25:1). This meant that most of the N in the treatments with high initial C:N ratios were used up by microbes and were not released throughout the composting period. With respect to higher concentrations of NH_4-N observed, Dresbøll and Thorup-Kristensen (2005) also observed an increase in NH_4-N contents during the first week of composting wheat straw and clover which declined later, but this was noted for as long as 6 weeks with additions of clover during composting. Arguably this is common during the active initial phase of microbial decomposition which results in elevation of pH due to assimilation of protons arising from the mineralization of organic N (Beck-Friis *et al.,* 2003). This meant treatments with C:N 20:1 and 25:1 had more organic N which facilitated this process in this study. The concentrations of N in these treatments are due to high amounts of grass/clover (feedstock) which had more N.

Considering the mean concentrations of TON and NH_4-N due to compost-mix and system interaction, significant differences were observed with initial C:N ratios of 20:1 and 25:1 in which case the Changu treatments had higher concentrations of TON than Chimato treatments and vice versa for NH_4-N (Fig. 3.8a & b).

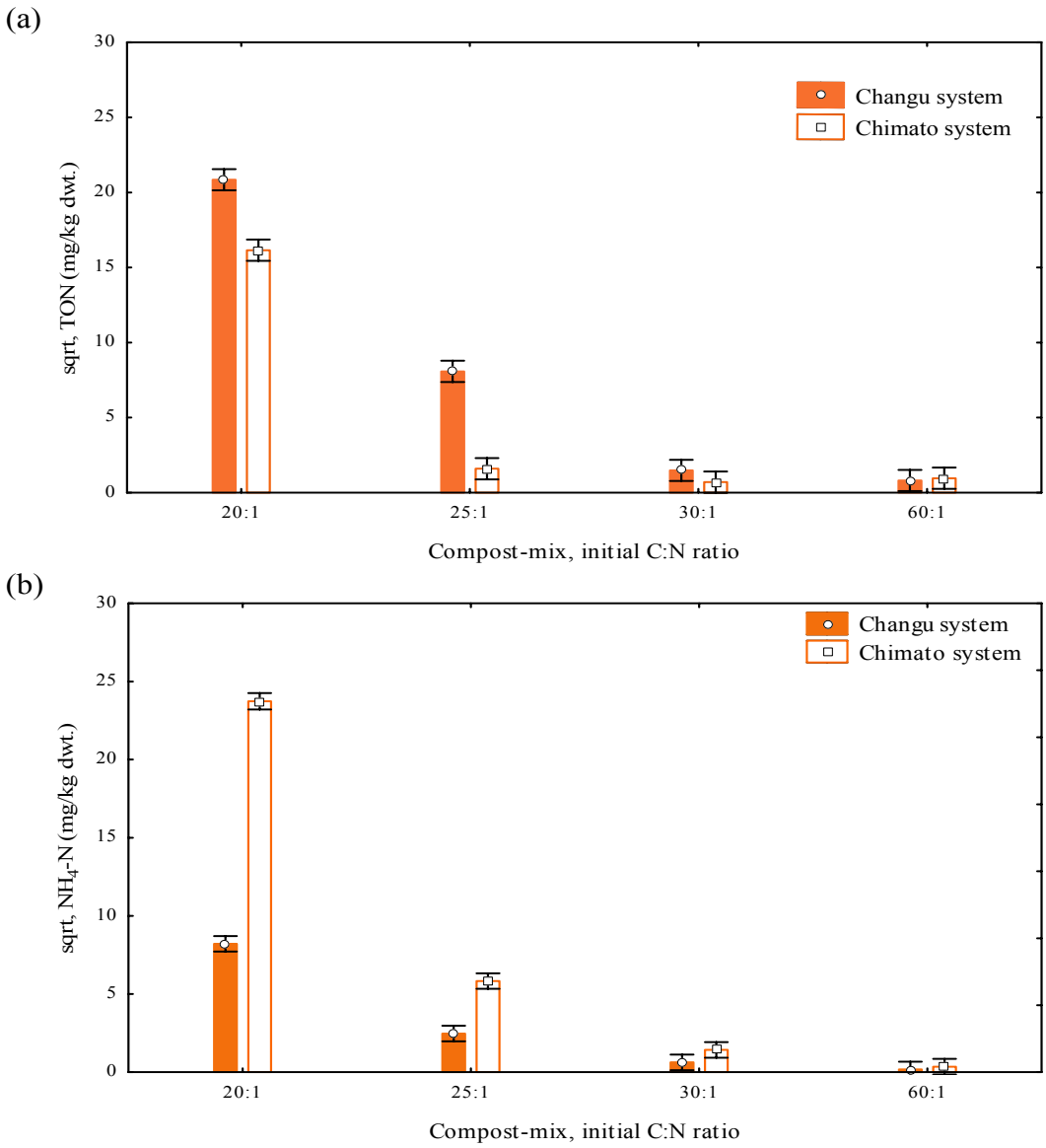

Figure 3.8 Mean concentration of (a) TON and (b) NH_4-N in the compost as influenced by the interaction of compost-mix and system during the 112 composting period; error bars denote 95% confidence intervals (CI); n = 30.

Considering the effect of system with time, the concentration of TON increased from Day 14 to Day 28, but declined between Day 28 and 112 in Changu system. Similarly, the concentration of TON increased from Day 14 to Day 28 in Chimato, but in this system it declined between Day 28 and 42 before it increased up to Day 112 (Fig. 3.9a). Significant differences were observed between the concentrations of TON for Changu and Chimato

systems on Day 28 and 42 only when Changu had more TON than Chimato. For both Changu and Chimato treatments, the peak of the TON emerged after the active composting period. This meant that, after active composting, is the time TON are released by the microbes and fixed to the compost matrix so that it can be preserved. This forms the bulk of the nitrogen which compost releases during post-compost mineralization (Maynard, 1994). For NH_4-N, Changu treatments had significantly lower contents of mean NH_4-N compared to Chimato systems from Day 28 to Day 112 (Fig. 3.9b). This is due to increased aeration which promoted the nitrification process, converting NH_4-N to TON than in Chimato. Generally Changu had low concentrations of NH_4-N compared to Chimato and the lower the initial C:N ratio, the higher the concentrations of NH_4-N (Fig. 3.10 & 3.11).

The Changu treatments had higher concentration of TON while Chimato had higher concentration of NH_4-N (Fig. 3.8 & Fig. 3.9) due to difference in aeration which affected the amount of oxygen available in the systems. This had implications on the ammonification and nitrification processes. The nitrification bacteria *Nitrosomonas* and *Nitrobacter* are obligate aerobes and cannot multiply or convert ammonia or nitrites in absence of oxygen. The turning process in Changu promoted the nitrification process due to increased amount of oxygen in contrast to Chimato, hence the higher concentration of TON in Changu and NH_4-N in Chimato. Furthermore, the mud coat in the Chimato systems protected the escape of ammonia gas increasing the concentration of NH_4-N in this system.

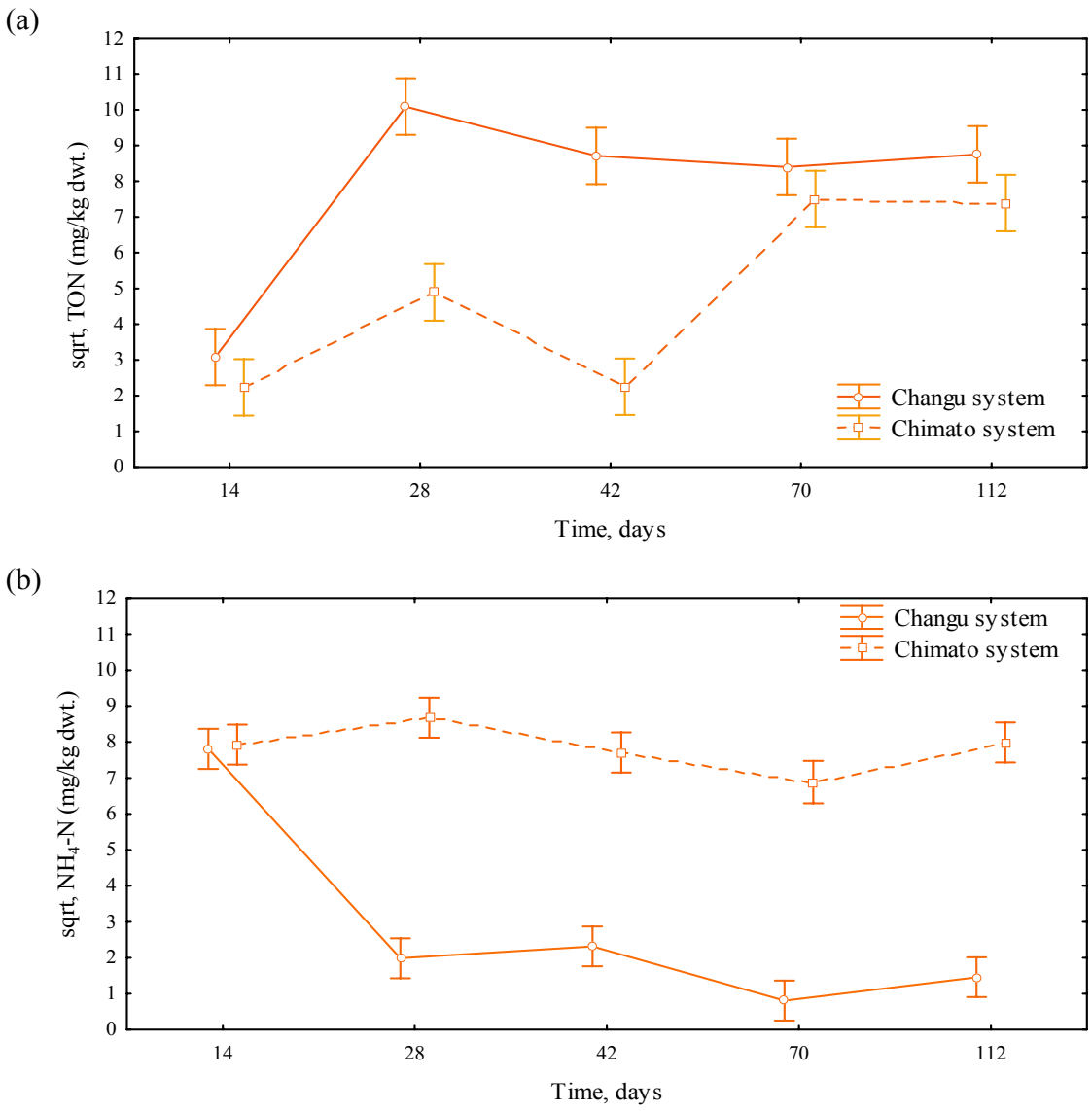

Figure 3.9 Amount of (a) TON and (b) NH_4-N in the compost as influenced by the interaction of time and system; error bars denote 95% confidence intervals (CI).

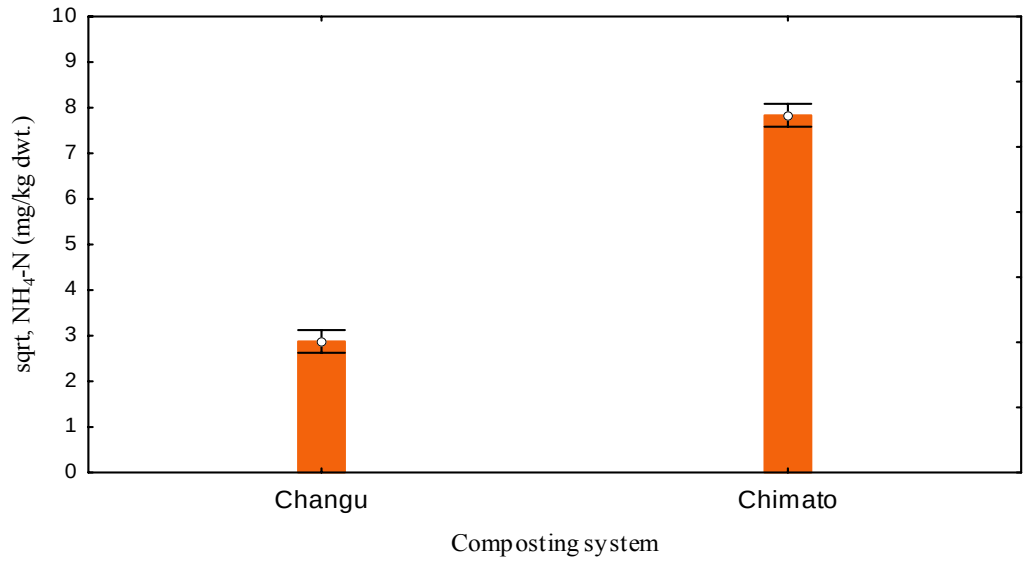

Figure 3.10 Mean concentration of NH_4-N in the compost as influenced by system during the 112 composting period; error bars denote 95% confidence intervals (CI); n = 60.

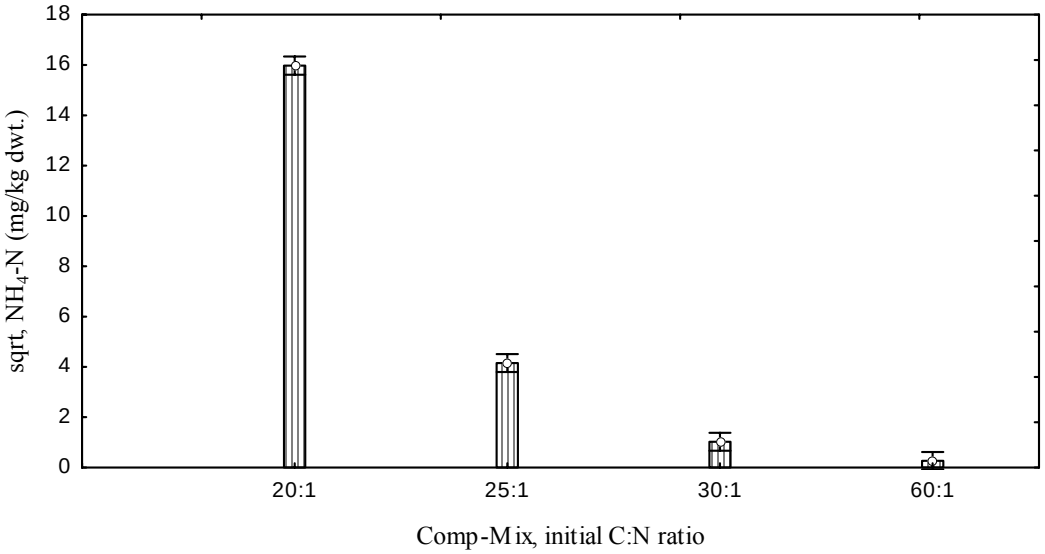

Figure 3.11 Mean concentration of NH_4-N in the compost as influenced by compost-mix during the 112 composting period; error bars denote 95% confidence intervals (CI); n = 30.

3.2.1.4 Potassium (extractable K) and phosphorus (Phosphate-P)

An example of the statistical analysis derived through Genstat Release 8.1 for Windows which has been used through out this study is presented below (Table 3.3). The significance of the tests run in this study was done at p = 0.05 (5% level) meaning that a factor was significant when the p value was less than 0.05. No direct effect was observed on the amount of extractable-K due to the initial C:N ratio (comp-mix) or system as indicated in Table 3.3 (*i.e*. p = 0.061 and 0.771 for initial C:N ratio and system respectively). The sampling day was significant *i.e.* p = 0.003 (Table 3.3 & Fig. 3.12 insert) indicating that the concentration of extractable-K changed with sampling time. Similarly, significant interactions were observed between system, initial C:N ratio and time *i.e*. p = 0.004 (Table 3.3 & Fig. 3.12). Significant differences were observed on Day 14 and 42. On Day 14, Changu treatments with initial C:N ratio of 20:1 and 30:1 had higher contents of extractable-K than Chimato 30:1 and Changu 60:1; and Changu 60:1 had lower extractable-K compared to Changu 25:1, Chimato 25:1 and Chimato 60:1. On Day 42, Chimato 30:1 had significantly higher concentrations of extractable-K than Changu 60:1 and Chimato 60:1.

Table 3.3 Analysis of variance for extractable potassium for the four initial C:N ratios (compost mix) composted under Changu and Chimato systems during the 112 days of composting period

Source of variation	*d.f.*	*(m.v.)*	*s.s.*	*m.s.*	*v.r.*	*F pr*
Rep stratum	2		3709925.	1854962.	0.22	
Rep x Comp-Mix x System						
Comp-Mix	3		79221869.	26407290.	3.10	0.061
System	1		751322.	751322.	0.09	0.771
Comp-Mix x System	3		6923609.	2307870.	0.27	0.845
Residual	14		119181702.	8512979.	9.17	
Rep x Comp-Mix x System x Day						
Day	4		16617489.	4154372.	4.47	0.003
Comp-Mix x Day	12		10699880.	891657.	0.96	0.497
System x Day	4		5732474.	1433119.	1.54	0.202
Comp-Mix x System x	12		31577783.	2631482.	2.83	0.004
Residual	56	(8)	52001230.	928593.		
Total	111	(8)	288713660.			

No differences were observed in the later part of composting despite the controls (Changu and Chimato 60:1) having the least concentrations of extractable-K than the other treatments. The differences observed were inconsistent suggesting that these were analytical in origin. Generally there were no temporal variations in the concentrations of extractable-K during composting, contrary to Lhadi *et al.,* 2004 who detected an increase in the concentration of K over time when they co-composted separated municipal solid waste and poultry manure.

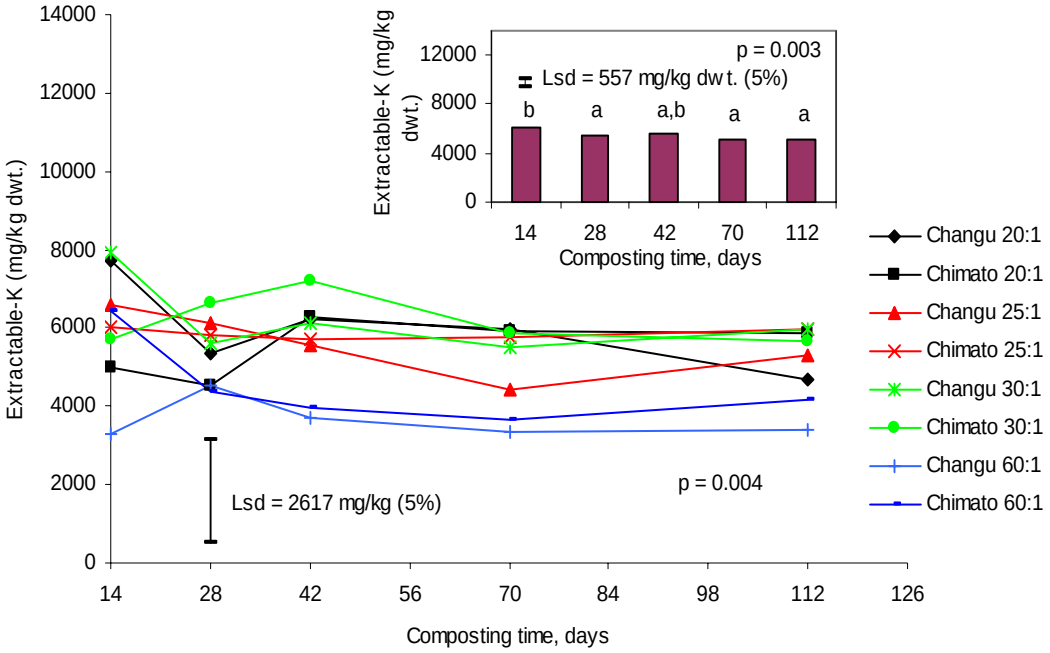

Figure 3.12 Potassium concentrations in the compost heaps of different systems and compost-mixes with time. Insert shows mean extractable-K concentration of compost with time; error bars represents LSD at 5%; same letter denotes that the means are not significantly different; n = 24.

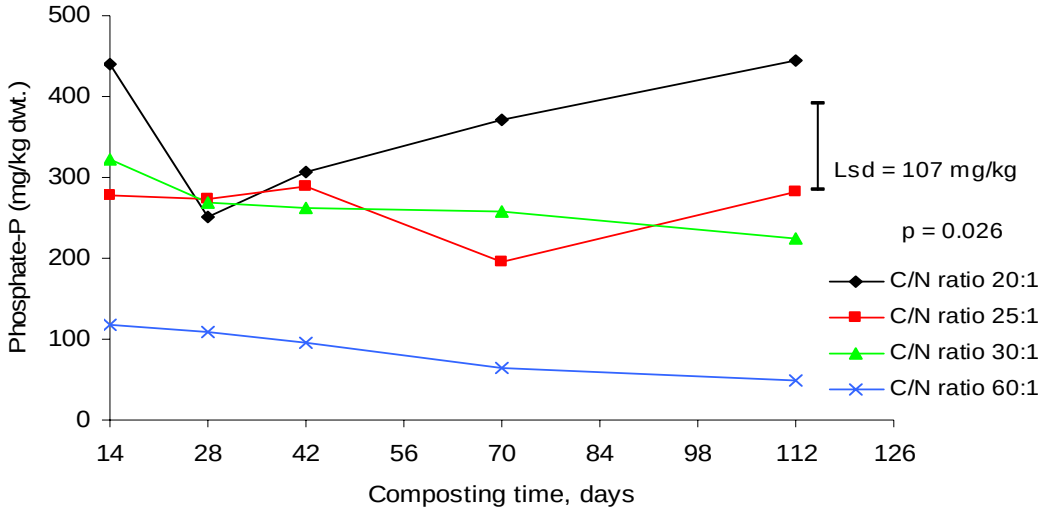

Figure 3.13 Mineralization of phosphorus in the compost heaps of different compost-mixes, initial C:N ratio with time; error bar represents LSD at 5%.

The behaviour of phosphate-P was variable between different compost-mixes. The control (C:N 60:1) had significantly lower concentrations of phosphate-P compared to the other treatments throughout the composting period (Fig. 3.13). Immobilisation of phosphate-P was observed for treatments with low initial C:N ratios *i.e.* C:N 20:1 and 25:1 the first 28 and 70 days respectively before the release of phosphorus commenced. Immobilization was consistent for the control and treatments with C:N ratio of 30:1. High concentrations of phosphate-P were associated with treatments of initial C:N ratio 20:1. These results indicate that microbial organic mineralization requires P to support the microbial multiplication and growth. During composting, microbial activities consume water-soluble P, bind it in complex forms and this is freed gradually when microbes die (Felton *et al.,* 2004). The amount of P in the compost is linked to the feedstock (Table 3.1) hence the treatments with high C:N ratio had low amounts of grass/clover ending with low P which could not satisfy the needs of micro-organisms in the short-term. This was reflected in the immobilization of P throughout the composting period.

3.2.1.5 Compost pH

pH changes in the composts ranged across 1.8 units in the two systems (Fig. 3.14). The pH trends of the different treatments were characterized by an initial decline over first 28 days supposedly due to production of organic acids as indicated by Beck-Friis *et al.,* 2003, and increased up to Day 70 before they started declining again. The exceptions were for treatments Chimato 25:1 and Changu 60:1 which increased during the first 28 days followed by a decline the next fortnight before it started increasing again. Treatments with initial C:N 20:1 had significantly lower pH during the later part of the composting process. This was the case since these were associated with high nitrification process (Fig. 3.7) compared to the other treatments. This process releases H^+ which lowers the pH. The pH at Day 112 for different treatments ranged between 7.1 and 8 (Fig. 3.14). Such range of the pH in these trials was unlikely to have been restrictive to microbial growth and activity.

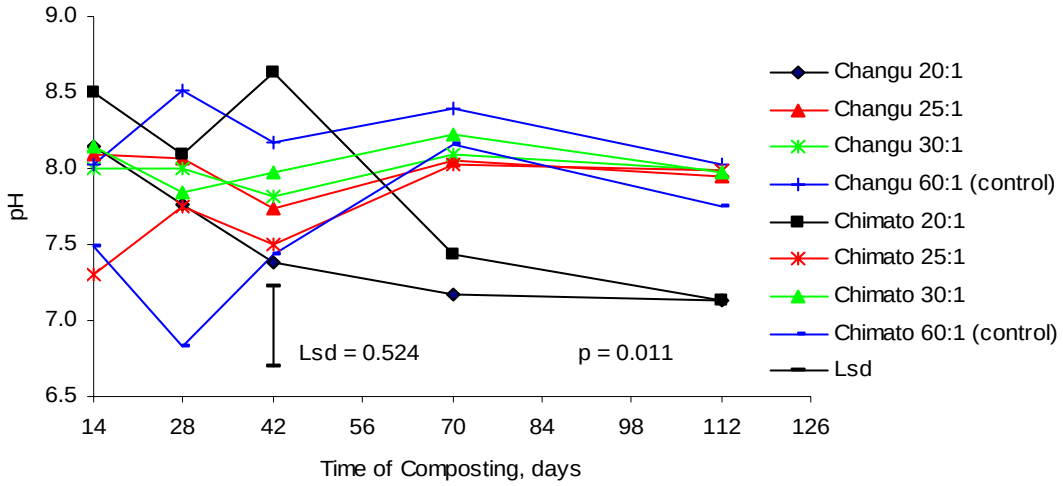

Figure 3.14 pH development during composting of different materials using Changu and Chimato systems; error bar represents LSD at 5%.

3.2.1.6 Cress seed germination

Results indicate that the feedstock used in this experiment contained relatively low concentrations of toxic substances during composting using criteria that attainment of ≥ 60% seed germination when cress seed was planted directly in the compost meant non-toxicity (Table 3.4). By Day 14 most of the treatments obtained germination percentages > 60% meaning that few toxic substances were produced. Nonetheless, treatments with initial C:N 20:1 registered a lower germination percentage on Day 14 indicating that it had relatively high concentration of toxic substances than the other treatments which hindered germination.

Table 3.4 Cress seed germination percentage obtained 10 days after direct seed sowing in compost sampled at 5 different composting durations for the four initial C:N ratios in the Changu and Chimato composting systems

Method	*Initial C:N*	*Germination %*				
	Day	*14*	*28*	*42*	*70*	*112*
Changu	20:1	52	64	77	87	96
	25:1	76	77	78	89	85
	30:1	72	80	83	94	86
	60:1	83	87	86	94	95
Chimato	20:1	61	69	72	92	91
	25:1	77	86	89	95	94
	30:1	82	93	86	92	86
	60:1	75	87	81	95	84

3.2.2 Overall performance of the Chimato and Changu systems

The Changu system was associated with a significantly longer mesophilic phase (17 days) and active composting time (24 days) compared to 14 days and 22 days for Chimato systems. Changu systems showed a greater decline in C:N ratio (*i.e.* 41%) compared to Chimato's C:N decline (*i.e.* 39%). The Changu system contained 61% higher concentration of TON than Chimato whereas Chimato contained 87% higher the concentration of NH_4-N than Changu treatments.

The compost-mix influenced the composting processes. The treatments with low initial C:N ratios promoted rapid microbial activities and self-heating of the heaps, resulting in higher temperatures (58 – 60^{o}C) than the other treatments, and similar mesophilic and thermophilic phases (12 days) while high C:N ratio treatments (30:1) had longer mesophilic phase (15 days) and shorter thermophilic phase (8 days) compared to low C:N ratio feedstock. No thermophilic phase was observed in the control (C:N 60:1). The low C:N ratio treatments were associated with the lowest final C:N ratio (*i.e.* 12:1) and with high concentrations of mineral N compared with treatments of high initial C:N ratios. This was further promoted by the compost system whereby the composting factors *i.e.* moisture and aeration was controlled. The absence of turning and watering effects in the Chimato systems resulted in patches of partly decomposed material in this system. This implies that the one hole created in the centre of the heap was not enough to aerate all the zones in the heap. Further to this, the mud coat placed on the feedstock compressed the material reducing its porosity and at the same time prevented the loss of NH_3 from the heap promoting the high concentration of NH_4-N observed in the Chimato treatments. Composts from treatments with initial C:N 20:1, 25:1 and 30:1 were fully matured by day 112 (Table 3.5).

No variations were observed in the amount of extractable-K despite the trends following the compost-mix ratios. Fixation of P was observed the first 70 days followed by release in the later days possibly due to death of some microbes. The concentration of extractable-P was related to the compost-mix (feedstock).

The results from this section confirm the hypothesis that the type and quality of the feedstock determines the behaviour of the composting systems *as per* Hypothesis 1 in Chapter 1. Thus, low C:N feedstocks and smaller particle sizes will result in faster decomposition, rapid heat build up and rapid loss of moisture, contrary to high C:N feedstocks in which case N will be in short supply limiting microbial growth and activity. It also supported the hypothesis that systems differ in their influence on composting processes due to their capacities to promote air circulation, retain moisture content and heat, hence the quality of the end product (*as per* Hypothesis 3 in Chapter 1). Changu

system predominantly had high levels of TON whereas Chimato had high levels of NH_4-N due to differences in the nitrification and ammonification processes as indicated in Section 3.2.1.3.

Table 3.5 Maturity and stability parameters obtained on Day 112 for four initial C:N ratios in the Changu and Chimato composting systems after composting wheat straw and grass/clover

Method	*Initial C:N*	*Maturity and stability parameters*			
		C:N ≤ 15-20	*NH_4^+/NO_3^- (< 0.16)*	*NH_4-N (< 0.04%)*	*Cress seed germination %*
Changu	20:1	12	0.006	0.008	95
	25:1	16	0.330	0.001	89
	30:1	20	0.000	0.000	93
	60:1	33	0.000	15	94
Chimato	20:1	12	1.830	0.060	92
	25:1	18	0.530	0.003	94
	30:1	19	0.330	0.000	92
	60:1	30	0.000	15.400	95

Critical values sources: Golueke, 1977 & 1991; Pare *et al.,* 1977; Bernal *et al.,* 1998

3.2.3 Conclusions

a. C:N ratio declined over time during incubation in the wheat and grass/ clover system at Silsoe indicating that composting took place.
b. The lower the C:N ratio, the higher the temperature which can be attained during composting when the other factors of composting are not limiting. It was also noted that the lower the C:N ratio, the longer the thermophilic phase achieved and the higher the concentrations of mineral N.
c. Composting requires low C:N material and composting time, the final C:N ratio and nutrient contents were dependent upon compost-mix ratio and compost systems.
d. The two systems under study had short initial mesophilic phases (2-3 days) and thermophilic phases (8-12 days) when composting wheat straw and grass/clover feedstock. This implies that most of the active composting was achieved within the first two weeks.

e. Changu systems were associated with significantly longer active composting phase than Chimato systems meaning higher microbial activities and composting was achieved in Changu as compared to Chimato systems. Notably, this was observed in the glasshouse. It is necessary to run this in the field to evaluate this further.
f. Measurements of temperature within the compost heaps suggested that the microbial activities and rate of composting in the compost heap were variable with more activity in the middle part of the compost heap compared to the upper and lower horizons.
g. The longer composting time with the Changu system appeared to have produced higher quality compost (in terms of TON or nitrates), whilst Chimato systems resulted in greater concentrations of NH_4-N.
h. It was observed that not all the organic materials compost at the same rate in Chimato systems due to lack of mixing and watering. Further, the mud coat compresses the compost material reducing the porosity of the heaps (see Chapter 2, Fig. 2.4).

3.3. Mineralization experiments

Section 3.2 established that the systems and compost-mix influenced the composting processes and quality of the end product. The work in this section explores the mineralization of the compost when applied into the soil under controlled conditions.

3.3.1 Results and discussion

3.3.1.1 Mineral nitrogen (TON)

The results in this post-compost mineralization were discussed in comparison to the control (un-amended soil). Immobilization was observed during incubation with respect to the control (soil only). The treatments with C:N 20:1 mineralized N during the 42 days

of incubation compared to the control when equivalent 10 t/ha of compost was applied to the soil whilst C:N 30:1 mineralized N the first 7 days only (Fig. 3.15a). The treatments with initial C:N ratio 20:1 were the only ones mineralizing when 30 t/ha of the compost was applied (Fig. 3.15b). The treatments with high initial C:N ratio *i.e.* 60:1 immobilized significantly more N compared to the other treatments at both rates of compost application (Fig. 3.15a, b). The immobilization increased over time until Day 35, when it started declining in all the treatments. The decline was possibly due to an initiation of N release from the microbial community from Day 35.

Interaction of composting systems and application rates with time did not alleviate the immobilization phenomenon for the higher initial C:N ratio treatments. This was evident when different rates and systems were considered at variable initial C:N ratios (Fig. 3.16a, b & c). The concentration of TON increased with time in all the treatments of Changu and Chimato until Day 35 when the contents started declining possibly due to initiation of N release from the microbial community. An exception to this scenario was Changu 10 t/ha and Chimato 30 t/ha (Fig. 3.16b) where TON decline the first 14 days before it started increasing. Chimato 30 t/ha and 10 t/ha and Changu 30 t/ha treatments had significantly lower concentrations of TON compared to the control, and the higher rates had significantly lower concentrations of TON compared to lower application rates in material from both systems (Fig 3.16b & c). But, Changu 30 t/ha had significantly higher concentrations of TON during incubation compared to the control when materials from C:N 20:1 were used (Fig. 3.16a).

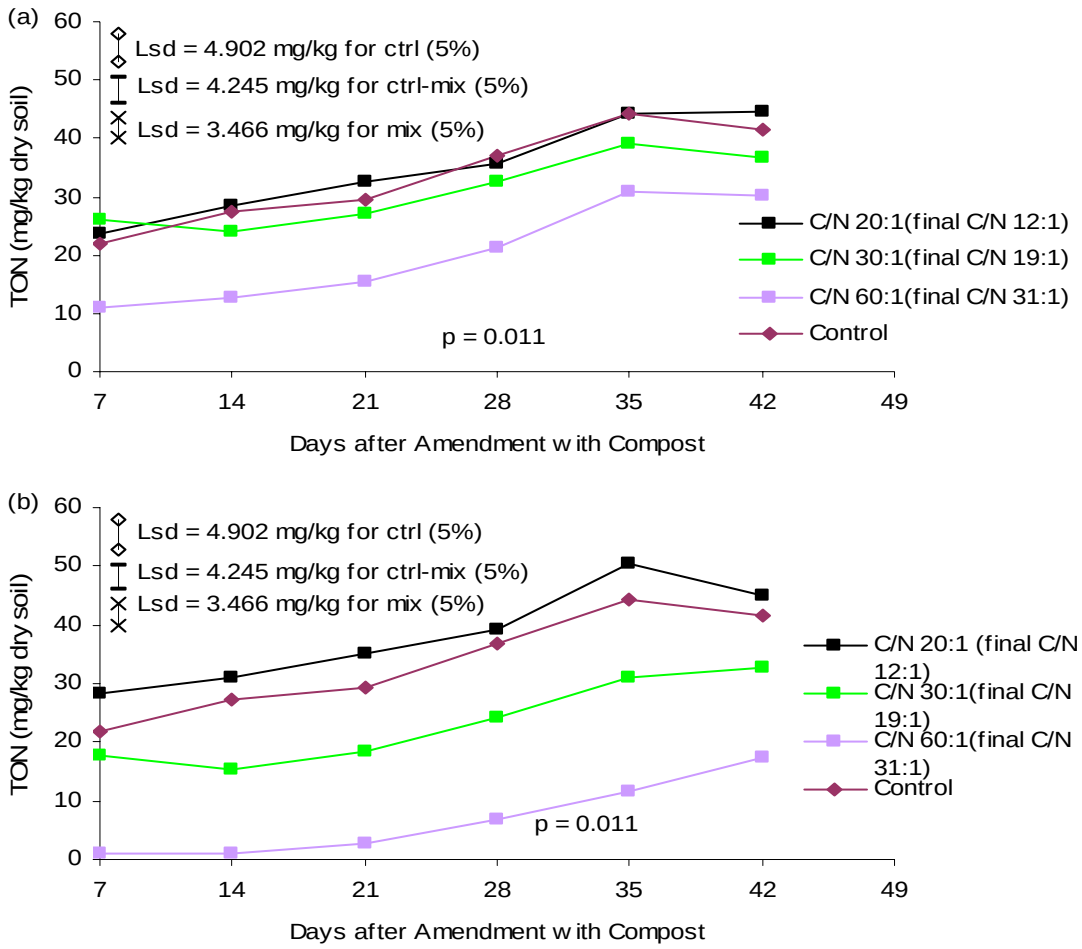

Figure 3.15 Mineralization of organic nitrogen during incubation of compost for (a) three initial C:N ratios when 10 t/ha of compost was applied and (b) three initial C:N ratios when 30 t/ha of compost was applied; error bars represent LSD at 5%.

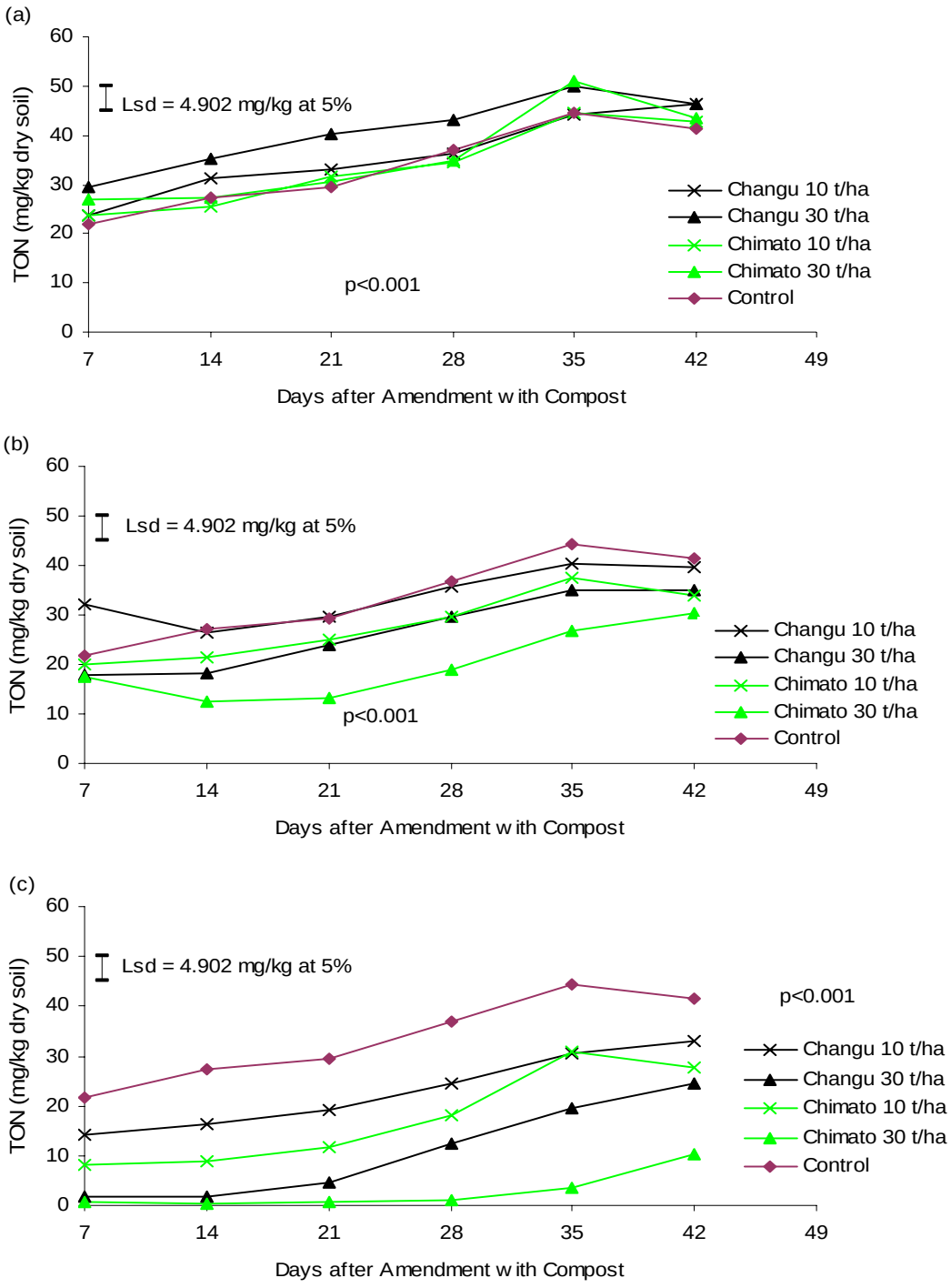

Figure 3.16 Mineralization of organic nitrogen during incubation of compost (a) made from material with initial C:N ratio of 20:1 and different application rates, (b) made from material with initial C:N ratio of 30:1 and different application rates, and (c) made from material with initial C:N ratio of 60:1 and different application rates; the error bars represent LSD at 5%.

Other researchers indicate that decomposition of crop residues with C:N greater than 25:1 will usually result with immobilization of N (Paul and Clark, 1989). This is due to microbial demand for N from the soil. The same argument could be advanced in this case that the immobilization experienced in this study is related to the immobilization of soil mineral N into the microbial biomass. This could be supported by the differences in the level of immobilization between the low C:N ratio treatments and the high C:N material; and the rates of application with higher rate (30 t/ha) resulting in greater immobilization due to excess C introduced demanding more N from the soil. This implies that less than 30 t/ha rate is ideal when using the compost made from the feedstock used in this research.

3.3.1.2 Extractable phosphorus and potassium

Concentrations of extractable-P showed a range of 9.6 mg/kg dry soil during incubation (Fig. 3.17). The treatments with low initial C:N ratio of 20:1 had significantly higher concentration of extractable-P than treatments with C:N 30:1 and 60:1 at the beginning of the incubation while treatments with C:N 30:1 had higher concentrations of extractable-P than those of C:N 60:1 on Day 7 (Fig. 3.17). Fixation of the extractable-P from treatments with initial C:N 20:1 and 30:1 was apparent over the first 7 days of incubation. No differences in the concentrations of P were observed between Day 14 and Day 42 of the incubation. Despite this scenario, the concentrations of extractable-P in all the treatments and the control were within the range suggested as adequate to cover most crop requirements *i.e.* 10-15 mg/kg (Allan and Killorn 1996).

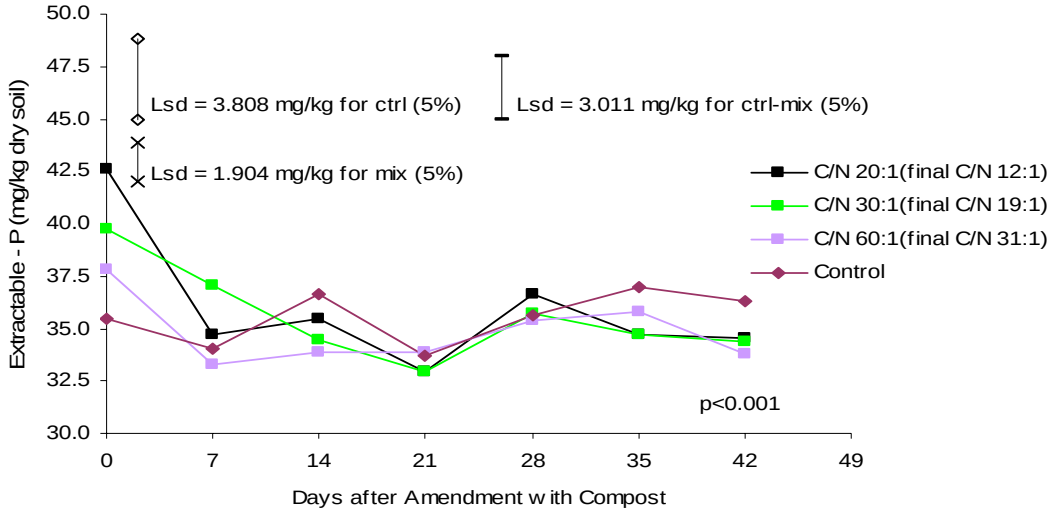

Figure 3.17 Mineralization of phosphorus during incubation of compost for three initial C:N ratios; error bar represents LSD at 5%.

Changu treatments had significantly higher concentrations of extractable-K on Day 14 than Chimato treatments while Chimato had higher concentrations of extractable-K on Day 42 than Changu treatments. No differences were observed between the systems on Day 21 and 35 (Fig. 3.18). The Changu and Chimato treatments had significantly higher concentration of extractable-K than the control (soil only). A similar trend was observed for K values considering materials from different initial C:N ratios (Fig. 3.19a, b & c). K was not limiting for the post-compost mineralization since the extractable-K concentrations increased over time an evidence of K release into the soil.

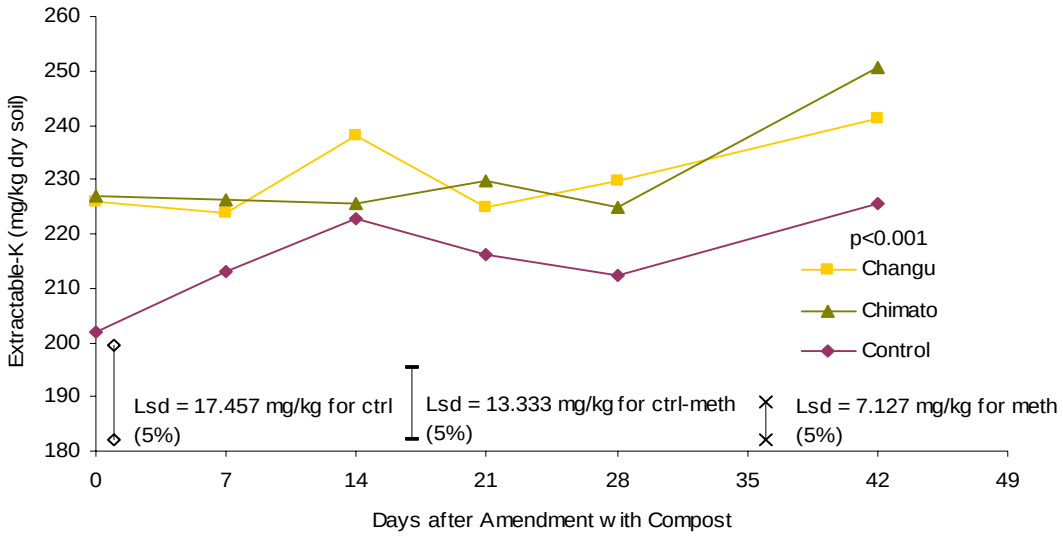

Figure 3.18 Mineralization of potassium during incubation of compost with materials from different composting systems; error bars represent LSD at 5%.

Analysis for compost application rate indicated that more K was observed with 30 t/ha compared to the control and 10 t/ha. Treatments with 30 t/ha had significantly high K contents than those with 10 t/ha during the incubation period (Fig. 3.20). No differences were observed between 10 t/ha application rates and the control except on Day 0 when treatments with 10 t/ha showed significantly high contents of K. The findings in this research show that the amount of extractable K was influenced by the rate of application, meaning that it depended on the type of the compost.

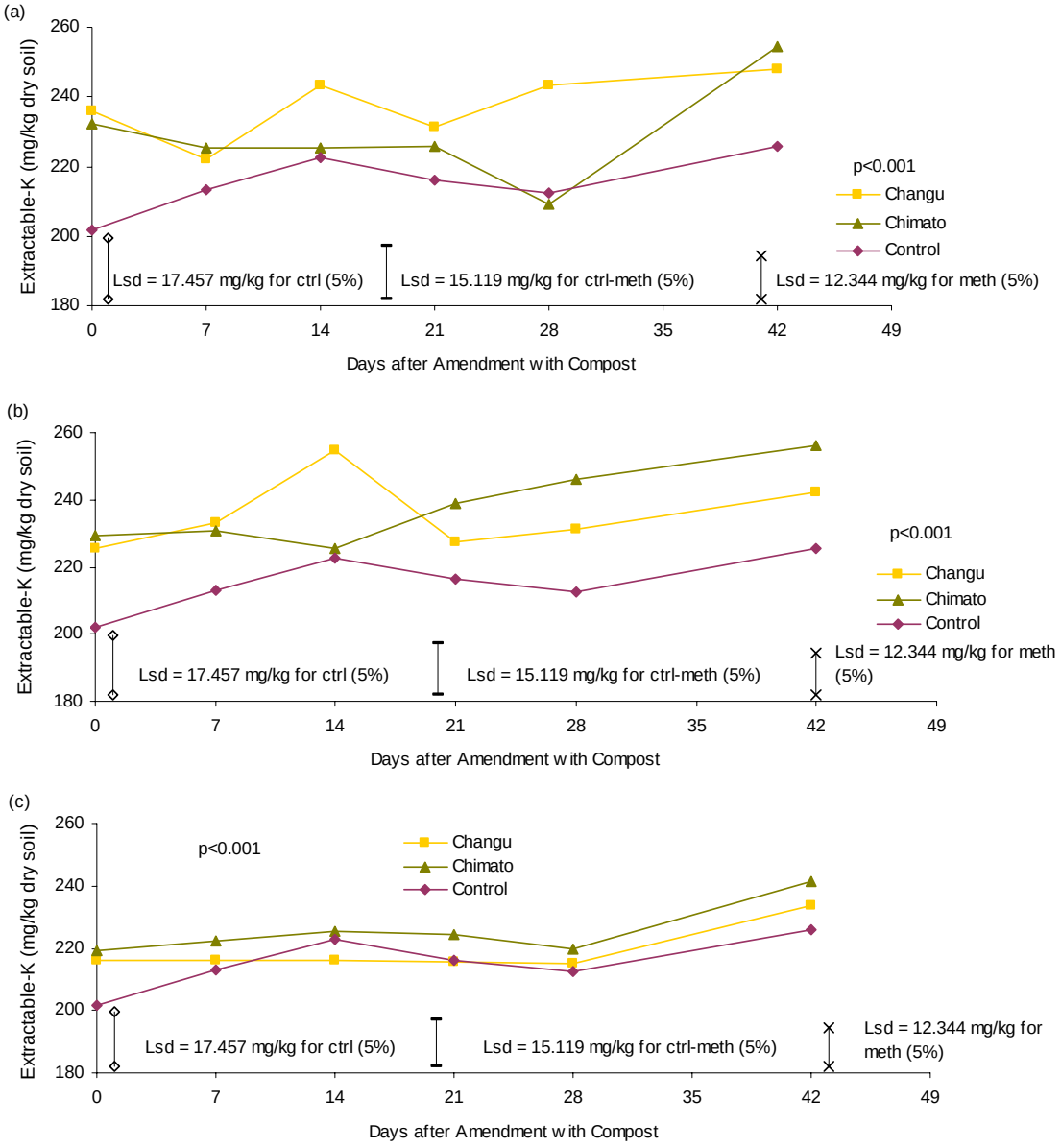

Figure 3.19 Mineralization of potassium during incubation of compost with materials from different systems of (a) initial C:N ratio 20:1 (b) initial C:N ratio 30:1 and (c) initial C:N ratio 60:1; error bars represent LSD at 5%.

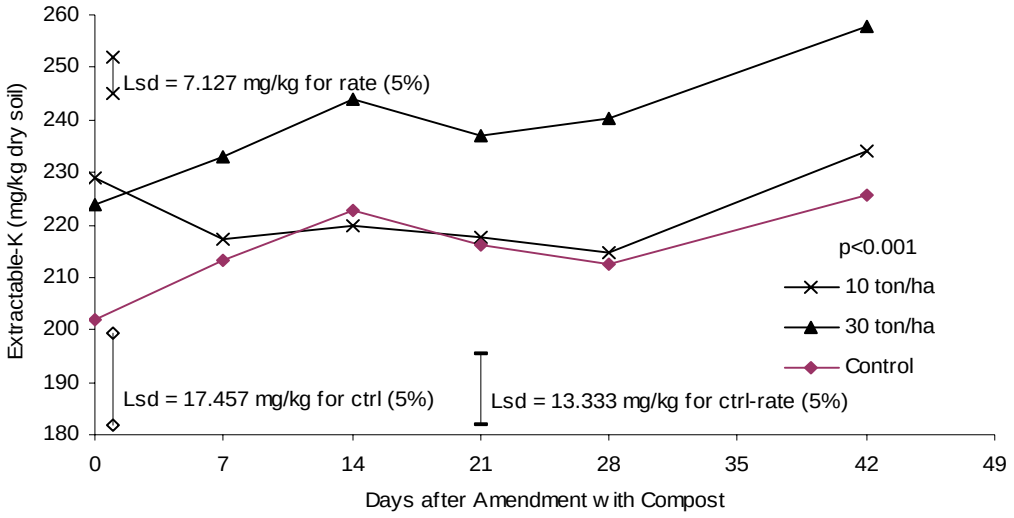

Figure 3.20 Mineralization of potassium during incubation of compost with different application rates; error bars represent LSD at 5%.

3.3.1.3 Soil pH

The pH in amended soils varied between pH 6.3 and 6.9 (Fig. 3.21). The pH of the different treatments declined with time during incubation of the compost in the soil, but this trend was observed in the control and could be attributed to soil processes independent of compost addition.

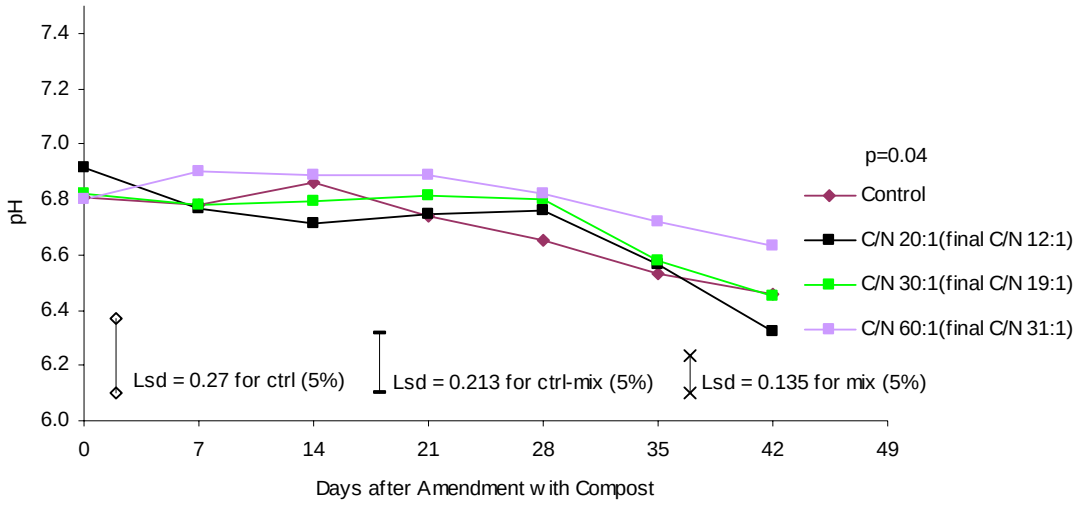

Figure 3.21 Development of pH during the incubation of compost of three different initial C:N ratios; error bars represent LSD at 5%.

The pH range during incubation was unlikely to be limiting to microbial metabolic activities and the decline in pH towards the end of the incubation was as a result of nitrification process which releases H^+ which reduces the pH as evidenced by the nitrification results in Section 3.3.1.1.

3.3.1.4 Cation exchange capacity (CEC)

CEC (Table 3.6) indicated that there was a tendency for the CEC to increase after addition of the compost. No differences were observed between the treatments at both rates of application. Increases in CEC are vital in the soil for increased nutrient retention and exchange for plant use. These results agree with Ouédraogo *et al.* (2001) who observed an increase of CEC of the soil from 4 to 6 cmol/kg when they used compost made from household refuse, crop residues, animal manure and ashes in the field in Burkina Faso.

Table 3.6 CEC (cmol/kg) of the soil on Day 0 & 42 of incubation of compost from the Changu and Chimato systems, four initial C:N ratios and two application rates.

Method	*Initial C:N*	*Cation exchange capacity, cmol/kg*			
		Rate	*10 t/ha*		*30 t/ha*
			Day 0	*Day 42*	*Day 0*	*Day 42*
Changu	20:1		4.6	8.6	6.1	6.4
	30:1		7.6	8.2	4.6	7.2
	60:1		5.8	7.1	6.3	7.3
Chimato	20:1		6.5	6.7	6.3	6.6
	30:1		5.1	8.4	6.1	7.9
	60:1		5.1	7.1	6.3	6.2
Control	Soil only		6.0	6.2		

Means are from 3 replicates. ANOVA determined that there was no significant interaction between compost system and initial C:N ratio for either 10t/ha or 30t/ha rate

3.3.2 Overall effect of the composting systems on nutrient release

No differences were observed between the systems during post-compost mineralization. However, a significant difference was observed on the compost-mix whereby the treatments with initial C:N 20:1 had a positive net-mineralization compared to the control and the rest of the treatments. These were mineralizing at both rates of application (10 t/ha & 30 t/ha). During the 42 days of incubation, all the other treatments except C:N 20:1 were immobilizing N compared to the control irrespective of application rate. This means that at the higher application rate, more C was added to the soil than the available N could support resulting in a removal of available N from the soil by the microbes.

P fixation was observed at the beginning of incubation. P concentrations were between 32.95 and 42.59 mg/kg and no major fluctuations were observed after 7 days of incubation. The concentrations of P observed here were within the requirements of most plants. K concentrations increased over time implying K release (mineralization). High application rate was associated with higher concentration of extractable-K (257 mg/kg) compared to low application rate (234 mg/kg). The CEC of the soil increased with time despite the increase not being significant. This is vital for the nutrient retention for plant uptake. The results here did not fully support the hypothesis that end form and type of the

nutrients in the compost is unique to a particular system and feedstock. The mineralization of the composts and their nutrient release is influenced by the amount and species of nitrogen and phosphorus available in the composts (*as per* Hypothesis 4 in Chapter 1).

It is hypothesized that maize establishment will be affected by the compost-mix and mineral N will be limiting in the treatments with high C:N ratio compost due to immobilization as established by the mineralization studies. However, P and K will not be limiting during the 25 days of maize establishment.

3.3.3 Conclusions

a. Treatments with low initial C:N ratio (20:1) mineralized nutrients during the 42 day incubation period while those with high C:N 30:1 and 60:1 immobilized N compared to the control. It is important to establish the time it takes for the compost from these systems to start mineralizing, to guide management for seed establishment and timing of compost application to avoid immobilization coinciding with peak demand for N when the seedlings are established.

b. Immobilization was responsive to compost application rate. The higher the application rate (30 t/ha), the greater the immobilization of N. This was due to less N available in the compost to support addition of C.

c. The availability of K was influenced by application rate, the higher the application rate the greater the amount of extractable-K meaning that K concentrations were related to the type of compost.

d. No differences existed between Changu and Chimato systems on the amounts of TON produced during incubation and no NH_4-N was detected during this period

e. Phosphorus and potassium were not limiting during incubation such that greater concentrations of extractable-P and K were detected compared to the control.

f. Compost application increased the CEC of the soil. This is likely to have affected the retention of plant nutrients in the soil.

3.4. Maize establishment experiments

3.4.1 Results and discussion

3.4.1.1 Germination of the seedlings, plant height, leaf length, leaf breadth and vegetative growth stage

No differences were observed with respect to days to germination, plant height, and leaf length, leaf breadth and vegetative growth stage using the compost produced from wheat straw by Changu and Chimato systems. Germination of the seeds was complete 4 days after sowing while all the treatments attained Vegetative Growth Stage 4 by Day 25 after germination. This implies that these parameters were not sensitive to the variations in the composts applied. The lack of significant difference with regard to leaf parameters could mean that P was not limiting in the treatments applied. Other researchers have found that leaf growth characteristics are influenced by P but not N (Muchow, 1988). The average leaf number of maize was not affected by the absence of N fertilization while Etchebest *et al.* (1998) found that P deprivation reduced early elongation of maize leaves in a controlled environment. Similarly, Lynch *et al.,* 1991; Colomb *et al.,* 1995; and Rodriguez *et al.,* 1998a reported that plants grown under low soil P concentration develop a smaller leaf area index (LAI), and that peak green leaf area is delayed.

3.4.1.2 Base stem diameter

Changu treatments had larger diameter stalks compared to Chimato treatments (Fig. 3.22). No differences were observed between the control and the other treatments from Changu and Chimato. Taking into account the compost-mix, treatments with initial C:N

20:1 produced plants with significantly larger base diameter than the control and the other treatments. It produced plants with 15% larger base diameter than those grown in treatments with initial C:N 60:1; and 7.30% with initial C:N 30:1 (Fig. 3.23). Treatments with C:N 60:1 produced the smallest diameter compared to the control.

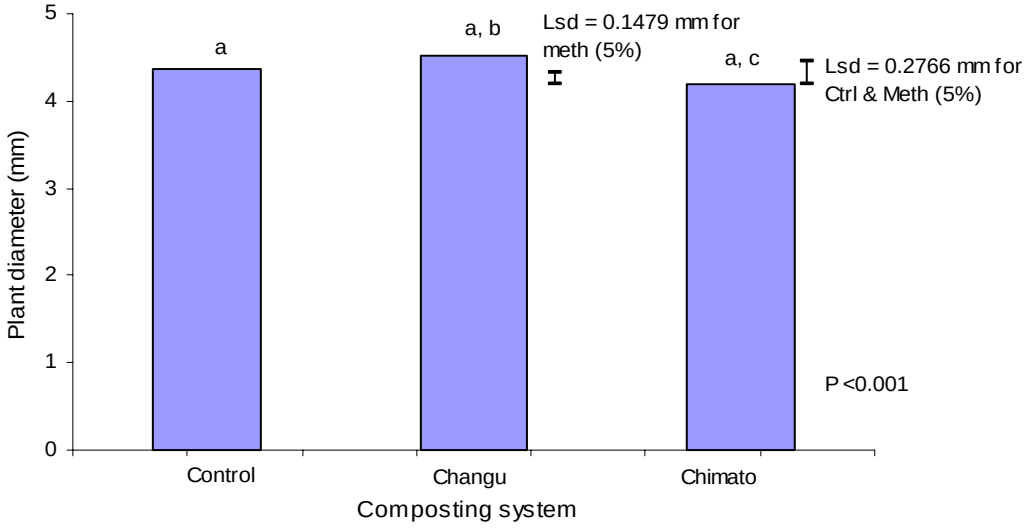

Figure 3.22 Effect of composting system on the size of the base diameter of maize plants; error bars are LSD at 5%; same letter denotes that the means are not significantly different; n = 12 for control and n = 72 for system.

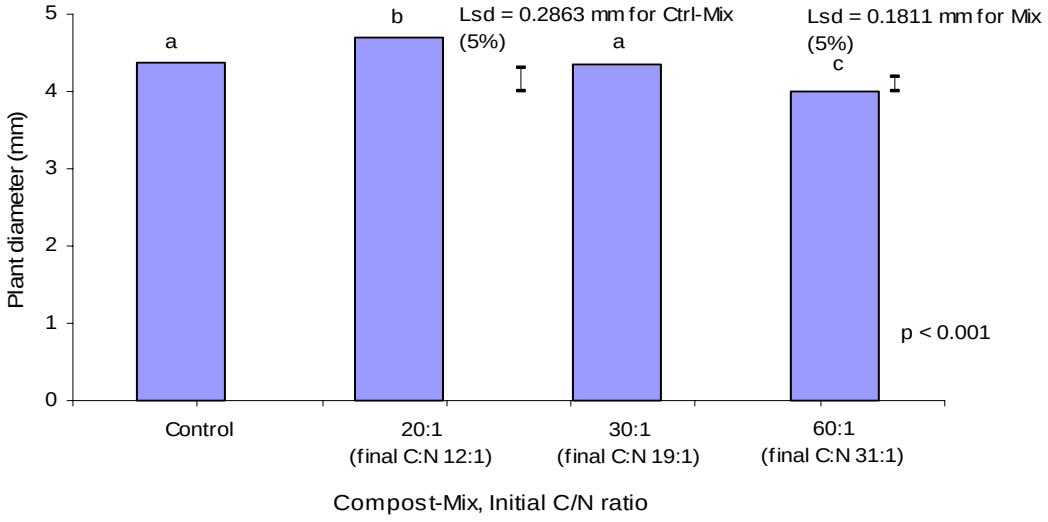

Figure 3.23 Effect of compost-mix on the size of the base diameter of maize plants; the error bar represents LSD at 5%; same letter denotes that the means are not significantly different; n = 12 for control and n = 48 for compost-mix.

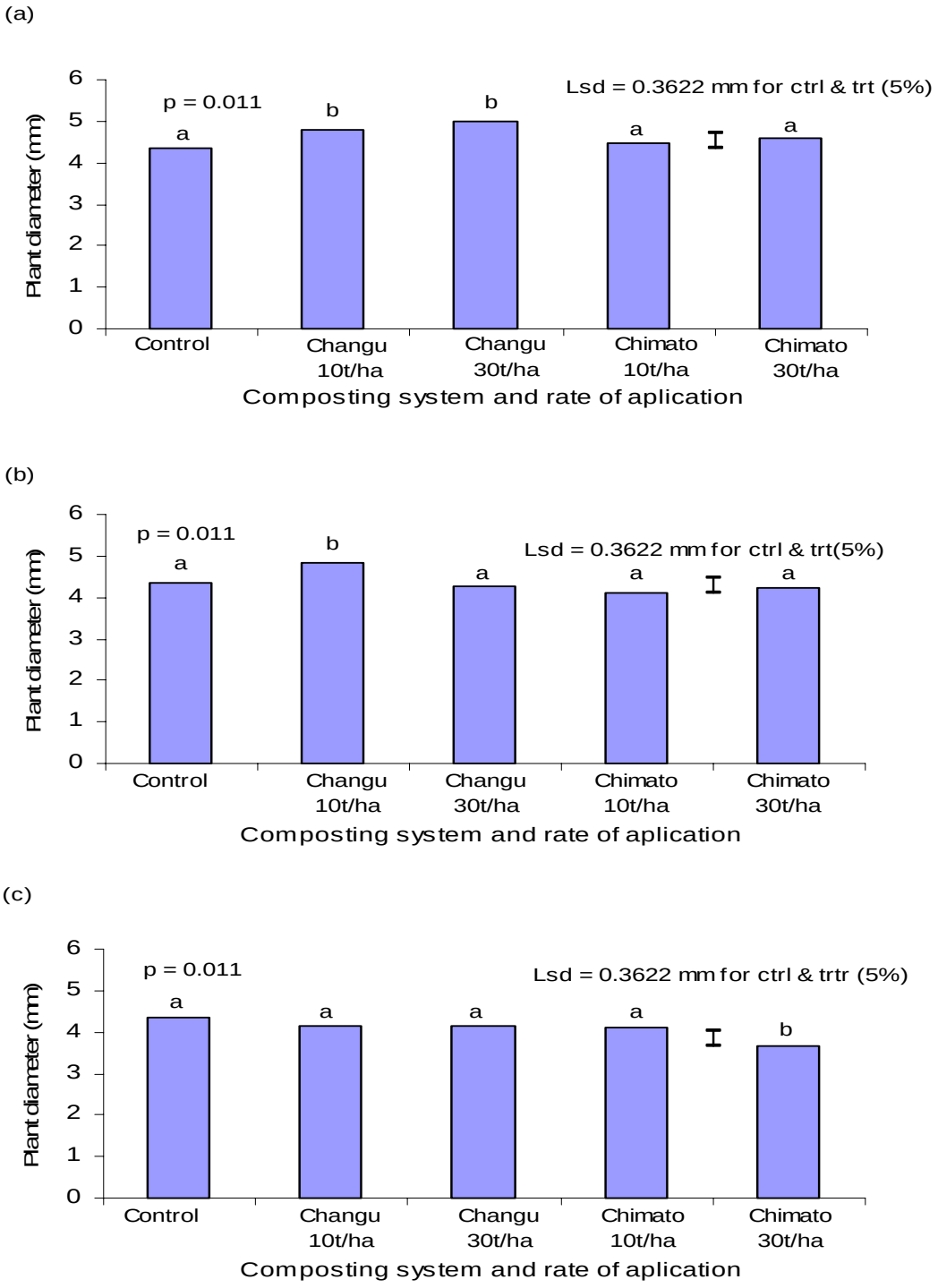

Figure 3.24 Effect of system and application rate for (a) initial C:N ratio 20:1, (b) initial C:N ratio 30:1 and (c) initial C:N ratio 60:1 on the size of the base diameter of maize plants; error bars represent LSD at 5%; same letter denotes that the means are not significantly different; n = 12 for control and n = 36 for system and rate interaction.

Comparison of the interaction of system, compost-mix and application rate indicated that for treatments with initial C:N of 20:1, Changu treatments applied at both 10 t/ha and 30 t/ha produced significantly larger stem diameter than the control (Fig. 3.24a) probably due to increased amount of TON reserved in the Changu treatments. A similar scenario was observed with materials of initial C:N 30:1 (Fig. 3.24b). For the materials from composts made of initial C:N 60:1, Chimato 30 t/ha had significantly the smallest diameters which were 16.37% smaller than those from the control (Fig. 3.24c). This indicates that compost N influenced the sizes of the maize stalk and treatments with more N resulted with larger stems.

3.4.1.3 Leaf area

No differences were observed between the control and the compost-mix (initial C:N ratio) *i.e*. 20:1, 30:1 and 60:1, but C:N ratios 20:1 and 30:1 supported significantly bigger leaf area development than treatments with C:N 60:1 (Fig. 3.25). This implies that, the soil used was not limiting irrespective of the compost addition. Furthermore, the treatments with C:N 60:1 were limited in nutrients due to the introduction of high C:N ratio material (final C:N 31:1) compared to other treatments (final C:N 12:1 & 19:1). This is true since P was not limiting in low C:N ratios as reported earlier.

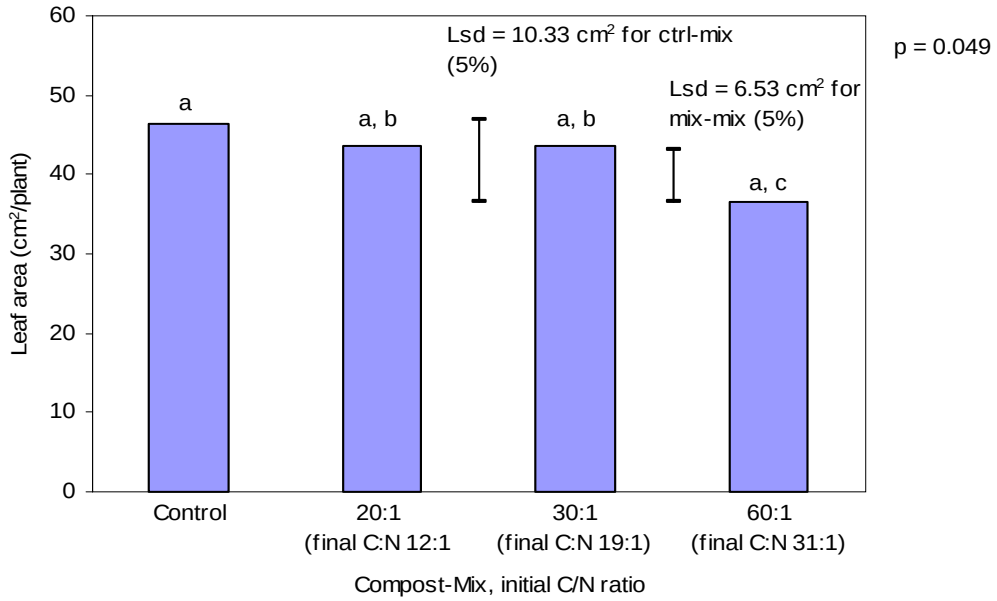

Figure 3.25 Leaf area of the 4th leaf of the maize plant determined 25 days after germination from three different compost-mix treatments (means from 4 replications); error bars represent LSD at 5%; same letter denotes that the means are not significantly different; n = 4 for control and n = 16 for compost-mix.

3.4.1.4 Plant biomass

No differences in plant biomass were observed between the systems (Changu and Chimato) and the control on the amount of plant biomass produced. Nonetheless, Changu treatments produced significantly more biomass which exceeded that of Chimato treatments by 14.3% (Fig. 3.26a). Considering the compost-mix, treatments with initial C:N 20:1 produced significantly more biomass than those for C:N 30:1 and 60:1, and C:N 30:1 produced more biomass than C:N 60:1 (Fig. 3.26b). This is attributable to the extra amounts of N provided by the low C:N treatments as was established in the composting and mineralization studies. Changu treatments were associated with more N which was eventually released during maize established and supported rapid growth compared to Chimato treatments. The treatments with C:N 60:1 produced biomass which was 28% lower than that of the control (soil only). This was because treatments with C:N 60:1 were made from wheat straw only and had low N and higher final C:N (31:1) when they

were applied into the soil. This induced immobilization of N making N scarce for plant growth.

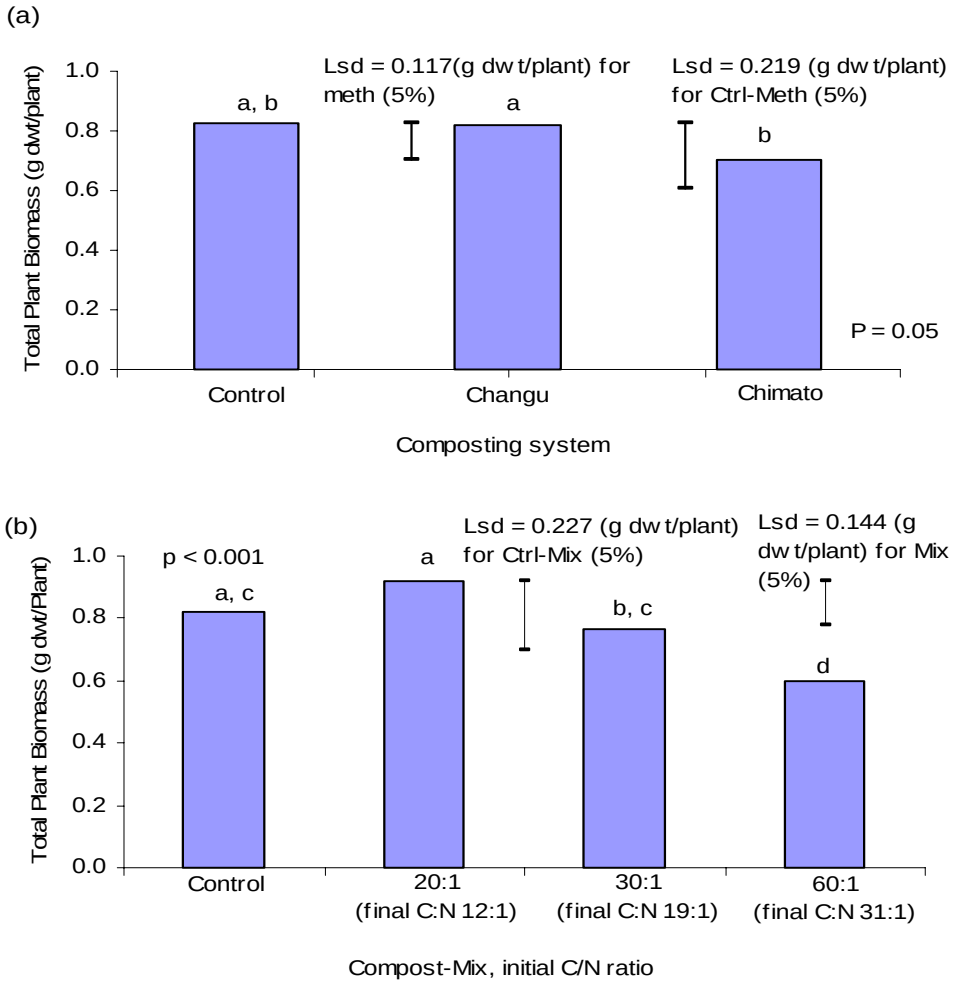

Figure 3.26 Effect of (a) Changu and Chimato systems, and (b) compost-mix (three initial C:N ratios) on plant biomass; maize biomass yielded 25 days after germination; error bars represent LSD at 5%; same letter denotes that the means are not significantly different; n = 4 for control, n = 24 for system and n = 16 for compost-mix.

3.4.1.5 Plant nutrient content

Changu treatments had significantly higher total N concentrations than Chimato treatments but no differences were observed between the control and the systems (Fig. 3.27a). The compost-mix effect showed that treatments with initial C:N 20:1 and 30:1

had significantly higher total N than for those with C:N 60:1. No differences were observed between the treatments and the control (Fig. 3.27b). This implies that N was not limiting during this period in the Changu treatments as compared to Chimato where luxury uptake of N by plants was not possible since micro-organisms were competing for the same N for their metabolism and mineralization process. The lower the initial C:N ratio, the higher was the amount of N contained in the plants. This meant that the lower the initial C:N, the greater the release of the N thereby having an immediate impact on the crop establishment.

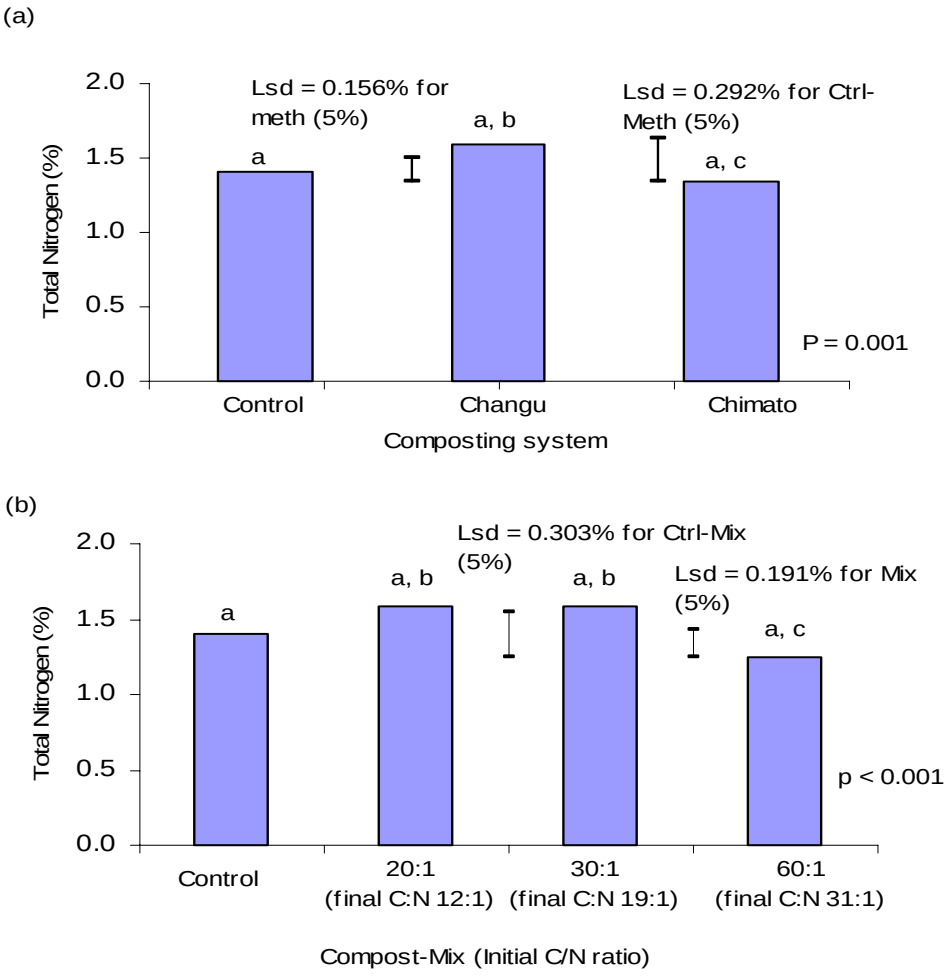

Figure 3.27 Effect of (a) Changu and Chimato systems and (b) Compost-mix (three initial C:N ratios) on the total N of the maize plants yielded 25 days after germination; error bars represent LSD at 5%; same letter denotes that the means are not significantly different; n = 12 for control, n = 72 for system and n = 48 for compost-mix.

Considering the compost-mix and application rate, no differences were observed in P between the control and the treatments and among the treatments at 10 t/ha rate (Fig. 3.28a). Nonetheless, treatments with initial C:N of 30:1 had significantly high amounts of total P than the control and the other treatments at 30 t/ha rate (Fig. 3.28b). The results indicate that the soil used in this experiment was not limiting in P. The treatment effects were therefore confounded by the type of soil used. With respect to the system, Changu treatments had significantly greater amounts of total K than Chimato treatments, but no differences were observed between the systems and the control (Fig. 3.29).

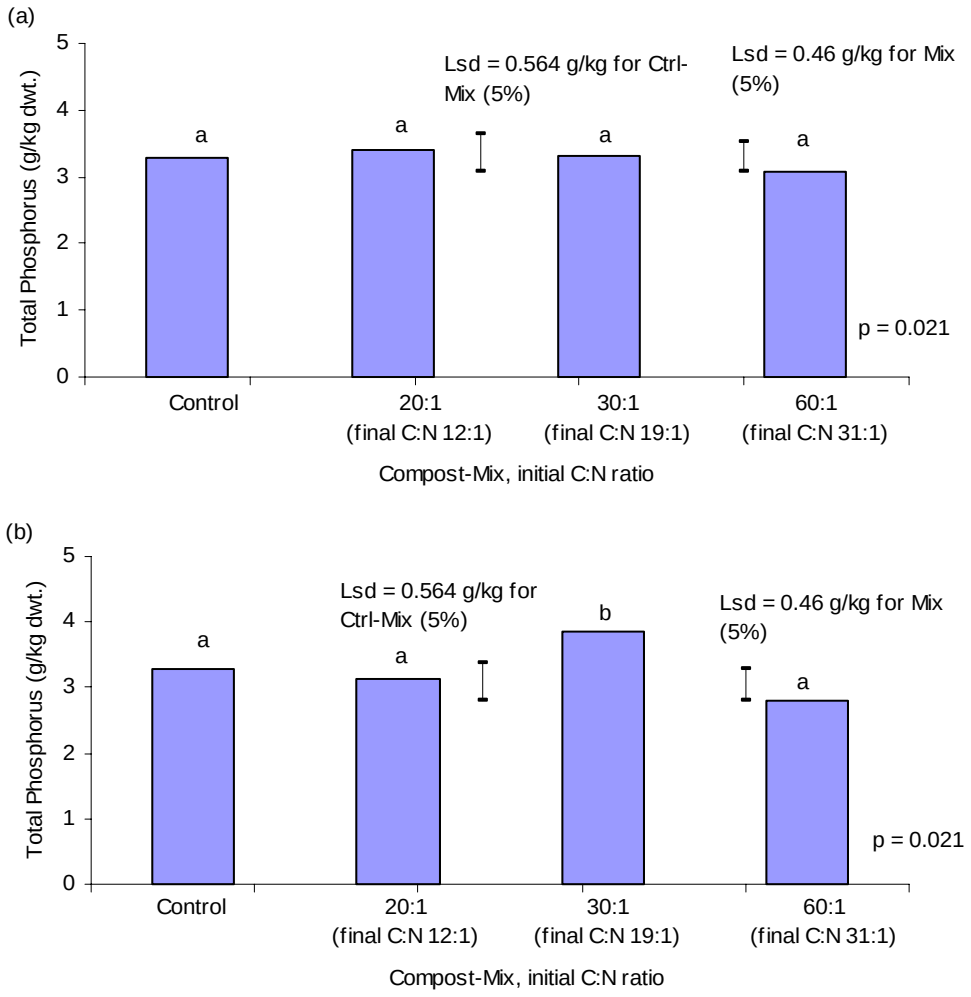

Figure 3.28 Effect of compost-mix at (a) 10 t/ha application rate and (b) 30 t/ha application rate on total P of the maize plant yielded 25 days after germination; error bars represent LSD at 5%; same letter denotes that the means are not significantly different; n = 8 for control and n = 32 for compost-mix.

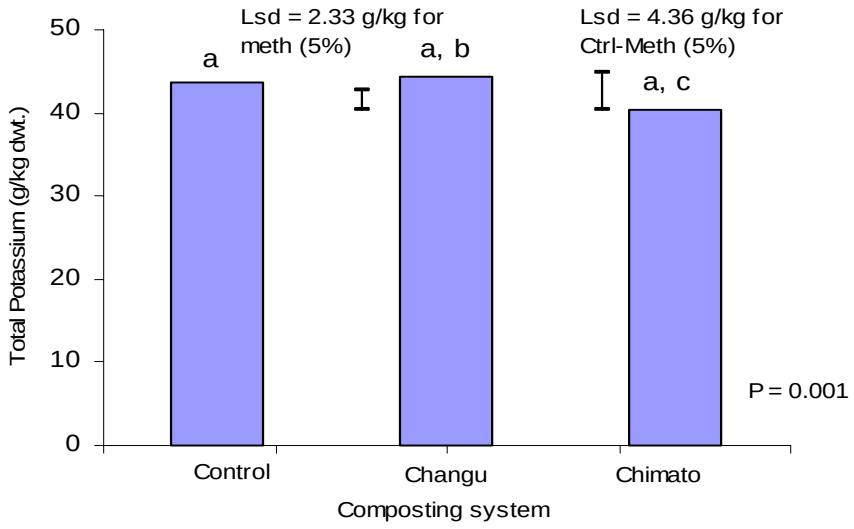

Figure 3.29 Effect of system on total K of the maize plant yielded 25 days after germination; error bars represent LSD at 5%; same letter denotes that the means are not significantly different; n = 8 for control and n = 48 for system.

When application rate and compost-mix interaction were considered, the only difference observed was between treatments with C:N 20:1 and 30:1 at 10 t/ha rate; no differences were observed between the control and the other treatments (Fig. 3.30a). At 30 t/ha rate, treatments with C:N 30:1 had significantly lower concentration of K than those from C:N 20:1; 60:1 and the control. No differences were observed between control and treatments with 20:1 and 60:1 (Fig. 3.30b). The trend is consistent with the mineralization extractable-K trend observed earlier on. Nonetheless, the cause of the decline in K uptake in treatments with C:N 30:1 at 30 t/ha application rate is not clear since it was observed that K availability depended on the application rate with higher rates resulting with greater concentrations of extractable-K.

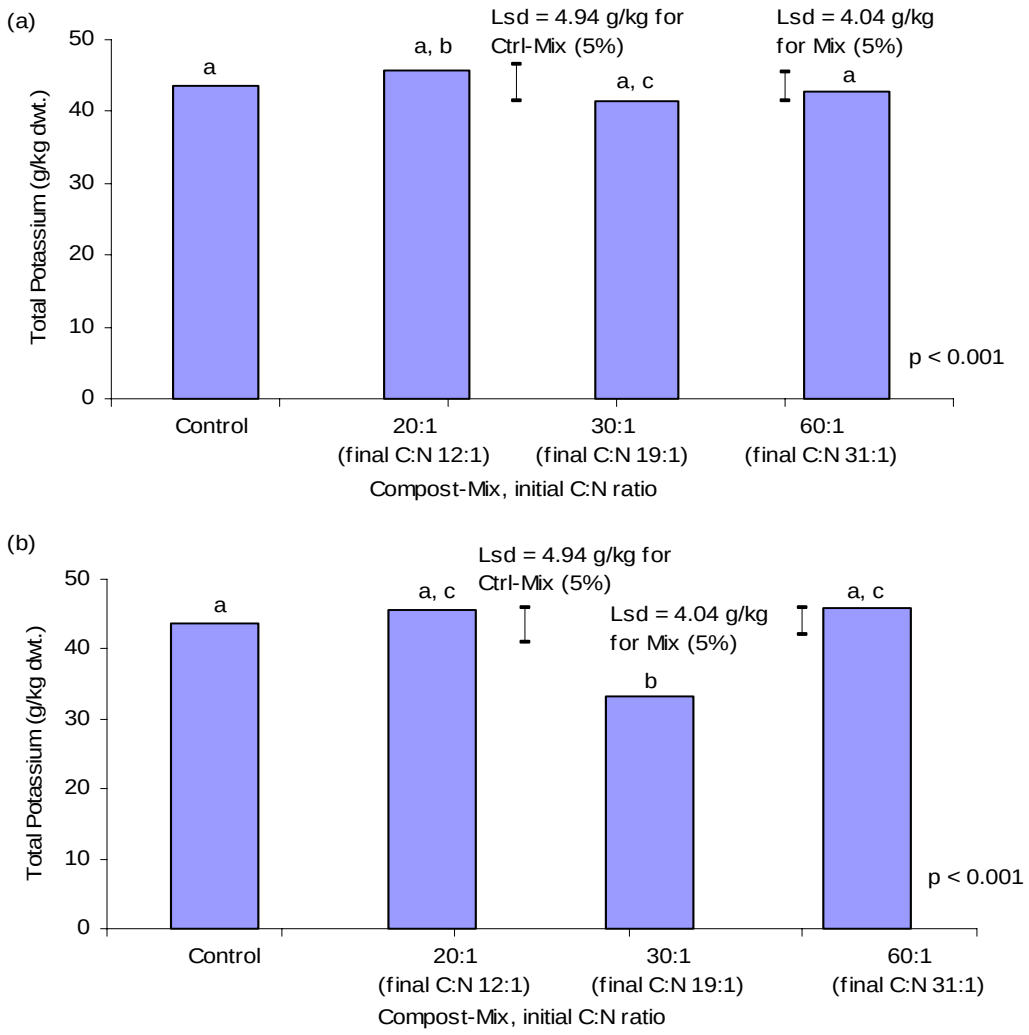

Figure 3.30 Effect of compost-mix at (a) 10 t/ha application rate, and (b) 30 t/ha application rate on total K of the maize plant yielded 25 days after germination; error bars represent LSD at 5%; same letter denotes that the means are not significantly different.; n = 8 for control and n = 32 for compost-mix.

3.4.2 Overall influence of compost on seedling establishment

Changu treatments resulted in greater diameter maize stalks (4.53 mm) and overall plant biomass (0.82 g dwt./plant) compared to Chimato treatments (4.19 mm & 0.70 g dwt./plant). Changu treatments also supported higher uptake of N (1.60%) and K (44.4 g/kg) than Chimato (N = 1.34% & K = 40.5 g/kg). Nonetheless, no differences were observed between the systems and the control except for plant diameter. This means the

soil used did not limit the plant growth during this period. The differences in the systems indicate that Changu systems produced compost with more N which supported additional C introduced into the soil and reduced soil N competition with the plants than was the case with Chimato.

The lower C:N ratios (final C:N 12:1 & 19:1) supported high plant uptake of N and P than the high C:N ratio treatments (final C:N 31:1). This resulted in larger diameters (4.7 mm) for C:N 12:1 treatments compared to 4.36 mm and 4.01 mm for C:N 19:1 and C:N 31:1 respectively. This was reflected in the overall biomass of the maize plants. Treatments with low final C:N 12:1 produced significantly more biomass (0.92 g dwt./plant) than C:N 19:1 (0.76 g dwt./plant) and C:N 31:1 (0.6 g dwt./plant). Importantly, the control had more biomass that the higher final C:N ratio (31:1). This means that immobilization of N took place in the higher C:N ratio treatments limiting the plant growth hence low biomass.

Nonetheless, there was no difference between the systems with respect to the vegetative growth stage after 25 days. The results found here support the hypothesis that different compost quality from the two systems will affect plant establishment differently with high quality compost promoting more rapid seedling establishment than low quality compost (Hypothesis 5 in Chapter 1).

3.4.3 Conclusions drawn

a) Low final C:N ratios (12:1 & 19:1) supported more plant uptake of N and P and consequently produced plants with larger stalks and biomass. The lower the C:N the easier the uptake of nutrients and the higher the biomass produced.

b) Changu treatments supported significantly more nutrient uptake (N and K) by maize plant indicating they had readily available nutrients for the plants compared to Chimato.

c) Changu treatments produced plants with larger stalks and which eventually contributed to more biomass compared to Chimato treatments.

d) The quantities of P and K uptake depended on the compost application rate with higher application rate resulting in more nutrient uptake. This implies that P and K contents depended on the compost source (feedstock type).

e) Composts with final C:N ratio ≥ 20:1 hindered plant growth due to nutrient limitations. It was not safe to put fresh compost in the soil with seed where C:N was greater than 20:1

f) The soil used (control) in the maize establishment studies did not limit the plant growth relative to the other treatments during the 25 days the experiment was run since there were no apparent difference between the rest of the treatments.

3.5 Summary

The Changu system was associated with a significantly longer mesophilic and active composting phase and a high decline in C:N ratios (composting) compared to Chimato. The Changu compost had more TON than Chimato systems (more NH_4-N). The compost-mix influenced the composting processes. The lower the C:N ratio, the higher the temperature levels attained and the longer the thermophilic phase. Furthermore, the lower the C:N, the lower the final C:N and the higher the mineral N contents. These were further promoted by the compost system whereby the composting factors *i.e.* moisture and aeration was controlled. The absence of turning and watering effects in the Chimato systems ended up with patches of partly decomposed material in this system.

The above results supported the Hypotheses 1 and 3. The composting process is controlled by feedstock quality and the systems influence composting processes and quality of compost. But, these results are confined to the glasshouse. It is recommended to carry out the composting experiment with these systems in the field to fully understand

their processes and behaviour (Hypothesis 2), which will be covered in Chapter 4. Nonetheless, this Chapter provided information which contributes to the attainment of Objective 1 and 2 (*as per* Chapter 1) to characterize the two composting systems and determine conditions for production of quality compost.

Despite the differences observed between Changu and Chimato during composting, no direct compost system effect was determined during post-compost mineralization. But, compost-mix differences from composting were manifested during post-compost mineralization with low C:N ratio treatments (final C:N 12:1) mineralizing N while the other treatments were immobilizing N during the 42 days of incubation. The results did not confirm Hypothesis 3, since the mineralization of the composts and their nutrient release was not influenced by the compost processes. There is need to further test this hypothesis with composts produced in the field, but also consideration be made on the duration of the test to evaluate the point when net-mineralization is effected. This has a direct implication for the methodology used in the data reported in Chapter 4. This chapter provided results which partially explain the nutrient release characteristics of composts from Changu and Chimato systems (Objective 3).

Changu treatments resulted in bigger maize stalks and overall plant biomass compared to Chimato treatments. This is attributed to the influence of the systems on the composting process and end product as observed during composting. The Changu treatments supported high nutrient uptake (N and K) than Chimato. The lower C:N ratios equally supported high uptake of N and P which resulted in larger diameters and consequently more overall biomass of the maize plants than the high C:N ratio treatments. The high C:N ratio treatments were associated with immobilization of N. This is a direct manifestation of the differences observed during composting and post-compost mineralization studies. Nonetheless, there was no difference between the systems on the vegetative growth stage. The results found here support Hypothesis 5, in that compost from the two systems did affect plant establishment differently. This information initiated the determination of maize establishment pattern with respect to compost systems (Objective 4).

Chop length (particle size) was not studied as stipulated in Hypothesis 1. It is strongly recommended here to look at the influence of chop length on composting process, with consideration to the practice of the smallholder farmer. This will be discussed in Chapter 4.

CHAPTER FOUR: Malawi – Bunda experimental results

4.1. Introduction

Chapter 3 established differences in composting processes between the Changu and Chimato systems. The systems differed in the temperature profiles and duration of active composting attained and the mineralization of N during composting. The Changu system was associated with a higher concentration of TON while Chimato had a higher concentration of NH_4-N indicating that system controlled mineralization of N in the composting material. The compost-mix (initial C:N ratio of the feedstock) directly influenced the composting processes. The lower the initial C:N, the higher the temperatures, the higher the TON concentration and the lower the final C:N ratio of the compost. But this was attained under glasshouse conditions in the UK.

This chapter further explores the composting process of the two systems but this time in the field in Malawi and using maize straw and green bean residues, in order to understand how the systems operate under local external conditions (*as per* Hypothesis 2 in Chapter 1). The treatments in this chapter included particle size (chop length) of the feedstock fully to test Hypothesis 1. This chapter also reports the extended post-compost mineralization experiments, which were intended to resolve the immobilization problem experienced during a similar trial in Chapter 3. Similarly, a new treatment (pre-incubation of soil/compost) was introduced in the maize establishment experiments to reduce the effect of immobilization of N in maize establishment. The post-compost mineralization and maize establishment experiments were all conducted in the UK in a controlled environment (see Chapter 2) but using the compost made in Malawi. Sandy loam soil (as in the earlier chapter) and sand soil were used for maize establishment to evaluate the performance of the maize in a low fertility soil.

The methods, treatments used and the sampling procedures are covered in Chapter 2. The data presented in this chapter were analysed by Genstat Release 8.1 for Windows. Differences between means were tested using LSD at $p = 0.05$. The results for different

experiments are presented in the following sections. Appendix 4 is presented in Annex on a CD-ROM.

4.2. Composting experiments

Maize straw and green bean residues formed the feedstock used in Malawi for the composting experiments (Table 4.1). The green bean residue had higher concentrations of total N, P and K than the maize residue. This meant that bean residues were the main source of nutrients required for decomposition and formed the bulk of the nutrients in the final compost product.

Table 4.1 Characteristics of the feedstock used for composting in Malawi

	Feedstock characteristics			
Material	*N %*	*C %*	*Total P (mg/kg)*	*Total K (mg/kg)*
Maize straw	0.60	45	273	15754
Green bean residue	3.59	42	2893	23003

4.2.1 Results and discussion

4.2.1.1 Temperature

Typical temperature profiles were observed in the field when maize straw and bean residues were composted (Fig. 4.1). In the field (Malawi), the ambient temperatures were relatively higher (mean of 27.4^{o}C, a range of 18.3 to 32.8^{o}C) compared to Silsoe in the glasshouse (mean of 19.3^{o}C, a range of 11.5 to 35.1^{o}C). Temperature profiles for the Changu system (Fig. 4.1a - d) differed from those of the Chimato system (Fig. 4.1e - h) revealing the influence of the different management procedures used in the composting process. The Changu treatments were characterised by alternate peaks and troughs. The peaks followed the weekly turning and watering of the compost material relating to the replenishing of oxygen which promoted microbial activity as evidenced by the renewed temperature peaks. The Chimato treatments were characterised by one large initial peak which declined with time, indicating depletion of oxygen which could not sustain higher microbial activity for long periods. This resulted in Chimato treatments reverting to

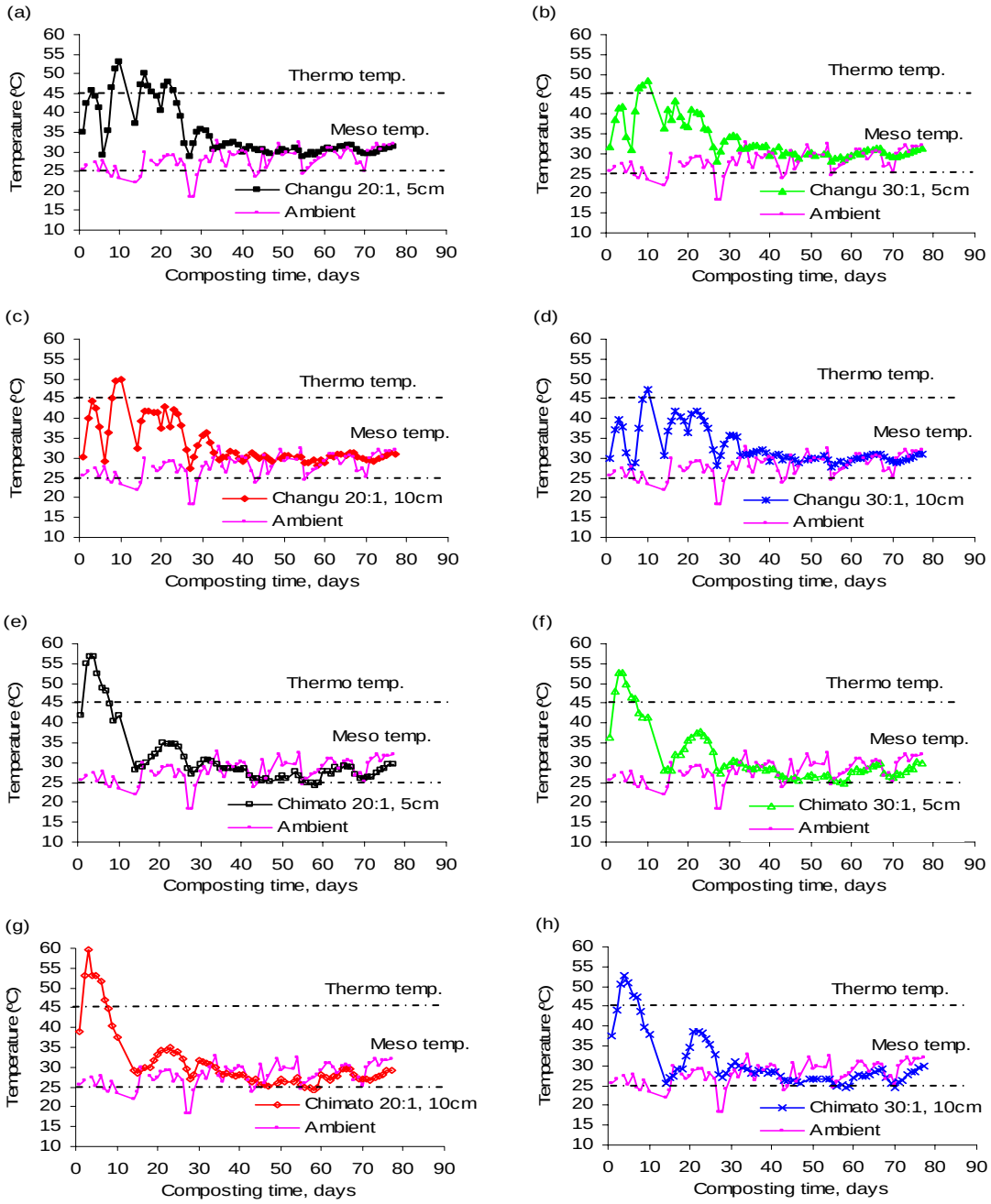

Figure 4.1 Temperature profiles for different treatments during the composting period using Changu (a-d) and Chimato (e-h) systems; the temperature values are means of the temperature measured at three positions (depths) in the heap. Thermo and meso temp. denote thermophilic and mesophilic temperatures. Mesophilic phase represents any temperature between 25°C and 45°C and that is above ambient temperature while thermophilic phase represent those temperatures above 45°C. The compost process reached maturation phase when the temperatures reverted to ambient temperatures.

ambient temperature eight days earlier than the Changu treatments (Fig. 4.1). All the treatments had thermophilic, mesophilic and the maturation phases (Fig. 4.1 & Table 4.2). All the treatments depicted mesophilic temperatures on the first day of composting. The Chimato treatments reached thermophilic temperatures within the first 2 days of composting while the Changu treatments had a delayed thermophilic phase which started 8 days from the compost initiation day. An exception to this was the Changu 20:1, 5 cm which reached thermophilic temperatures after 3 days. This resulted in the Chimato treatments having a longer thermophilic phase while the Changu treatments maintained an extended mesophilic phase. This was due to the mud coat in the Chimato which protected the heaps from the excess loss of heat and water due to wind effects. Despite the insulation, the temperature dropped rapidly, most likely due to lack of oxygen and moisture. As for the Changu treatments, the extended higher temperatures were possible because of the aeration process (weekly turning) and watering which sustained the microbial activity until the substrate became limiting. The Chimato treatments reached a maximum of 60^{o}C while the Changu treatments reached 53^{o}C.

Table 4.2 Length of mesophilic, thermophilic and maturation phases (in days, d) during the 77 day experimental period for four initial C:N ratios and two chop lengths in the Changu and Chimato composting systems (Malawi experiment)

System	*Initial C:N*	*Chop length (cm)*	*Mean length of phase, d*		
			Mesophilic	*Thermophilic*	*Maturation*
Changu	20:1	5	22.9	4.1	50.0
		10	22.1	4.9	50.0
	30:1	5	17.2	4.7	55.0
		10	12.4	3.4	61.1
Chimato	20:1	5	13.1	6.0	57.9
		10	11.6	6.6	58.9
	30:1	5	9.2	6.6	61.2
		10	8.4	4.6	64.0

The length of the maturation phase is the difference between the total 77 d period and the sum of the mean meso- and thermo-philic phases. ANOVA determined that there was not a significant interaction between compost system, initial C:N and chop length for either of the Mesophilic and Thermophilic phase length variables.

With respect to initial C:N ratio of the compost material, the lower the C:N ratio, the higher the temperatures attained, the longer the mesophilic phase and the longer the

active composting period (Fig. 4.1 & Table 4.2). The influence of C:N on the temperature phases was independent of the composting system ($p > 0.05$).

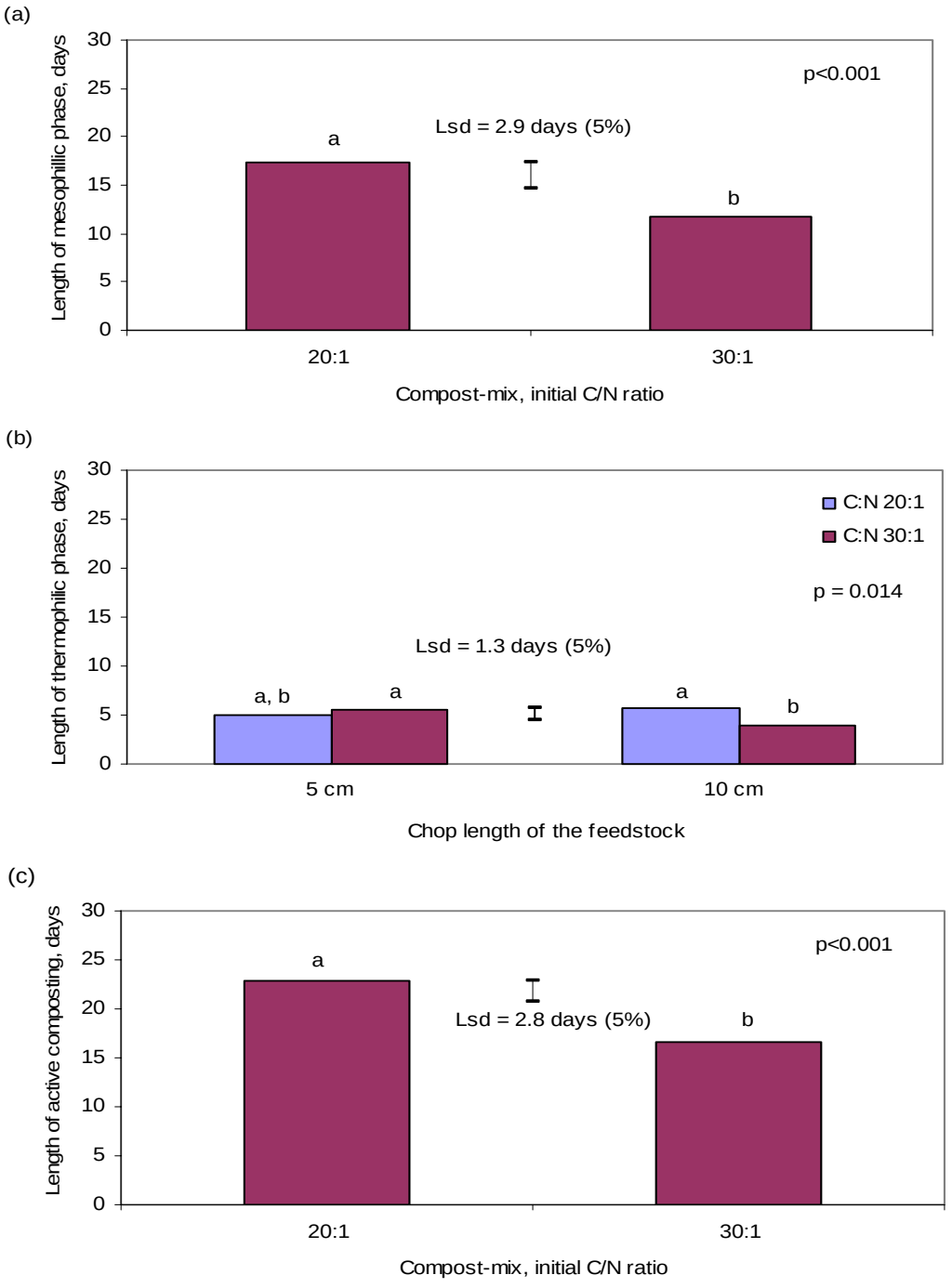

Figure 4.2 Effect of compost-mix and combined effect of compost-mix and chop length on the length of (a) mesophilic phase (n = 36) (b) thermophilic phase (n = 18) and (c) active composting period (mesophilic + thermophilic), (n = 36) during the 77 day period of composting; error bars represent LSD at 5%; same letter denotes that the means are not significantly different.

Significant differences were observed in the length of mesophilic, thermophilic and active composting phases due to compost-mix effect (Fig. 4.2). The treatments with low C:N ratio (*i.e.* 20:1) had significantly longer mesophilic, $p<0.05$ (17 days) and active composting periods, $p<0.05$ (23 days) compared to 12 days and 17 days respectively for C:N 30:1 (Fig. 4.2a & c). Even when interaction of compost-mix and chop length was considered, treatments with 20:1 C:N ratio had a longer thermophilic phase ($p<0.05$) than 30:1 C:N ratio material (Fig. 4.2b). This was due to the fact that the low C:N ratio material had an easily mineralizable substrate which sustained more prolonged microbial activity than the 30:1 C:N. This confirms the findings in Chapter 3. Chop length did not directly influence the length of composting phases in this study except when it interacted with compost-mix, initial C:N 30:1 where 10 cm composts resulted with a short thermophilic phase (Fig. 4.2b).

Further analysis of the effect of composting system on length of composting phases indicated that the Changu system had significantly longer mesophilic and active composting phases ($p<0.05$) than the Chimato system (Fig. 4.3a & c). However, the Chimato system had significantly longer thermophilic phase ($p<0.05$) than the Changu system (Fig. 4.3b). The turning and watering in the Changu treatments significantly improved the oxygenation and moisture regime of the compost thereby improving and sustaining microbial activity relative to the Chimato treatments. The mud coat in the Chimato systems protected the adverse effects of cooling and drying winds and colder ambient temperatures and managed to conserve heat, hence the longer period of the thermophilic phase observed.

Significant differences were also observed in the variation of temperature phase length within the heap. The centre had significantly longer mesophilic, thermophilic and active composting phases than the upper and lower horizons (Fig. 4.4). This could be explained by the mass above and below the horizon which acts as an insulating blanket, protecting the middle from the colder ambient and ground temperatures, thereby promoting microbial activity.

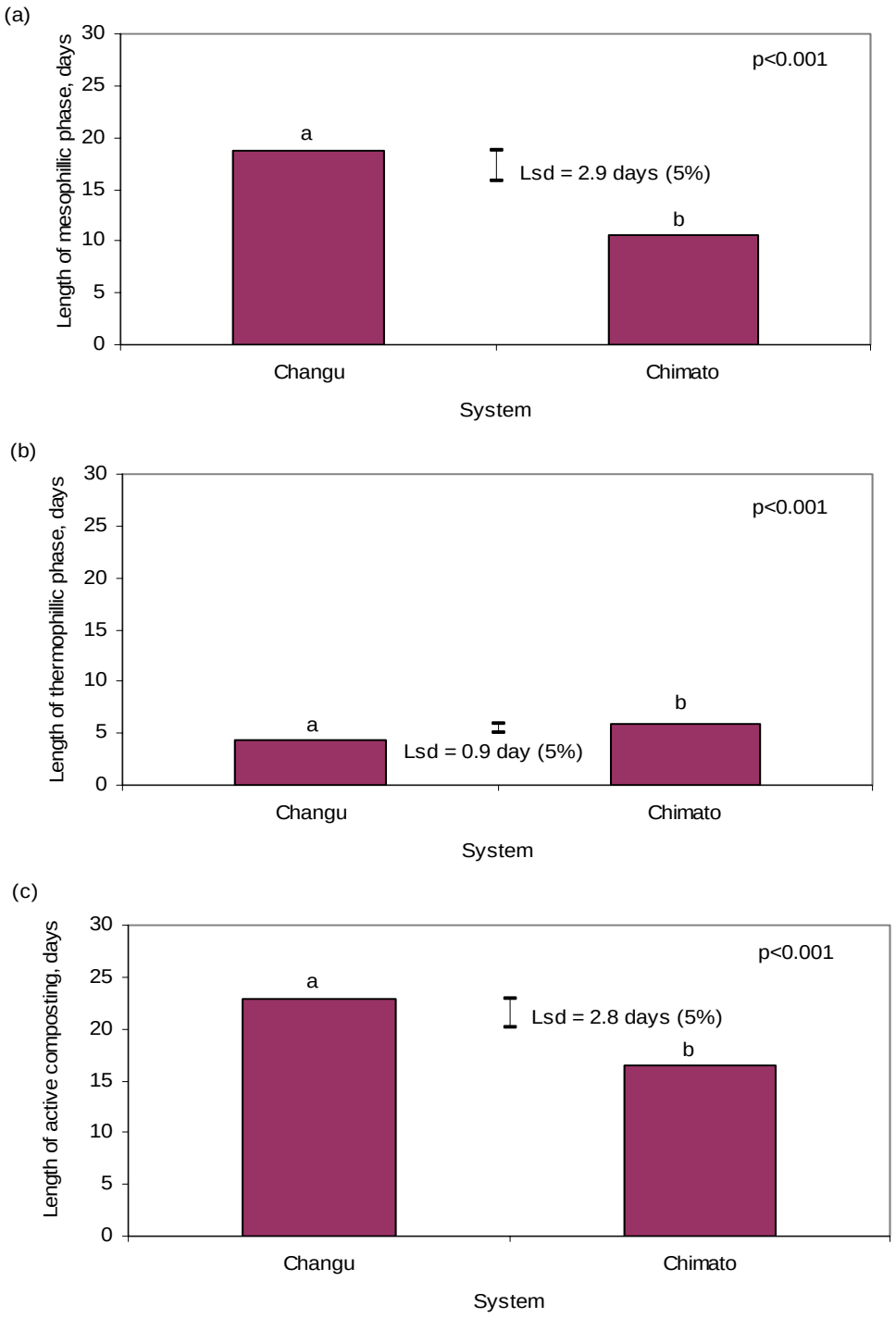

Figure 4.3 Effect of composting system on the length of (a) mesophilic phase (b) thermophilic phase and (c) active composting during the 77 day period of composting; error bars represent LSD at 5%; same letter denotes that the means are not significantly different; n = 36.

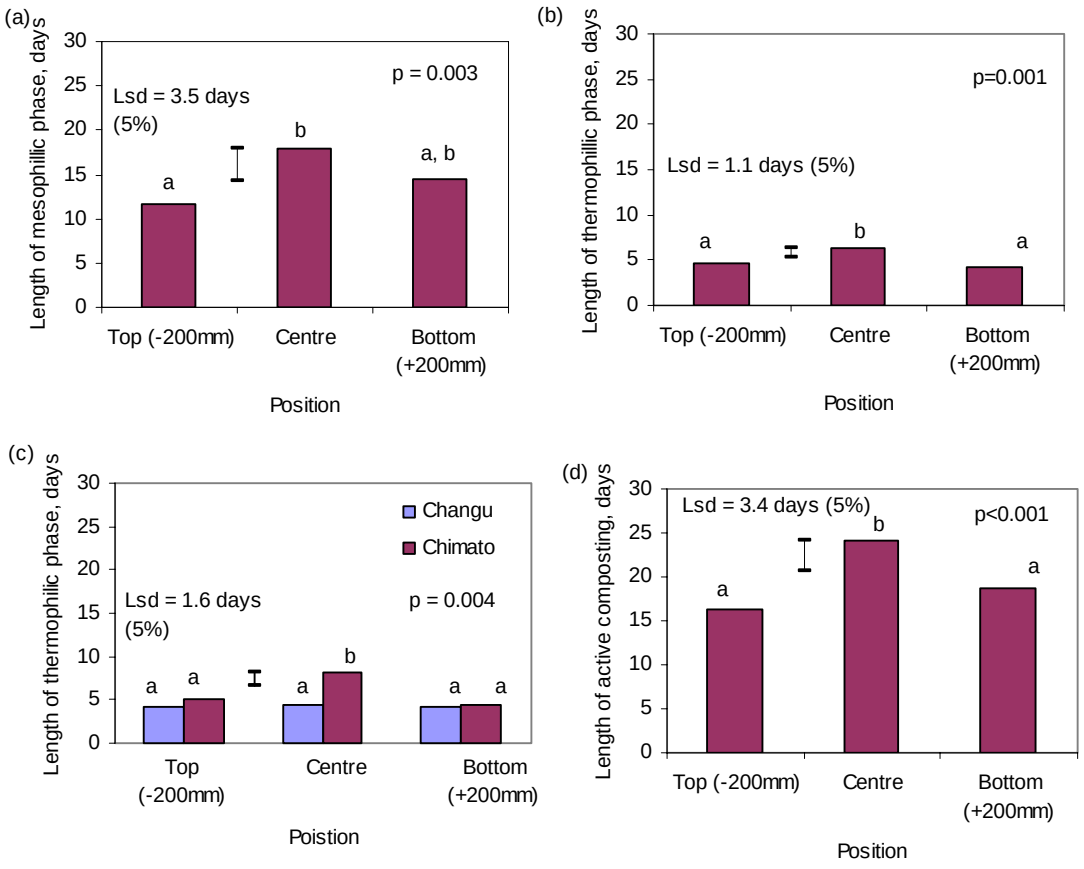

Figure 4.4 Effect of position on the length of (a) mesophilic phase (n = 24), (b) thermophilic phase (n = 24), (c) combined effect of system and position on thermophilic phase (n = 12) and (d) active composting (n = 24) during the 77 day period of composting; error bar represents LSD at 5%; same letter denotes that the means are not significantly different.

4.2.1.2 C:N ratio

Total carbon profiles indicated that C declined with time for all the treatments (Fig. 4.5a). Comparably, the rate of decline of C for treatments with initial C:N 30:1 was steeper than those with C:N 20:1. Despite this, treatments with initial C:N 30:1 had significantly higher concentration of C than C:N 20:1. Treatments with C:N 30:1 had as high as 20% C while those of C:N 20:1 had 16% after 77 days.

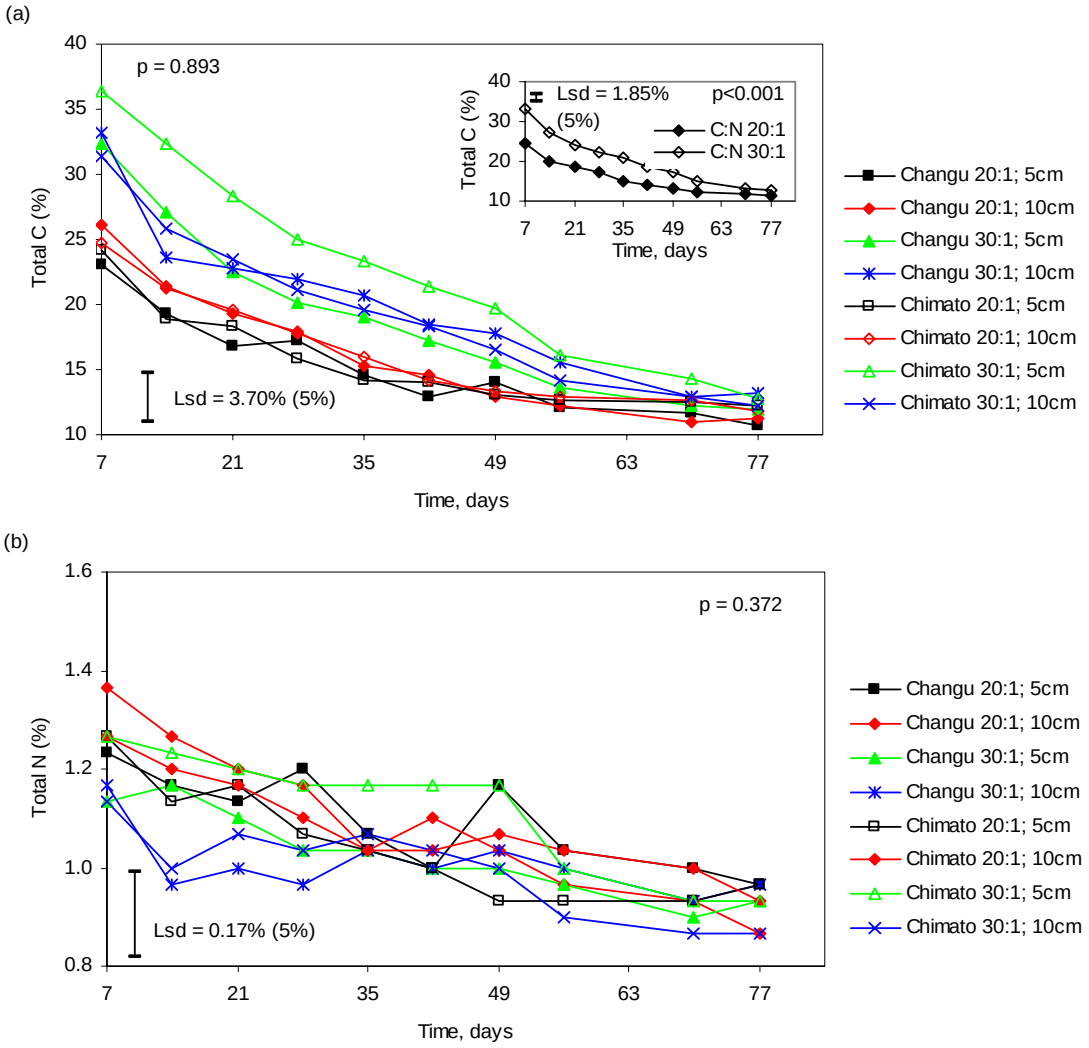

Figure 4.5 Changes of (a) total C (%) and (b) total N (%) for different treatments of initial C:N ratios and chop lengths in Changu and Chimato composting systems during composting of maize straw and bean residues. ANOVA determined no significant interaction between compost system, initial C:N ratio, chop length and time for total N, but there was significant difference for initial C:N and time for total C. Insert show mean across C:N ratios.

Likewise, the contents of total N in the compost declined over time during composting until when the microbial activities stabilized from Day 56 (Fig. 4.5b). N could have been lost through NH_3 volatilization or through volatile organic N containing compounds. There were no significant differences in the decline of N between the Changu and Chimato treatments. Overall, the declining trends of C and N in the different treatments

resulted in the reduction of the C:N ratio of the compost indicating that composting took place (Fig. 4.6 a-b).

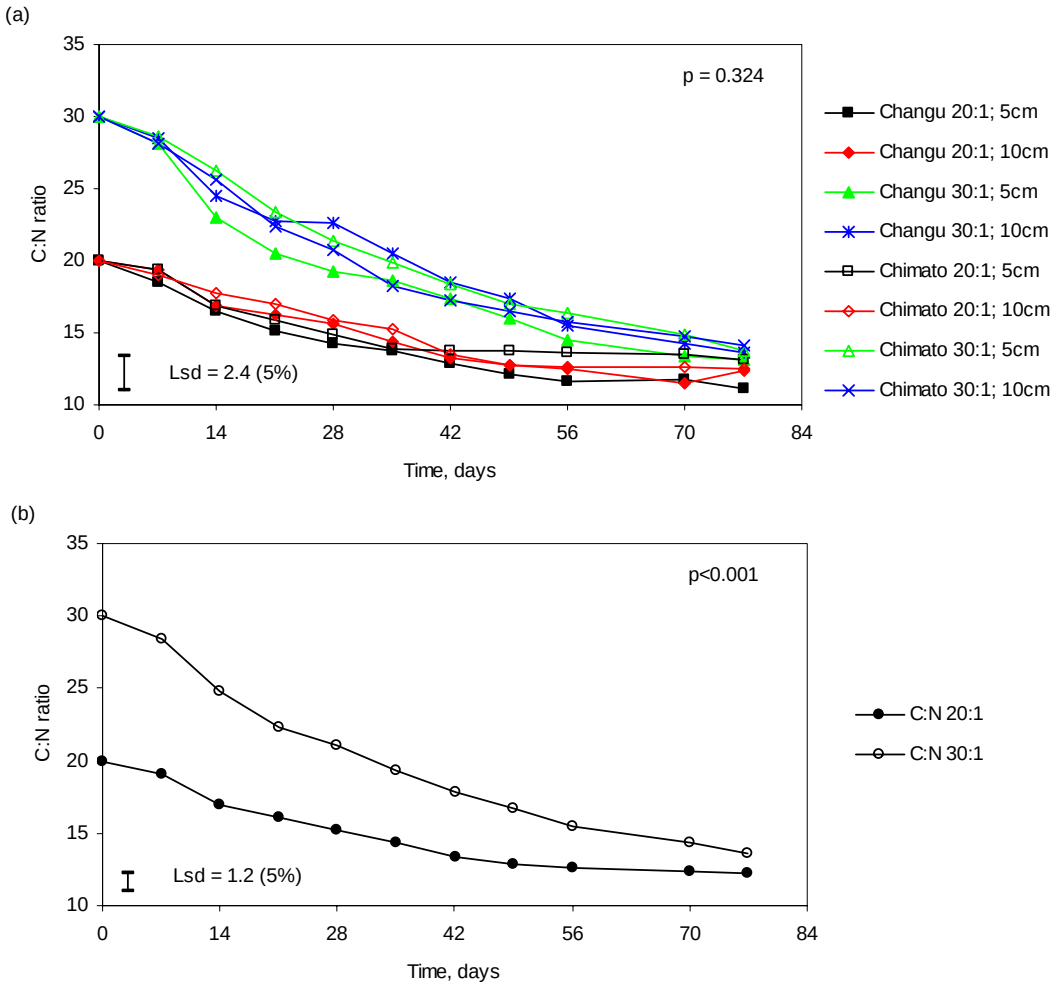

Figure 4.6 C:N ratio trends for (a) compost system, initial C:N ratio, chop length and time interaction and (b) initial C:N ratio of compost and time interaction during composting; ANOVA for interaction of compost system, chop length and time determined no significant differences.

Composting of the maize straw and bean residues was aimed at reducing the C:N ratio of the feedstock to ≤ 20:1. Figure 4.6 indicates that C:N of the different treatments declined from 20:1 and 30:1 to as low as 12:1 and 14:1 respectively. The Changu 20:1 treatments had a C:N decline of 40 – 44% compared to 35 – 38% decline for the Chimato 20:1 treatments over the 77 days during which the composting experiments were run. The Changu treatments had C:N decline percentage of 56% at 30:1 C:N while Chimato had a

decline of 54% for a similar treatment. No differences were observed in the decline of C:N ratio with time between the Changu and Chimato systems despite the differential management processes. This meant that the demands for C and N by microbes were similar in both systems during composting of maize straw and bean residues. The treatments with C:N 30:1 had a greater decline than those of C:N 20:1 since they had more potential C to be oxidized than the low C:N ratio material. Considering the effect of compost-mix and time, C:N 20:1 had consistently lower C:N ratios over time, which were significantly different from those of C:N 30:1 (Fig. 4.6b).

The final C:N ratio was controlled by the initial C:N ratio. The lower the initial C:N ratio, the lower the final C:N ratio by the end of the composting process (Day 77) since these had easily mineralizable substrates. The chop length was not significant in this case.

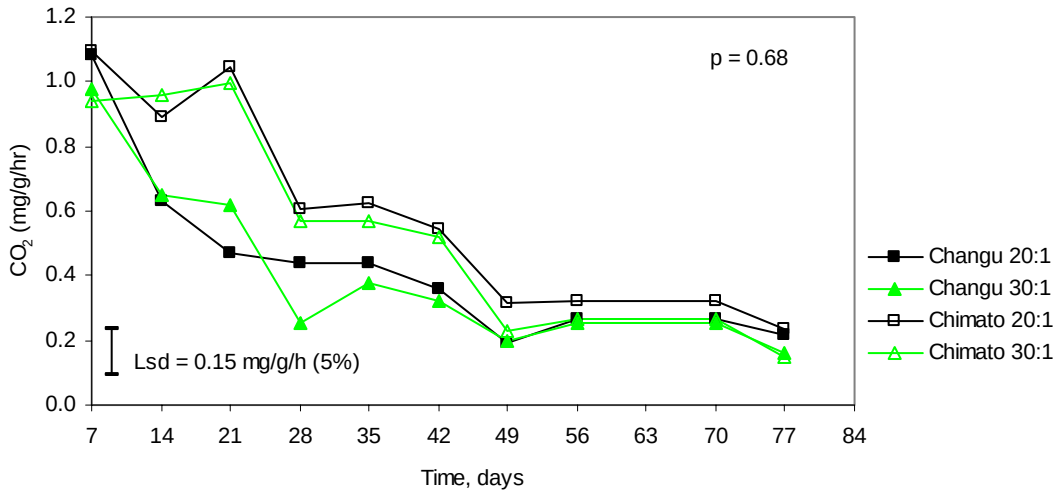

Figure 4.7 Compost respiration profiles for two initial C:N ratios under two composting systems; error bars represent LSD at 5%

Compost respiration rate declined over time indicating that microbially-available carbon substrate was used up by the micro-organisms (Fig. 4.7). The Chimato treatments had higher respiration rates compared to Changu treatments for the majority of the composting period. Despite this trend, the microbial activity for all the treatments declined greatly by Day 49. This coincided with reversion of compost temperature to

ambient levels (Fig. 4.1) and the end of the steep decline of C:N ratio (Fig. 4.6). This implies that the microbial activities were arrested because of exhaustion of available substrates (principally C & N) in the composting material.

Further analysis indicated that treatments with initial C:N ratio 20:1 had significantly higher rates of respiration than those of C:N 30:1 (Fig. 4.8a) and that feedstock made from 5 cm material had significantly higher rates of respiration than those with 10 cm material (Fig. 4.8b). Finally, the Chimato treatments had higher rates than Changu treatments (Fig. 4.8c). For C:N ratio, the low C:N ratio treatments had easily mineralizable C and N which supported higher rates than C:N 30:1. Likewise, the 5 cm materials presented a larger surface area which increases accessibility of the substrate to microbes, accounting for the increased microbial activity *c.f.* the 10 cm material. As for the systems effect, the fact that the Chimato had higher CO_2 released than Changu could be due to differences in the thermophilic phases whereby Chimato had a longer phase than Changu. The complex microbial dynamics during the establishment of the thermophilic microflora could be responsible for the difference based on the findings of Mari *et al.,* (2003). In their study, looking at respiration profiles during composting of olive press cake, they indicated that respiration measurements done at 35°C were good indicators of the mean metabolic potential in the compost piles whereas those measurements taken at higher temperatures (48.5°C) were better indicators of the respiration activity occurring in situ. Furthermore, following the initial thermophilic phase, the respiration potential of the composts at high temperatures (42–63°C) increased drastically compared to their respiration potential at lower temperatures (17–42°C). With reference to the current study, this implies that a higher concentration of CO_2 was released in the thermophilic phase than the later part. Since Chimato had a longer thermophilic phase than Changu (Fig. 4.3b), this resulted in the higher concentration of CO_2 than in Changu. The same argument could be advanced for all the Chimato treatments compared to the Changu treatments in the earlier part of composting.

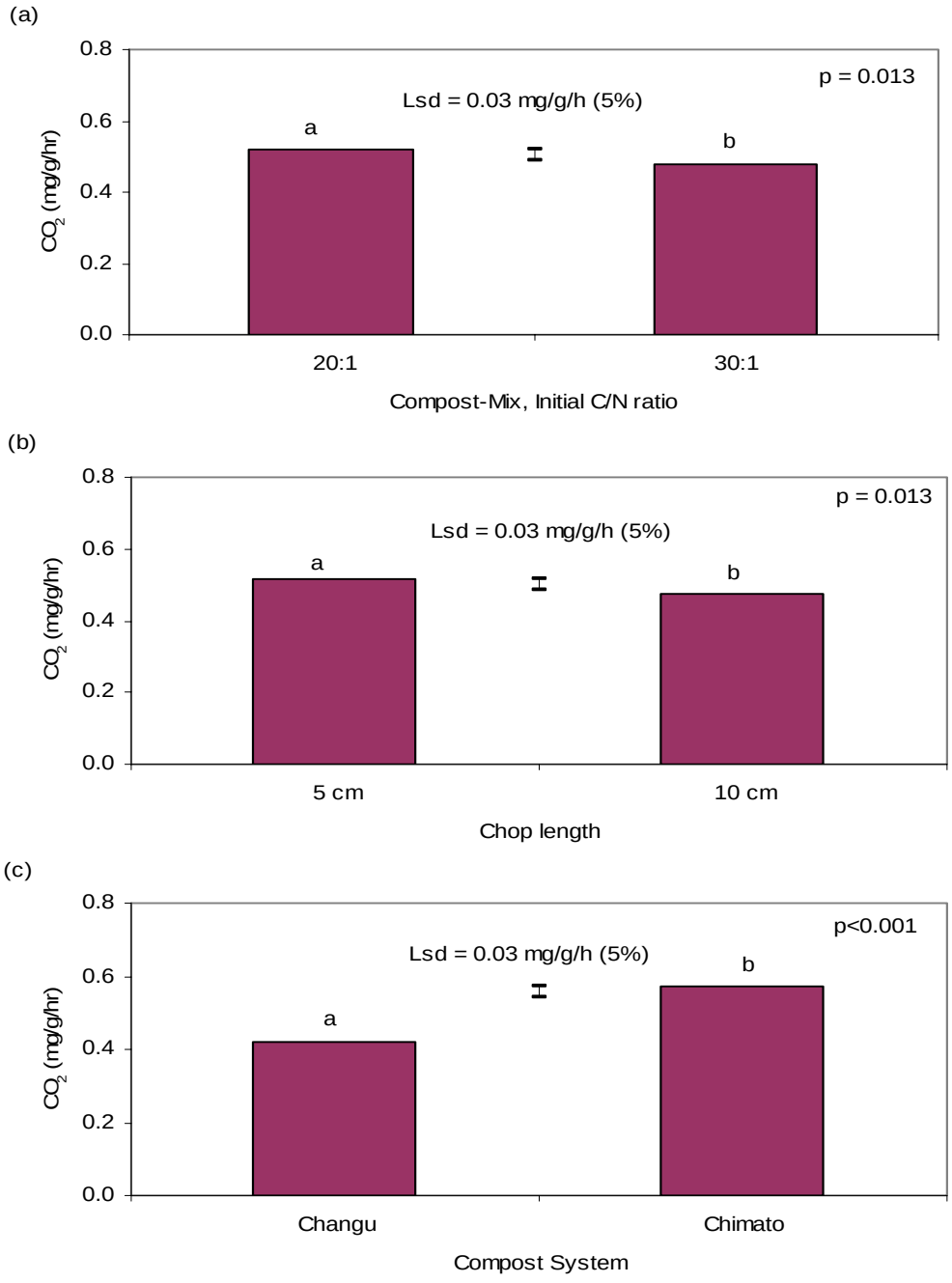

Figure 4.8 Effect of (a) compost-mix (b) chop length and (c) composting system on the mean compost respiration during the 77 day period of composting; error bars represent LSD at 5%; same letter denotes that the means are not significantly different; n = 360.

4.2.1.3 Mineral Nitrogen (N)

NO_3-N and NH_4-N concentrations were measured during composting of maize straw and bean residues. Generally, NO_3-N concentrations increased over time while NH_4-N declined in all the treatments (Fig. 4.9 - 4.12). The NO_3-N concentration ranged from 66 to 809 mg/kg from Day 7 to Day 77 in the Changu system while it ranged from 52 to 650 mg/kg within the same time in the Chimato system.

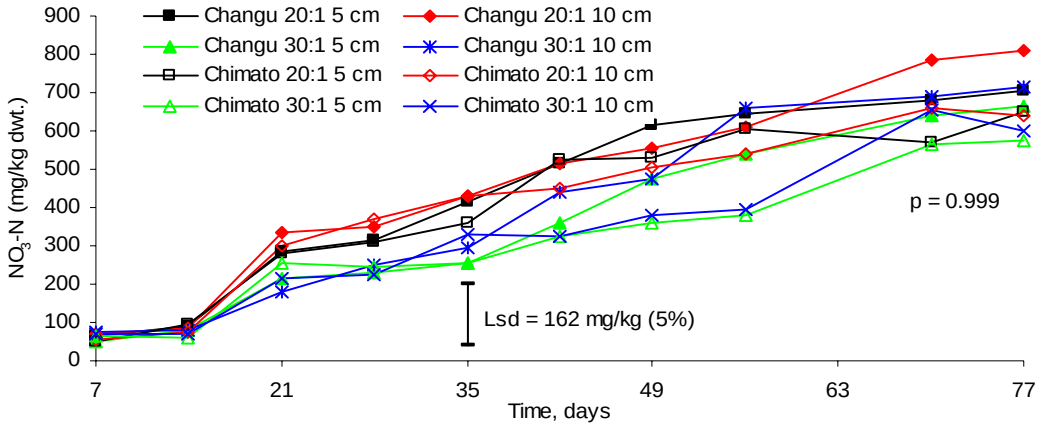

Figure 4.9 NO_3-N concentration in the compost as influenced by the interaction of system, compost-mix (C:N ratio), chop length and time of composting; error bar represents LSD at 5%

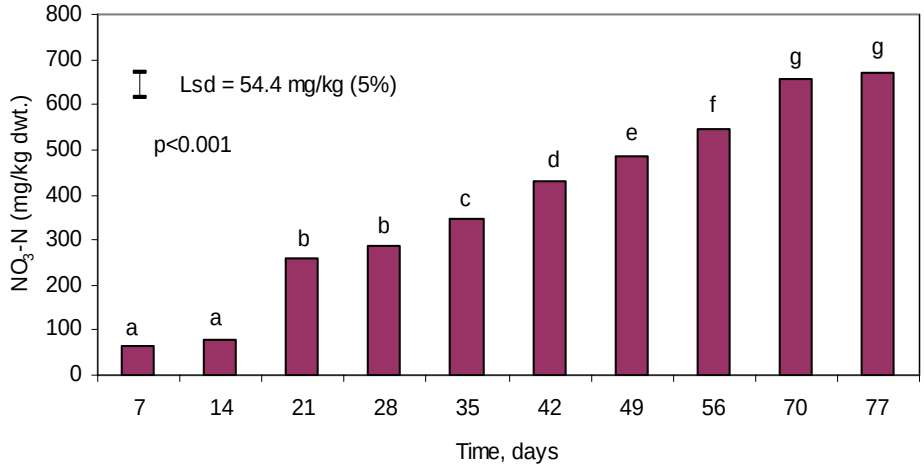

Figure 4.10 Mean NO_3-N concentration of the compost with time; LSD at 5%; same letter denotes that the means are not significantly different; n = 24.

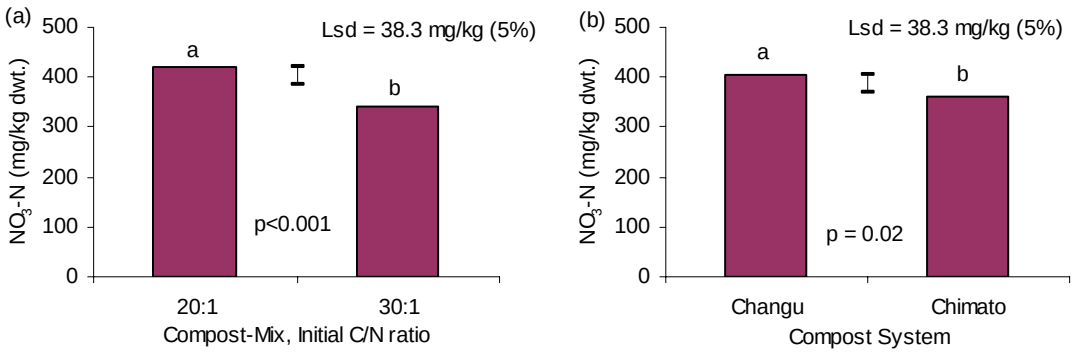

Figure 4.11 The effect of (a) compost-mix and (b) composting system on mean NO_3-N concentration in the compost during the 77 day period of composting; error bars denote LSD at 5%; same letter denotes that the means are not significantly different; n = 120.

NH_4-N concentration ranged from 3 to 111 mg/kg in the Changu system and from 3 to 117 mg/kg in the Chimato system (Fig. 4.12a-c). Analysis for compost-mix effect indicated significant differences where the C:N 20:1 treatments had higher NO_3-N and NH_4-N concentrations than C:N 30:1 treatments (Fig. 4.11a, 4.13a & 4.12b). This was due to increased proportion of easily mineralizable N in C:N 20:1 and that these treatments had more of bean residues (with more organic N) compared to C:N 30:1. Comparing for system effect, Changu system had significantly higher NO_3-N concentration whilst Chimato had a greater NH_4-N concentration (Fig. 4.11b, 4.13b & 4.12c). This is again explained by the differences in management in which turning and watering in Changu sustained microbial activity and mineralization of N compared to Chimato which was limited by insufficient aeration. Furthermore, the differences in aeration and moisture contents affected the ammonification and nitrification processes. The nitrification bacteria *Nitrosomonas* and *Nitrobacter* do not multiply or convert ammonia or nitrites in absence of oxygen. The turning process in Changu promoted the nitrification process due to increased amount of oxygen in contrast to Chimato, hence the higher concentration of TON in Changu and NH_4-N in Chimato. On the other hand, the mud coat in the Chimato systems protected the escape of ammonia gas increasing the concentration of NH_4-N in this system. Other researchers also reported relatively high concentrations of NH_4-N during composting (*e.g.* Dresbøll & Thorup-Kristensen, 2005).

This is common during initial phases of microbial decomposition and elevates pH (Beck-Friis *et al.,* 2003).

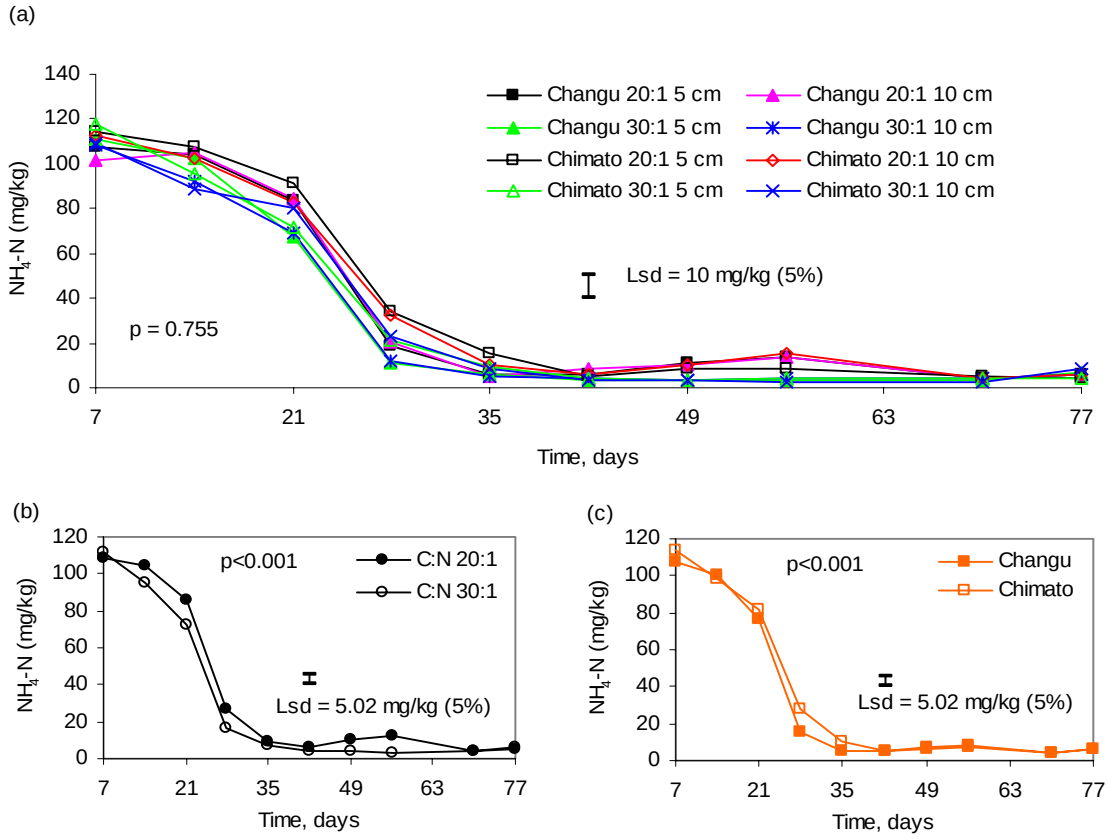

Figure 4.12 Amount of NH_4-N as influenced by interaction of (a) composting system, compost-mixes and chop lengths with time (b) compost-mix and time and (c) composting system and time; error bars represent LSD at 5%

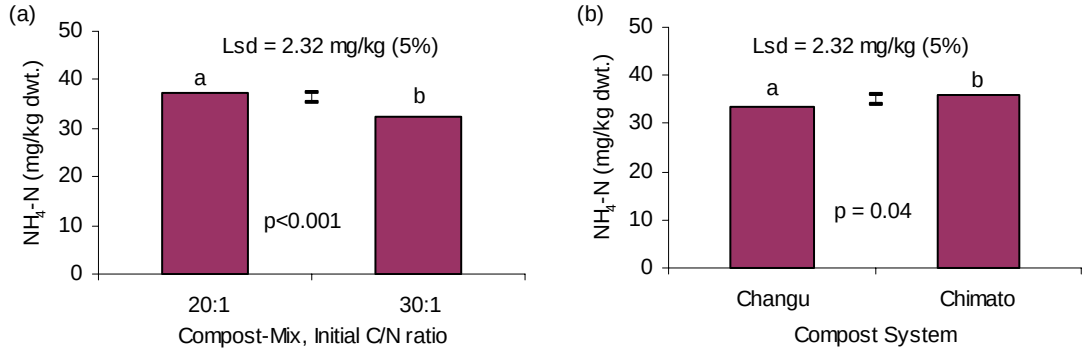

Figure 4.13 The effect of (a) compost-mix and (b) composting system on the contents of mean NH_4-N in the compost during the 77 day period of composting; error bars represent LSD at 5%; same letter denotes that the means are not significantly different; n = 120.

A negative linear relationship was established between NO_3-N and NH_4-N concentrations during composting at C:N 20:1 compared to that for C:N 30:1 (Fig. 4.14a & b). Similarly, linear relationships were also observed between NO_3-N and NH_4-N for Changu and Chimato systems (Fig. 4.14c & d). Thus, the amount of NO_3-N in the compost was related to the concentration of NH_4-N through the nitrification process. The decomposers (bacteria, actinomycetes and fungi) chemically modify the nitrogen found in the organic matter from NH_3 to NH_4-N through mineralization process. Later NH_4-N is converted to NO_3-N by chemical oxidation (nitrification) accomplished by bacteria *Nitrosomonas* and *Nitrobacter*. This implies that the concentration of NH_4-N in the solution determined the concentration of NO_3-N produced.

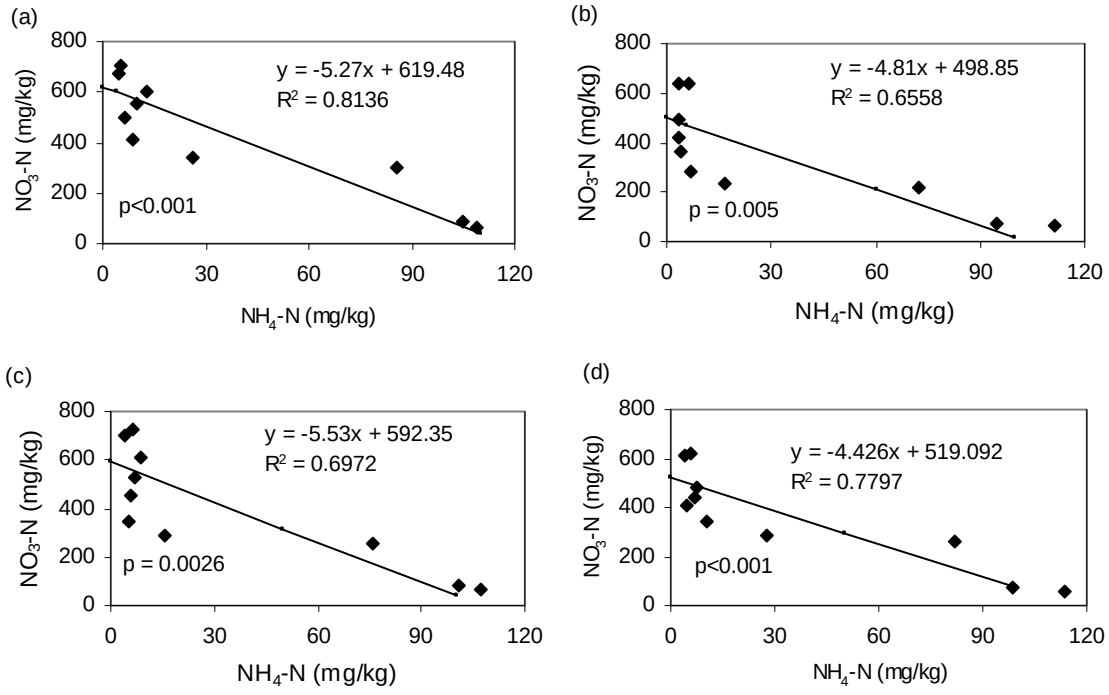

Figure 4.14 Linear regression for NO_3-N and NH_4-N during composting for (a) initial C:N 20:1; (b) initial C:N 30:1; (c) Changu System and (d) Chimato system treatments; R^2 coefficient of determination.

4.2.1.4 Potassium (extractable K) and phosphorus (phosphate-P)

Generally, no differences were observed due to interaction of system, compost-mix (initial C:N ratio) and chop length (Fig. 4.15). The concentration of extractable-K did not show significant temporal variation unlike those observed by Lhadi *et al.,* (2004) who recorded an increment of K over time during composting municipal waste and poultry manure. Nonetheless, on average, over time, there was a direct effect of compost-mix and system on the amount of extractable-K in the compost (Fig. 4.16). Treatments with low initial C:N ratio were associated with higher amounts of K than with C:N 30:1 while the Chimato system had 6% more extractable-K than the Changu system. For the compost-mix, the higher concentration of K can be explained by the higher concentration of the K in the bean residue (Table 4.1). The 20:1 C:N treatments had more bean residue compared to C:N 30:1. The fact that the Chimato system had higher concentration of K meant that the prolonged activities of microbes in Changu (see Fig. 4.1 *i.e.* temperature profiles) demanded more K than in Chimato. Thus, more K was ingested and fixed by the microbes in Changu treatments reducing the concentration extractable-K in the solution. This implies that microbes require K for their activity *i.e.* K was limiting.

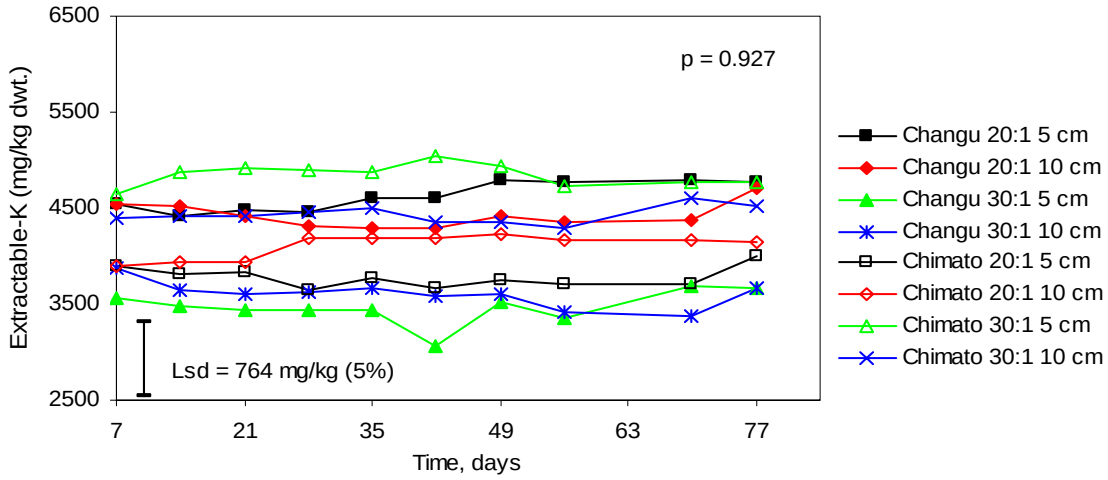

Figure 4.15 Potassium mineralization during composting of different C:N ratios, chop length and compost systems; error bar represent LSD at 5%

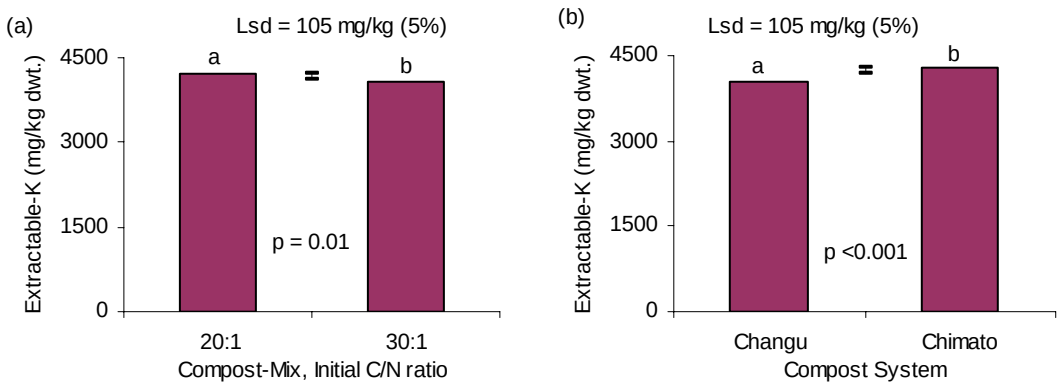

Figure 4.16 Effect of (a) compost-mix and (b) composting-system on the concentration of mean extractable-K in the compost during the 77 day period of composting; error bar LSD at 5%; same letter denotes that the means are not significantly different; n = 120.

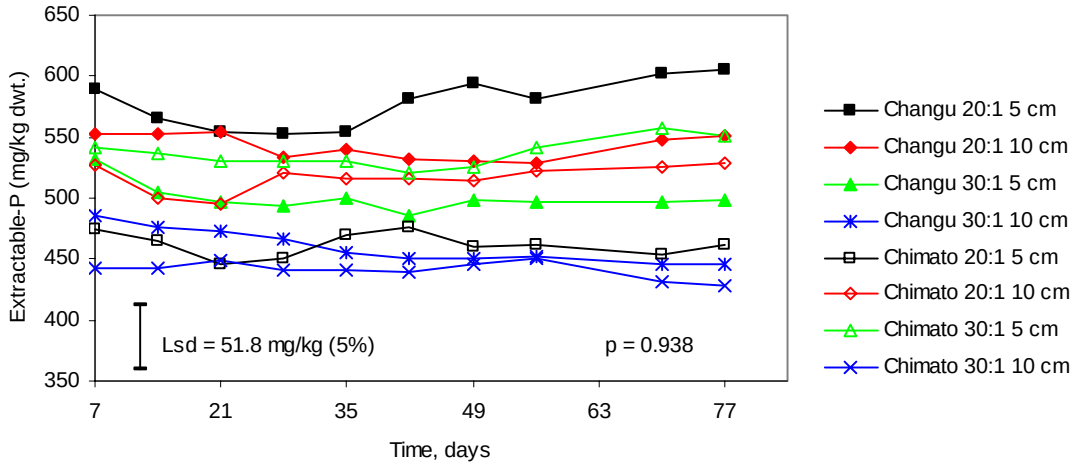

Figure 4.17 Mineralization of phosphorus during composting of different C:N ratios, chop length and compost systems; error bar denotes LSD at 5%.

Generally, there was a decline in extractable-P over the first 35 – 42 days followed by a release as time progressed (Fig. 4.17). On average, treatments with C:N 20:1 had significantly higher concentrations of extractable-P than C:N 30:1 while the Changu system had significantly more extractable-P than Chimato (Fig. 4.18a & b). The results further indicated significant differences between chop lengths where 5 cm compost was associated with more P than 10 cm compost (Fig. 4.18c). There was also significant interaction of chop length with system and mix (Fig. 4.19). The results indicate that the lower the C:N ratio and the shorter the chop length, the higher the amount of P

mineralized. This is due to the high amount of bean residue used in the low C:N ratio treatments which contained more P. On the other hand, the low C:N ratio treatments were also associated with higher microbial activity as shown by the temperature profile (see Section 4.2.1.1) and this released more extractable-P. Similarly, Changu treatments were associated with prolonged microbial activity (see Fig. 4.1). The increased activities facilitated the mineralization of P which consequently increased the concentration of extractable-P in the solution and compost. As for chop length, the 5 cm material exposed a larger surface area for microbial activity and hence more P was mineralized. The results imply that organic mineralization of C and N requires P to support microbial multiplication and growth, hence mineralization of P which is eventually released when the microbes die (Felton *et al.,* 2004).

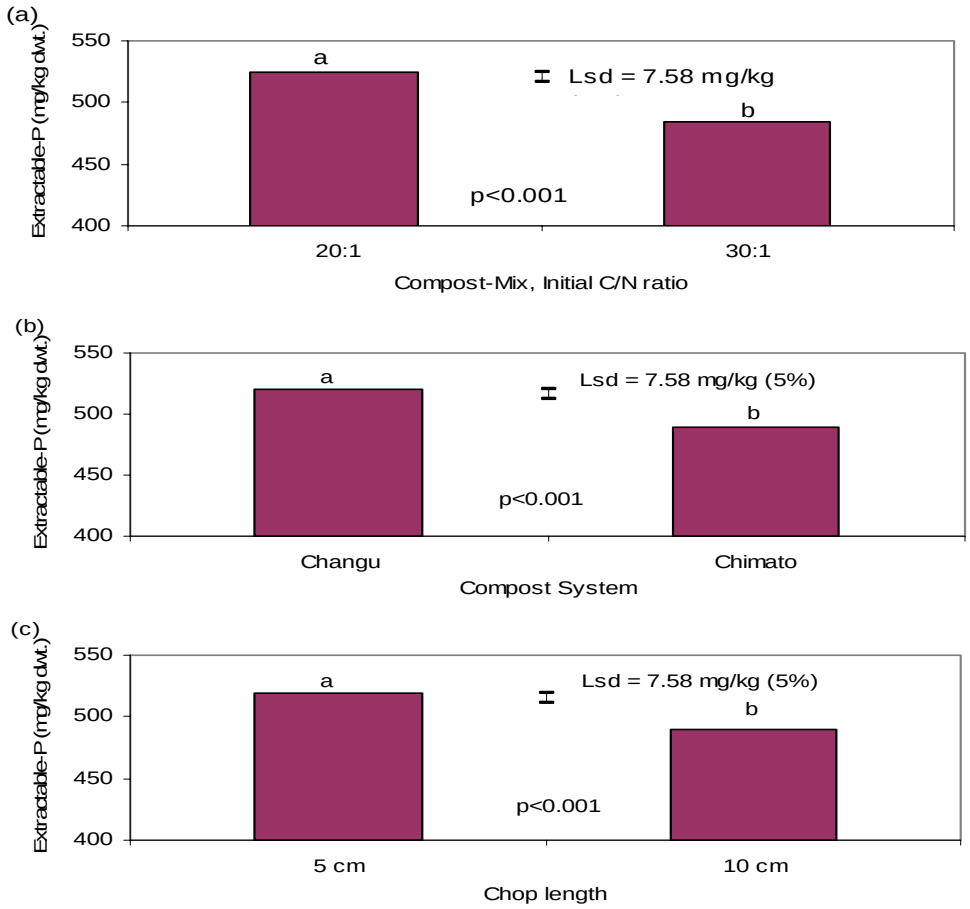

Figure 4.18 Effect of (a) compost-mix, (b) composting system and (c) chop length on the concentration of mean extractable-P of the compost during the 77 day period of composting; error bar is LSD at 5%; same letter denotes that the means are not significantly different; n = 120.

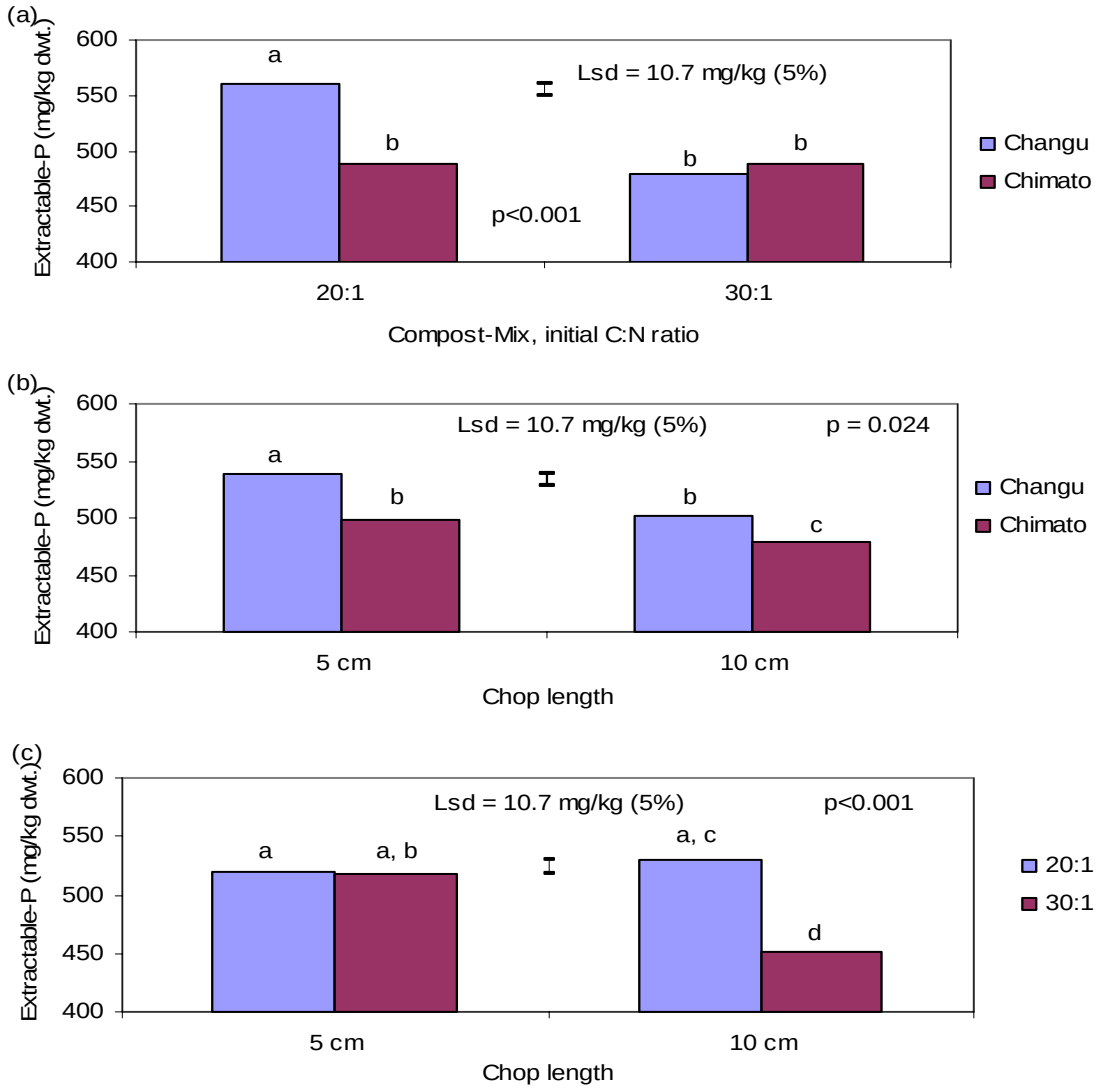

Figure 4.19 Effect of (a) compost-mix (initial C:N ratio) and system, (b) chop length and system, and (c) chop length and compost-mix on mean extractable-P concentration in the compost during the 77 day period of composting; error bars LSD at 5%; same letter denotes that the means are not significantly different; n = 60.

4.2.1.5 Compost pH

The pH of the compost ranged across 1.7 units during the composting of maize straw and bean residues (Fig. 4.20). The pH of different treatments generally increased in the first 14 to 28 days and decreased until Day 35 when it elevated again until Day 49 when it

finally dropped. The first peak of the pH increase coincided with the high concentrations of NH_4-N (Fig. 4.12) and the drop which followed could be due to the production of the organic acids which is expected in the initial phase of composting due (Beck-Friis *et al.,* 2003). The cause of the subsequent peak could be due to the complex interactions of microbes within the compost matrix. The decline after Day 49 could be as a result of nitrification process. Overall, the range of the pH during composting was unlikely to have been restrictive to the microbial growth and activity. No further correlations were observed between the pH and NH_4-N concentrations during the 77 day composting period.

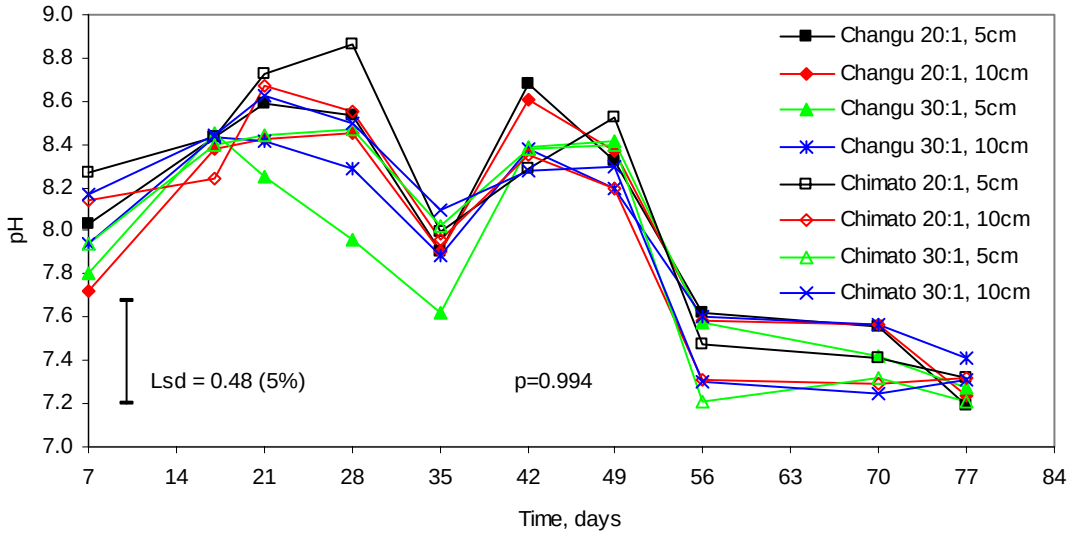

Figure 4.20 pH developments during composting of different materials using Changu and Chimato systems; error bar represents LSD at 5%.

4.2.1.6 Cress seed germination

Cress seed germination was assessed on all compost sampled at different dates (see Chapter 2, Section 2.8.1). Compost was assessed as matured when it obtained ≥ 60% of cress seeds germinated when planted direct into the compost. The sampling day for which the samples met the set criteria was the day it was deemed that the particular treatment matured. Results indicated that Changu 20:1, 5 cm, Changu 30:1, 5 cm and Chimato 20:1,

10 cm were matured by Day 42. The other treatments matured by Day 49 of composting when their seed germination met the set criteria (Table 4.3). The results showed that composting of maize straw and green bean residues produced toxic substances which could hinder plant growth if immature compost is used to amend soil for crop production.

Table 4.3 Cress seed germination percentage obtained 10 days after direct seed sowing in compost sampled at 8 different composting durations for the two initial C:N ratios and two chop lengths in the Changu and Chimato composting systems in Malawi

System	*Initial C:N*	*Chop length (cm)*	*Germination % Day*							
			14	*21*	*28*	*35*	*42*	*49*	*56*	*77*
Changu	20:1	5	6	5	32	36	62	88	83	82
		10	1	4	36	53	54	83	77	75
	30:1	5	5	24	25	52	70	83	69	80
		10	2	12	36	53	59	79	75	82
Chimato	20:1	5	4	12	18	41	56	83	65	76
		10	3	5	26	46	66	81	79	75
	30:1	5	8	6	22	49	55	83	76	70
		10	7	15	45	40	36	76	75	76

4.2.1.7 Compost yield from different treatments

The results of the total compost yield presented as dry weight indicated the impact of the composting system on the total yield (Table 4.4). The Changu treatments produced 15% more matured compost compared to the Chimato treatments. This was attributed to the system's capacity in promoting composting factors *i.e.* oxygen and moisture of which in abundance promoted increased and prolonged microbial activity. The lack of turning and watering in the Chimato systems created dry and anoxic conditions. This was prevalent especially in the areas close to the mud coat which was away from the aeration hole created during the construction of the heap. This resulted in little or no decomposition of the organic material reducing the total amount of the matured compost yielded from the Chimato treatments. Contrary to this, the Changu treatments were turned on weekly basis and moisture adjusted accordingly promoting even decomposition of the organic material thereby increasing the amount of the matured compost obtained from this system.

Table 4.4 The total dry compost yield obtained at the end of composting two initial C:N ratios and two chop lengths using Changu and Chimato systems in Malawi

System	*Initial C:N*	*Chop length (cm)*	*Total compost yield (kg dwt./heap)*
Changu	20:1	5	93
		10	93
	30:1	5	89
		10	89
Chimato	20:1	5	79
		10	79
	30:1	5	76
		10	76

4.2.2 Overall performance of the Chimato and Changu systems

The composting process of maize straw and bean residues in the field was influenced both by the compost-mix and the composting system. The treatments with low C:N ratio (20:1) were associated with higher temperatures, and a significantly longer mesophilic (17 days) and active composting period (23 days) than high C:N ratio (30:1) compost (12 days and 17 days respectively). The compost-mix also influenced the final C:N ratio of the compost and the nutrient contents of the compost. The lower the initial C:N ratio, the lower the final C:N ratio. The low final C:N ratio (12:1) compost contained 18% more NO_3-N, 8% more extractable-P and 3% more extractable-K than the high final C:N compost (C:N 14:1). This was due to the fact that the lower C:N ratio feedstock contained more bean residues, which had more organic nitrogen, phosphorus and potassium compared to the higher C:N ratio feedstock. This promoted higher microbial activity and more nutrient mineralization.

The Changu system was associated with a significantly longer mesophilic (19 days) and active composting phase (23 days) than Chimato treatments (11 and 17 days respectively) despite the Chimato system having a longer thermophilic phase than the Changu system. The Changu treatments were characterised by temperature profiles which indicated response to aeration management applied and this promoted longer microbial activities as evidenced by the peaks of the temperature profiles. This was contrary to Chimato, which

had only one peak in the temperature profile, which was followed by a constant decline in microbial activity (declining temperatures). This scenario resulted in a significantly higher NO_3-N concentration in the Changu system which was 12% higher than that in Chimato system. The Changu treatments were also associated with higher concentration of P whereas the Chimato contained more K and NH_4-N. Unlike in Changu, Chimato had some patches of partly decomposed material, an indication of limited aeration in the system which can be deduced from the temperature profiles. This meant that the mud coat, despite protecting the heap from adverse weather and cooling and drying winds, compressed the feedstock reducing the porosity of the material. This combined with lack of turning worsened the aeration status. All the treatments were classified as matured by Day 77 (Table 4.5) although NH_4-N concentration was high. This meant that all the resultant compost produced from the feedstock with initial C:N ratios 20:1 and 30:1 was safe for use in crop production.

No direct effect of chop length was observed with respect to C:N, temperature, mineral N and extractable-K. With extractable-P and compost respiration, the smaller length (5 cm) was associated with more P and higher respiration rates. This is most likely due to increased plant-matter surface area for microbial activity.

The results from this section consolidated the hypothesis tested in Chapter 3 that the type and quality of feedstock determines the behaviour of composting system (Hypothesis 1 in Chapter 1), and this applies in the field. It further supported the hypothesis that systems differ in their influence on composting process (Hypothesis 3) as was established in Chapter 3. But this section provided new information on the influence of the environment on composting process. Compost rates were greater when composting in the field (Malawi) compared to the study in the glasshouse where the ambient temperature was higher than in the winter months in the UK, which promoted a more rapid composting. The composting took 77 days in Malawi compared to 112 day in the UK for wheat straw. As much as this could also be due to the differences in the feedstock used between Malawi and the UK, the ambient temperature differences contributed to the increased

composting process. This supports Hypothesis 2 (in Chapter 1), that environmental conditions influence the rate of composting.

Table 4.5 Maturity and stability parameters obtained on day 77 for two initial C:N ratios and two chop lengths in the Changu and Chimato composting systems after composting maize straw and bean residues

System	*Initial C:N*	*Chop length* (cm)	*Maturity and stability parameters*				
			C:N {≤ 15-20}	*CO_2 {< 1 mg/g/h}*	*NH_4^+/NO_3^- {< 0.16}*	*NH_4-N {< 0.04%}*	*Cress seed germination % {≥ 60%}*
Changu	20:1	5	11	0.23	0.009	6.24	82
		10	12	0.21	0.007	5.56	75
	30:1	5	13	0.19	0.011	7.12	80
		10	14	0.13	0.008	5.66	82
Chimato	20:1	5	13	0.19	0.007	4.31	76
		10	13	0.28	0.009	5.81	75
	30:1	5	14	0.17	0.008	4.49	70
		10	14	0.12	0.014	8.44	76

{Critical values} sources: Golueke, 1977 & 1991; Pare *et al.,* 1977; Bernal *et al.,* 1998

4.2.3 Conclusions

a. Composting took place in the field (Malawi) with maize straw/green bean residues evidenced by the decline in C:N ratio with time.
b. The lower the initial C:N ratio, the lower the final C:N ratio of the compost and longer the thermophilic, mesophilic and active composting period. Furthermore, the lower the initial C:N ratio, the higher the concentration of the nutrients in the final compost produced.
c. There was no direct influence of chop length (5 & 10 cm) on the composting of maize straw/bean residues system at a smallholder scale. This means that the farmers can safely use the bigger chop length without adversely affecting the composting process, thereby reducing labour costs in the process.
d. The Changu treatments were associated with longer mesophilic and active composting phases whereas Chimato had longer thermophilic phases when composting was done in the open field.

e. The mud coat in the Chimato system is effective in protecting the heap from cooling but it restricts aeration and shortens the active composting phase. Consequently, not all organic materials compost at the same rate.
f. The weekly turning and watering of Changu heaps is an effective method of aeration of compost heaps at the smallholder scale and promoted longer composting, which resulted in higher levels of nutrients (especially mineral N) compared to Chimato treatments. However, this requires a greater labour, water and time input.

4.3. Mineralization experiments

4.3.1 Results and discussion

4.3.1.1 Total C, N and C:N ratio of the soil/compost mixture during incubation

The total N content of the soil/compost mixtures from the different treatments showed a temporal variation during incubation of compost in the soil. Nonetheless, no significant decline of N was observed between Day 0 and Day 84 in all the treatments (Fig. 4.21a - c). This scenario was also observed for total C (Fig. 4.22). The trend of the C:N ratio during incubation mimicked that of the total C and total N (Fig. 4.23). There was a slight increase in the C:N ratio at the end of incubation in the control whereas it declined in the different compost-mix treatments (Fig. 4.23). The increase in C:N in the control was as a result of the relative decline in total N to total C. Despite there being no differences between the end C:N ratios of the control and the other treatments, the control had a higher C:N ratio meaning that it had a greater carbon to nitrogen content which consequently limited the mineralization of N.

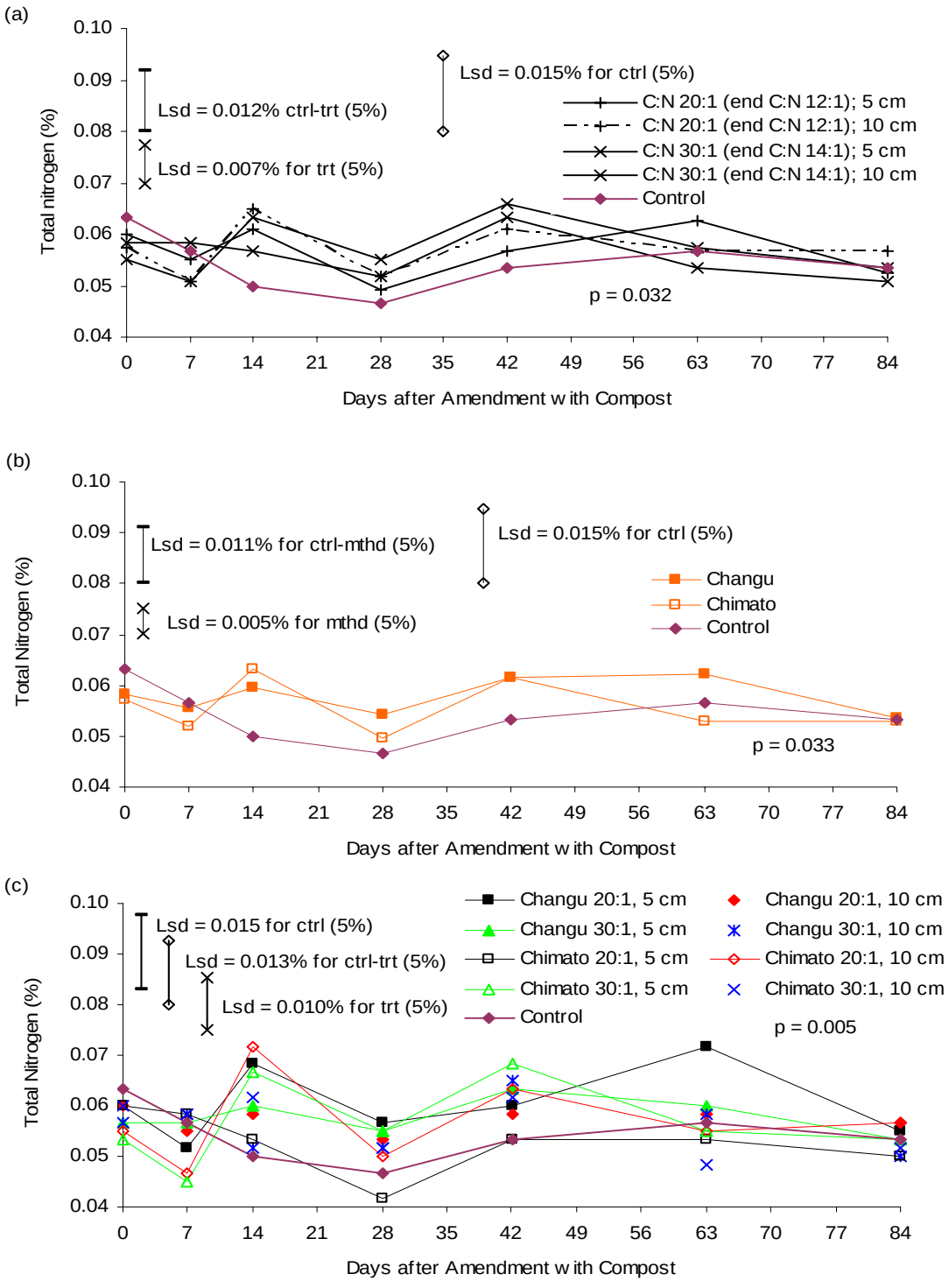

Figure 4.21 Total nitrogen of the soil during incubation of compost for (a) different C:N ratios and chop lengths, (b) composting systems and (c) interaction of composting system, compost-mix ratio and chop length; error bars represent LSD at 5%.

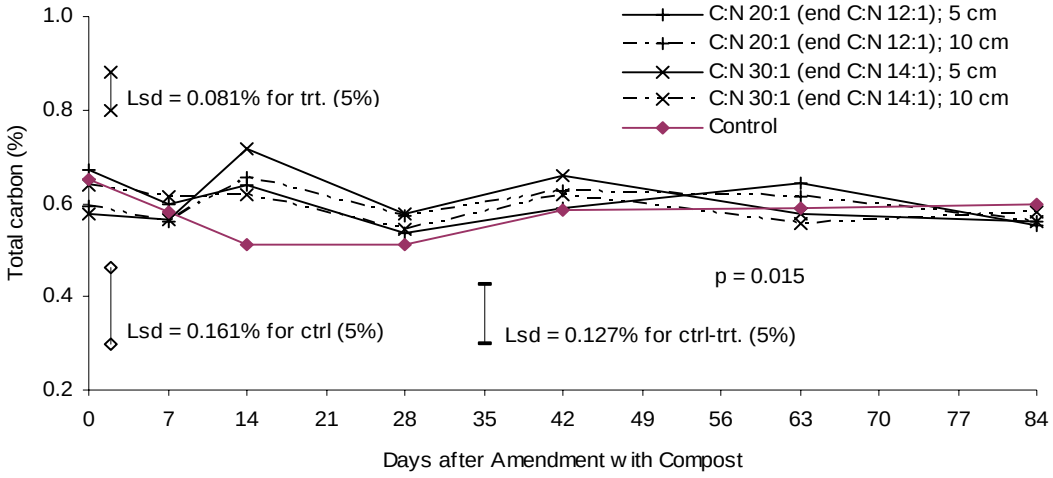

Figure 4.22 Total carbon of the soil during incubation of compost of different C:N ratios and chop lengths; error bars represent LSD at 5%.

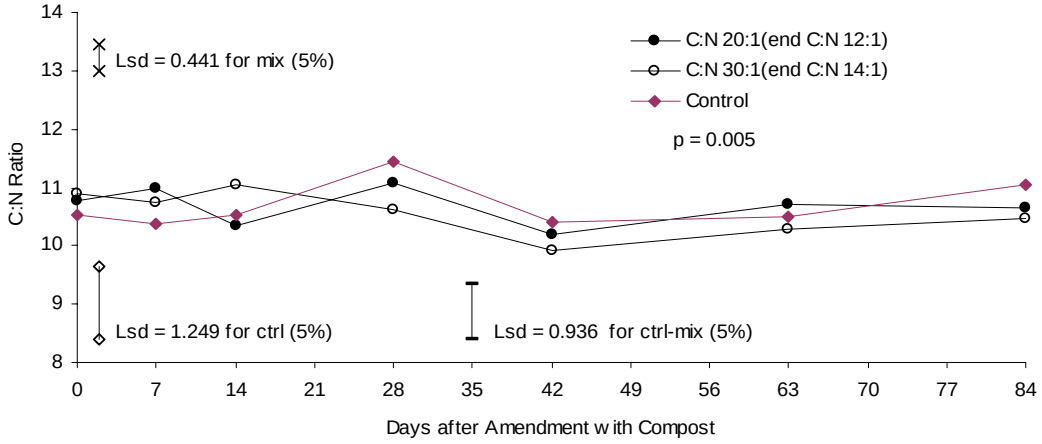

Figure 4.23 C:N ratio of the soil during incubation of compost of different C:N ratios; error bars represent LSD at 5%.

4.3.1.2 Mineral Nitrogen (TON)

During incubation of soil amended with compost made from maize straw and bean residues, no NH_4-N was observed, but only TON. With respect to TON, no interactions of system, initial compost-mix, chop length and application rate was observed.

Nonetheless, there was a direct effect of compost-mix and composting system on mineralization of TON following amendment of soil with compost (Fig. 4.24). Mineralization of organic N was observed throughout the 84 day incubation of the compost in both the C:N ratio treatments compared to the control. The amount of TON increased with time in all the treatments and the control due to increased microbial activity with time. Treatments with the final C:N 12:1 (initial C:N 20:1), mineralized significantly more TON than the control throughout the incubation except on Day 7 (Fig. 4.24a). Similarly, treatments with final C:N 14:1 (initial C:N 30:1) mineralized significantly more TON than the control on Day 42. Comparison of the two C:N treatments indicated that final C:N 12:1 had significantly more TON than final C:N 14:1 during the entire incubation period except on Day 7. These results suggest that the compost used in this experiment had sufficient amounts of N required for initiation of microbial organic N mineralization. It also indicated that the low C:N ratio compost contained more readily available N than high C:N compost. Thus, no immobilization of N was observed with respect to the control using the treatments tested here as was the case in the UK sourced compost experiments (Chapter 3). This is evidenced by the results of the C:N ratio of the different compost-mixes (C:N ratios) and the control above (Fig. 4.23) in which case the different compost-mix treatments had similar C:N ratios to that of the control.

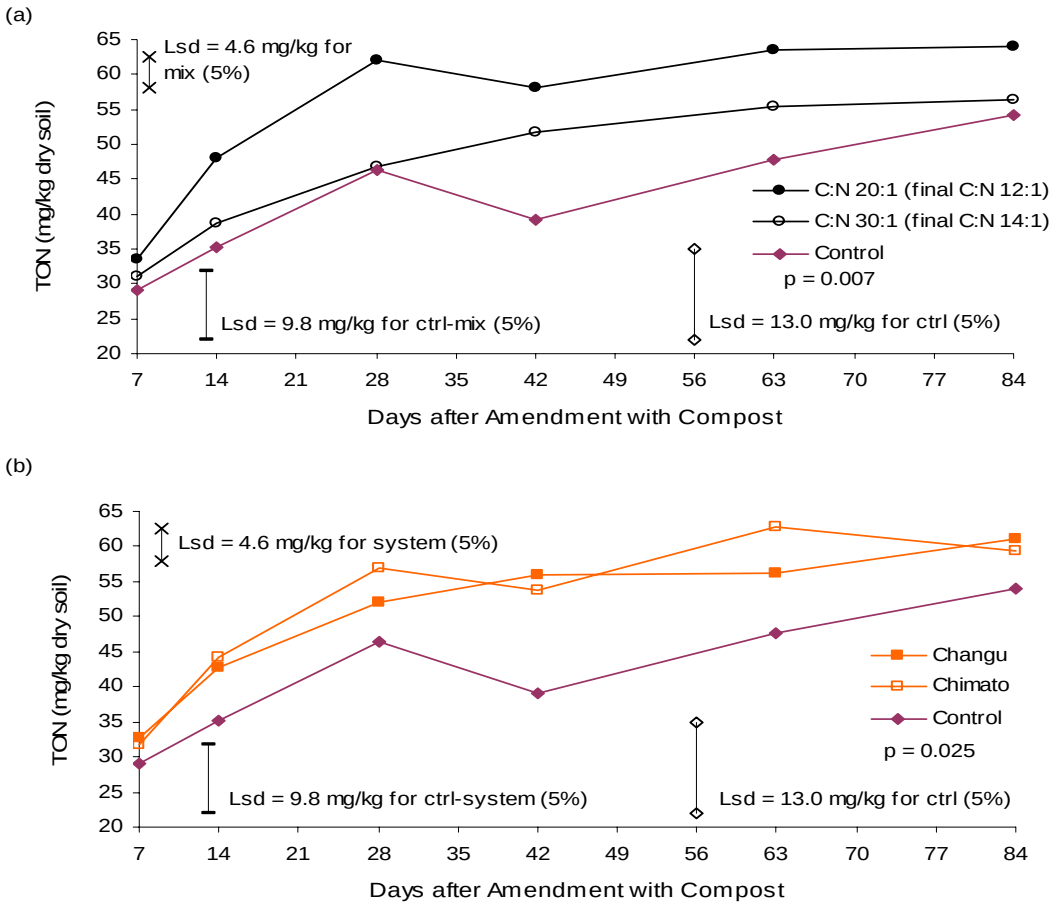

Figure 4.24 Mineralization of organic nitrogen during incubation of compost for (a) two initial C:N ratios and (b) two composting systems when compost was applied into the soil; error bars denote LSD at 5%.

With respect to the composting system, the concentration of TON increased over time. The Changu treatments had a significantly greater concentration of TON than the control on Day 42 while Chimato had a greater concentration of TON than the control from Day 28 to Day 63 (Fig. 4.24b). On the other hand, the Chimato treatments had a significantly greater concentration of TON than Changu on Day 28 and Day 63. Nonetheless, there were no significant differences in the total amount of TON mineralized between the systems. The lack of the differences in the total amount of TON mineralized is due to the fact that there were no differences observed in the final C:N ratios obtained from the treatments involving the two systems (Section 4.2, Fig. 4.5 & 4.6). This meant that there was a similar content of total C and total N which was liable to mineralization. The

variations in the TON concentrations between the two systems during incubation could be due to variations in the microbial activity due to fluctuations in moisture content.

4.3.1.3 Extractable phosphorus and potassium

The concentrations of extractable-P showed a range of 11.1 mg/kg during incubation of the compost (Table 4.6). A decline of extractable-P was observed in most of the treatments and the control in the first 14 days followed by a release peak by Day 28. There was a gradual decline of P from Day 28 to Day 84 and generally no differences were observed in all the treatments tested during the same period except for the rate effect (Table 4.6). Since the pH during incubation was between 6 and 7 (see later this section, when most soil-P is available), the decline in extractable-P was likely not as a result of chemical fixation *i.e.* forming insoluble complexes with manganese (Mn), iron (Fe) or calcium (Ca). This implies that this was as a result of microbial demand at the onset of mineralization process.

Treatments with low initial C:N ratio 20:1 (final C:N ratio 12:1) had significantly lower extractable-P concentration compared to the control in the first 14 days but no differences were observed between the control and initial C:N 30:1 (final C:N 14:1) (Table 4.6). Treatments with low initial C:N had significantly lower concentration of P compared to those with higher C:N the first 14 days (Table 4.6). The Changu treatments had significantly lower concentration of P on Day 0 only compared to the control while Chimato treatments contained significantly lower P concentration over the first 14 days compared to the control (Table 4.6). Comparison of the two systems indicated that the Changu had higher concentration of extractable-P compared to the Chimato in the first 14 days only. There were no differences observed due to chop length of the material in the later days of incubation. The significant differences were observed in the first 14 days when 5 cm compost contained more P which was significantly different from that of the control (Table 4.6). The only difference between the control and 10 cm compost was on Day 0. The differences between 5 cm and 10 cm compost were variable and showed no distinct trends (Table 4.6).

Table 4.6 Mineralization of phosphorus during incubation of soil amended with compost made of maize straw and bean residues for the two C:N ratios, two composting systems, two chop lengths and two application rates

	Day						
Treatment effect	0	7	14	28	42	63	84
Compost-mix effect				mg/kg			
C:N 20:1 (end 12:1)	19.3a	22.4a	18.8a	29.1a	26.6a,c	26.3a,c	24.8a
C:N 30:1 (end 14:1)	21.9b	21.1a	20.6b	29.1a	27.7b,c	24.9b,c	24.2a
Control	23.6b	22.3a	21.6b	29.4a	28.8c	26.3c	25.1a
LSD	1.04 mg/kg for the mix & 2.21 mg/kg for control-mix						
System effect							
Changu	20.9a	22.3a,c	20.6a,c	28.6a	27.4a	25.9a	24.5a
Chimato	20.3a	21.2b,c	18.9b	29.6a	26.9a	25.3a	24.5a
Control	23.6b	22.3c	21.6c	29.4a	28.8a	26.3a	25.1a
LSD	1.04 mg/kg for the system & 2.21 mg/kg for control-system at 5%						
Chop length effect							
5 cm	21.3a	22.0a	18.7a	28.6a	27.4a	26.0a	24.2a
10 cm	19.8b	21.5a	20.7b,c	29.5a	26.9a	25.2a	24.9a
Control	23.6c	22.3a	21.6c	29.4a	28.8a	26.3a	25.1a
LSD	1.04 mg/kg for the size & 2.21 mg/kg for control-size at 5%						
Rate effect							
10 t/ha	20.5a	22.2a	19.2a	28.4a,c	26.4a	25.4a	24.2a
30 t/ha	20.6a	21.3a	20.2a,b	29.8b,c	27.9b,c	25.8a	24.8a
Control	23.6b	22.3a	21.6b	29.4c	28.8c	26.3a	25.1a
LSD	1.04 mg/kg for rate & 2.21 mg/kg for control-rate at 5%						

Means within the same column and treatment effect followed by the same letters are not significantly different ($p > 0.05$).

With regard to compost application rate, the control had significantly more extractable- P than equivalent 10 t/ha rate on Day 0, 14 and 42, but differed with 30 t/ha only on Day 0 when 30 t/ha contained significantly lower P concentrations (Table 4.6). On the other hand, treatments with 10 t/ha rate contained significantly lower P concentrations compared to 30 t/ha rate on Day 28 and 42.

The higher concentration of extractable-P in the control compared to the rest of the treatments at the beginning of the incubation are accredited to the fact that the soil had readily extractable-P at the onset whereas the composted incubations contained more organic-P which required microbial mineralization to release it into the soil solution. In addition, the microbes would have required some P at the beginning of the mineralization process of the composted soils which suppressed the extractable-P levels (generally in the first 14 days). When the mineralization process was fully initiated, there were no differences between the control and the rest of the treatments (Table 4.6). The observed higher concentrations of extractable-P in the Changu treatments compared to the Chimato treatments is as a result of the observed higher concentrations of the same during composting (Fig. 4.18 in Section 4.2). Since P is not mobile, the P was retained in the compost, which was later observed during incubation of the compost. The higher concentration of the extractable-P resulting from the high compost application rate is due to the concentration of the P supplied by the compost which increased the amount of P mineralized with time. Nonetheless, the amount of extractable-P observed during incubation of the all the treatments was within the range considered adequate to cover most crop requirements *i.e.* 10 – 15 mg/kg (Allan & Killorn, 1996).

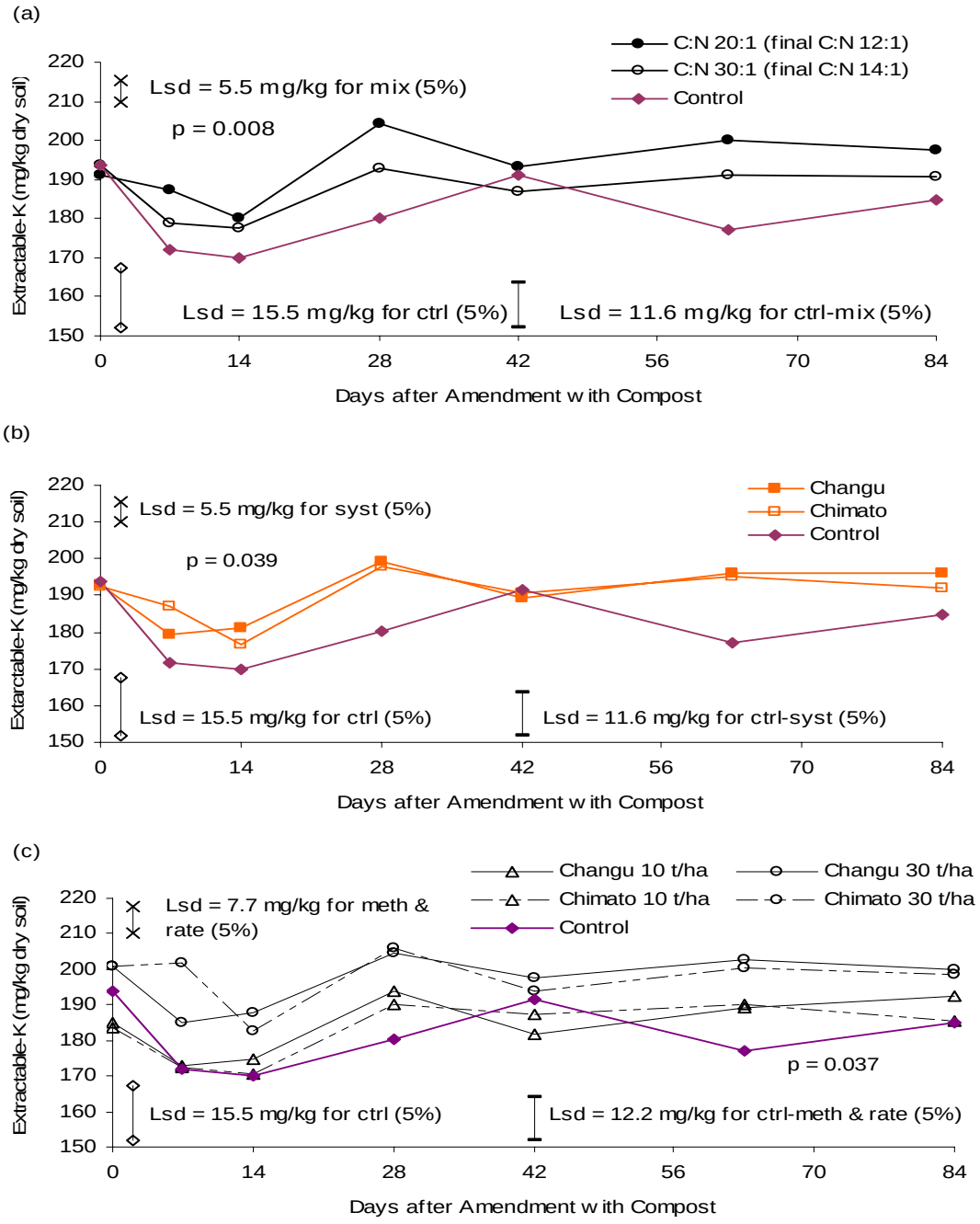

Figure 4.25 Mineralization of potassium during incubation of compost for (a) two different C:N ratios (b) two composting systems (c) system and application rate; error bars represent LSD at 5%.

Generally, there was immobilization of K in the first 14 days which was followed by K release (Fig. 4.25 & 4.26). The soil amended with compost exhibited higher contents of extractable-K than the control during most of the incubation period. This was the case

since the compost introduced in the soil was made from feedstock which had more K (Table 4.1).

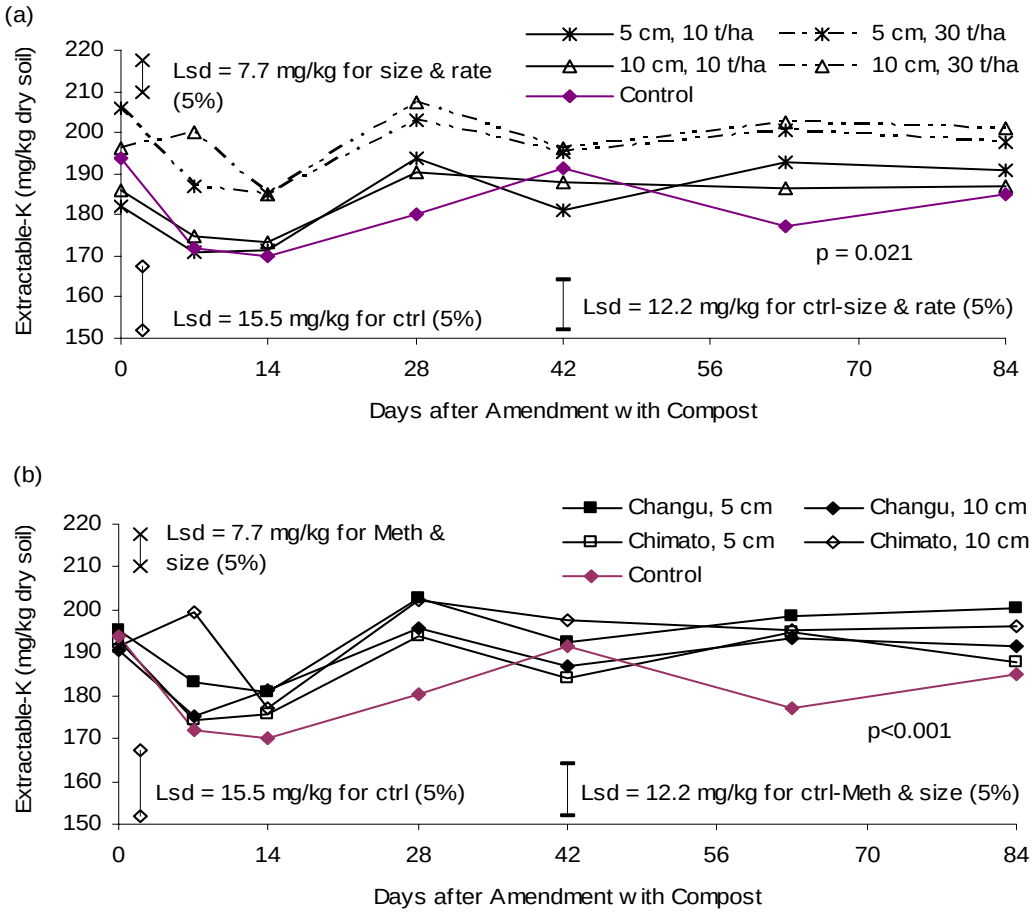

Figure 4.26 Mineralization of potassium during incubation of compost for (a) two different chop lengths and application rates (b) system and application rate; error bars represent LSD at 5%.

The compost-mix and compost application rate influenced the mineralization process of K (Fig. 4.25 & 4.26). The lower the initial C:N ratio the higher the amount of extractable-K released into the soil solution. Similarly, the higher the application rate, the higher the amount of extractable-K obtained. This agrees with the findings in Section 4.2 where the treatments with initial C:N 20:1 had more extractable-K than those with initial C:N 30:1. The source of the high amounts of K in this case is the bean residue which formed a larger proportion in the low C:N feedstock than in the high C:N feedstock. The higher

application rate introduced a higher concentration of K into the soil compared to the low rate, thereby promoting more release of extractable-K. Notable differences were observed with respect to compost-mix during incubation when treatments with initial C:N 20:1 (final C:N 12:1) contained significantly more K than the control during incubation except on Day 0, 14 and 42 (Fig. 4.25a). Similarly, treatments with initial C:N 30:1 (final C:N 14:1) contained significantly more K than the control on Day 28 and 63. Treatments with low C:N ratio had significantly more K than those of high C:N ratio for most of the incubation period. No differences were observed between the two compost-mixes on Day 0 and 14 (Fig. 4.25a). On the other hand, treatments with 30 t/ha had significantly more K than those of 10 t/ha rate for both composting systems (Fig. 4.25c).

No apparent influence of the system and chop length was observed on K mineralization. Since the compost generated by these systems contained similar amounts of the organic-K, with similar conditions of incubation, the mineralization and release of the extractable-K was governed by the compost type, hence not discriminated by the system. Chop length did not influence the composting process and mineralization of K during composting (see Section 4.2), it was not therefore surprising that the same scenario prevailed during post-compost mineralization. The significant differences between the systems and the control were observed between Day 7 and 63 when the Changu and the Chimato treatments contained significantly more K than the control. No differences were observed between Changu and Chimato treatments except on Day 7 when Chimato had significantly more K (Fig. 4.25b). The combined effect of the system and chop length and combined effect of rate and chop length was not consistent but all the treatments had more K than the control during most of the incubation period (Fig. 4.26).

4.3.1.4 Soil pH

The pH of the amended soils showed a range of 0.7 units (Fig. 4.27). The pH generally declined over time despite a peak over the first 7 days. This was observed for the compost-mix treatments, the composting systems, chop length and application rates (Fig. 4.27a - d). This trend was observed equally in the control indicating that it is a soil process affected by the initiation of the microbial activity. Importantly, the trend suggests

a nitrification process which releases hydrogen ions, thus reducing the pH. This can be explained by the general trend of nitrification results observed earlier (Section 4.3.1.2).

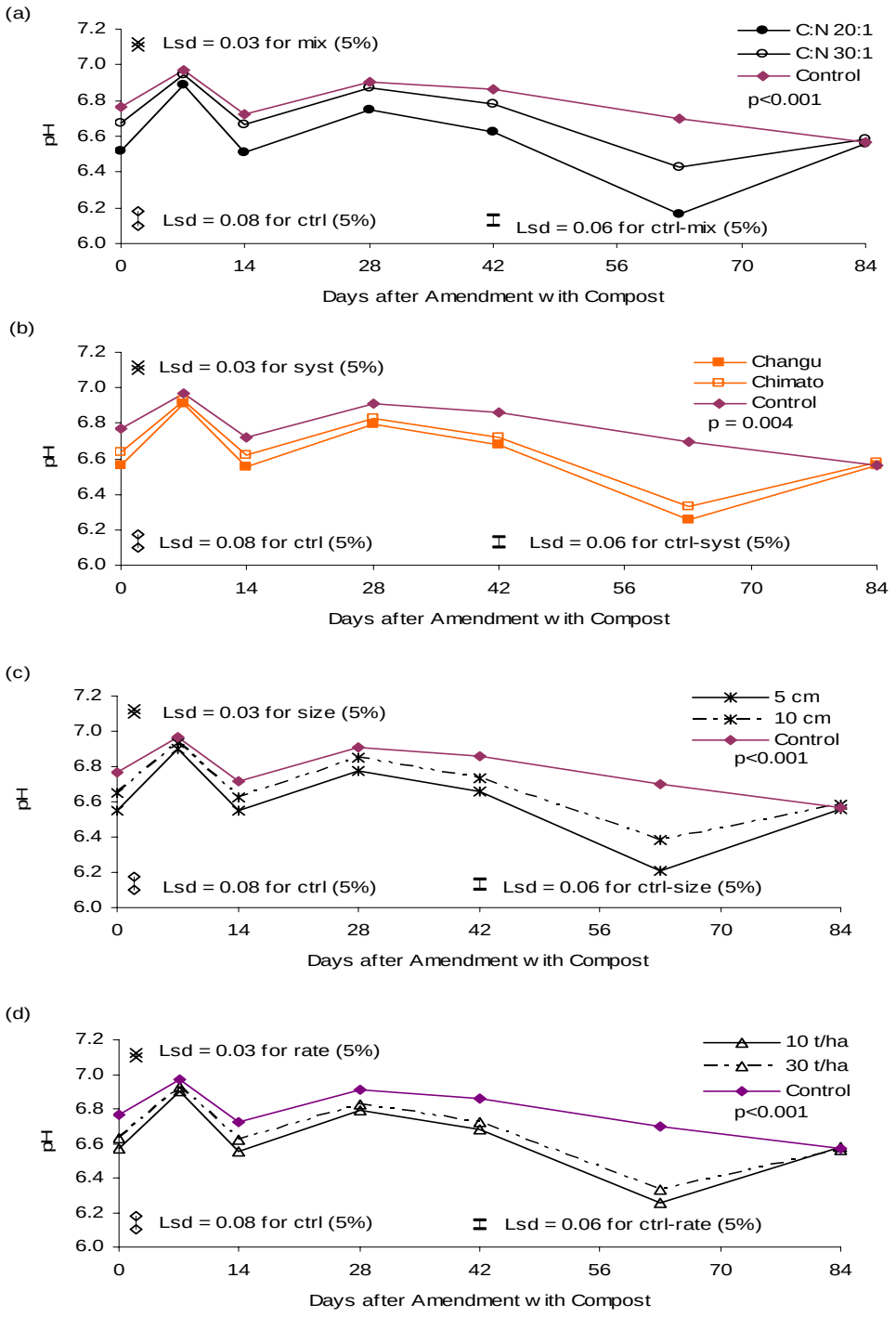

Figure 4.27 Development of pH during the incubation of compost of (a) two different C:N ratios and (b) two composting systems (c) two different chop length (d) two application rates; error bars represent LSD at 5%.

4.3.1.5 Cation exchange capacity (CEC)

There was an increase in CEC from Day 0 to Day 84 due to the application of compost (Table 4.7). The increase was observed in all the treatments and application rates. No interaction was observed among the system, compost-mix and chop length, but direct effects of system and compost-mix existed. In a study elsewhere CEC also increased from 4 to 6 cmol/kg when compost was applied in the field (Ouédraogo *et al.,* 2001).

Table 4.7 CEC (cmol/kg) of the soil on Day 0 & 84 of incubation of compost from different treatments.

System	*Initial C:N*	*Chop Length (cm)*	*Cation Exchange Capacity, cmol/kg*			
			Rate	*10 t/ha*	*30 t/ha*	
				Day 0	*Day 84*	*Day 0*	*Day 84*
Changu	20:1	5		6.3	8.3	7.0	7.3
	20:1	10		6.3	6.6	5.1	5.8
	30:1	5		6.0	6.4	6.5	6.5
	30:1	10		6.7	7.0	5.7	7.7
Chimato	20:1	5		6.7	7.6	5.4	5.2
	20:1	10		5.2	5.3	4.9	6.4
	30:1	5		6.2	6.9	4.7	5.7
	30:1	10		4.8	6.2	4.6	6.7
Control	Soil only			5.2	5.5		

Means are from 3 replicates. ANOVA determined that there was no significant interaction between compost system, initial C:N ratio, and length for either 10t/ha or 30t/ha rate

4.3.2 Overall effect of the composting systems on nutrient release

No immobilization of N was observed with respect to the control indicating that the compost had sufficient N to meet microbial demand during initiation of the mineralization. Despite the Changu treatments having significantly more mineral N during composting, they did not cause consistently significantly higher TON concentration compared to the Chimato treatments during mineralization studies. The Changu treatments had similar concentrations of TON to that of Chimato treatments. This was possibly due to the fact that some of the mineral N produced in the Changu

treatments during composting was lost from the system as ammonia before stabilization of the compost such that in the final product, there were similar contents of organic N. Treatments with low C:N ratio feedstock contained significantly more TON than high C:N ratio compost and the control indicating that these had more and easily mineralizable N than the high C:N compost. These met the nitrogen needs of the microbes quickly and the excess was released into the soil and hence potentially available for plant uptake.

Extractable-P declined in the first 14 days followed by release, indicating that micro-organisms required some form of P during the initiation of the mineralization process before it was liberated for the plant uptake. The P concentrations varied between the systems during incubation. There was generally a similar trend of P mineralization in all the treatments including compost-mix, composting system, application rate and chop length. Similarly, immobilization of K was observed in the first 14 days before release due to the same reasoning as above. Significantly more K was mineralized in low C:N treatments than in the high C:N compost and the control since the low C:N compost was made up with more bean residues, which had a greater concentration of K. The composting system was associated with significantly more K than the control and the higher the rate of application, the higher the amount of K mineralized since the higher rate subjected more K for microbial mineralization than the low rate. The 30 t/ha had more extractable-K compared to 10 t/ha. It was also observed that there were no significant differences in the increased amount of CEC of the soil during incubation. Generally, the amount of CEC increased by 2.1 cmol/kg.

The results here did not confirm Hypothesis 4 (in Chapter 1) due to the fact that the final compost from the different systems contained similar forms of nutrients hence similar mineralization process during post-compost incubation. The results obtained suggest that Hypothesis 4 be re-written as follows: ″Mineralization of the composts and their nutrient release is influenced by the compost-mix and initial mineral composition of the feedstock. The lower the initial C:N ratio of feedstock, the higher the quality of the resultant compost and the higher the quantity of the nutrients released into the soil".

4.3.3 Conclusions

a. Treatments with initial C:N 20:1 (final C:N 12:1) mineralized significantly more N than initial C:N 30:1 (final C:N 14:1). The lower the C:N, the higher the mineralized N, meaning that they contain mineralizable N.
b. No immobilization of N was observed during incubation using maize straw/bean residue compost of initial C:N 20:1 (final C:N 12:1) and initial C:N 30:1 (final C:N 14:1) meaning that these had sufficient N to meet microbial demands from the initial phase of mineralization.
c. The different compost treatments mineralized significantly more N than the control (soil only) implying that compost made from the maize straw/bean residue is an efficient soil fertilizer when feedstocks are made with initial C:N ratio of ≤ 30:1.
d. There was decline of P and K at the beginning of incubation indicating that mineralization process requires some P and K to proceed.
e. The amount of K mineralized was influenced by compost-mix and application rate. The lower the C:N ratio and the higher the application rate, the higher the mineralized K. This means that the concentration of K is as a result of the feedstock type and compost-mix ratio.
f. The pH of the soil during incubation was favourable for the mineralization process and nutrient release of N, P, and K into the soil for plant uptake.
g. The compost mineralization during the 84 days when the incubation were conducted elevated the CEC of the soil suggesting that use of compost made from the maize straw would improve the nutrient retention capacity of the soil.

4.4. Maize establishment experiments

4.4.1 Results and discussion

4.4.1.1 Germination of the seedlings, vegetative growth stage and total plant biomass

Analysis for days to germination, vegetative growth stage and plant total biomass did not show any significant differences when maize was grown in sandy loam and sand soil mixed with compost made from maize straw and bean residues. Germination of the seeds took 5 days after sowing in both the sand and sandy loam soil. The maize plants reached Vegetative Growth Stage 4 and 5 for sand and sandy soil respectively. The lack of differences in seedling germination meant that the controlled germination conditions in the incubators were favourable throughout this period and that the seeds used were viable. With respect to vegetative growth, the 25 day period during which the experiments were run was not long enough to discriminate the compost treatment effects on the number of fully grown leaves of the maize plants since the demand for nutrients was still low as the plants were still small.

4.4.1.2 Base stem diameter

Significant differences were observed in stem diameter when maize was planted in both sand and sandy loam soil (Fig. 4.28 & 4.29). For sand soil, treatments with 10 t/ha rate had stem diameters which were 8% significantly smaller than those of 30 t/ha rate but these were significantly larger than those of the control by the same magnitude (Fig. 4.28). Treatments with 30 t/ha had stem diameters which were 15% larger than those of the control. This result supports the fact that the higher the rates of application, the more nutrients were being supplied into the soil, and these additional nutrients were rendered available to the plants. This greater concentration of the nutrients therefore improved the nutrient mineralization and uptake by the plants thereby facilitating increased plant growth and activities.

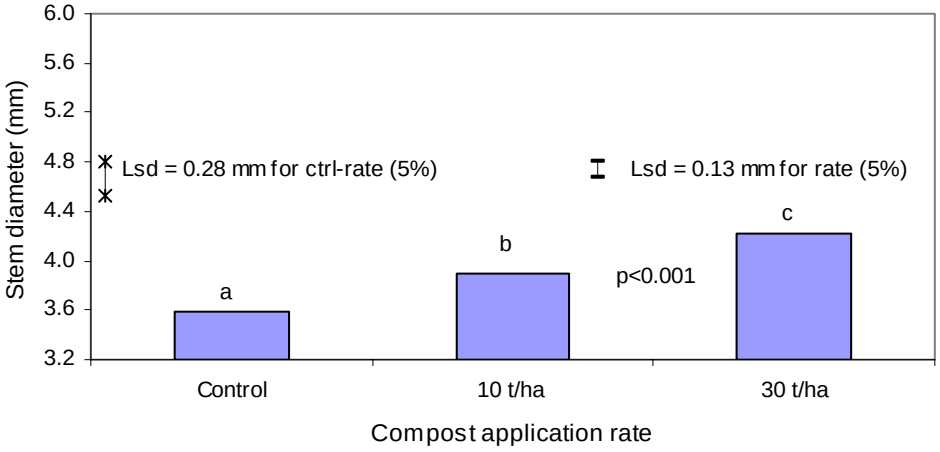

Figure 4.28 Effect of application rate on the mean base diameter of maize plants in sand soil during the 25 day period of maize plant growth; error bars are LSD at 5%; same letter denotes that the means are not significantly different; n = 12 for control and n = 96 for rate.

There was a compost-mix effect in sandy loam soil where treatments with initial C:N 20:1 (final C:N 12:1) had significantly larger stem diameters than those of initial C:N 30:1 (final C:N 14:1) and the control. These were 6% larger than initial C:N 30:1 and 7% larger than the control (Fig. 4.29). This can be explained by the fact that the low C:N ratio compost had more bean residues, which contained a greater concentration of the nutrients *i.e.* N., P, K. than the high C:N ratio compost. These nutrients were retained during composting and later released when applied in the soil through mineralization for plant use, as evidenced in the incubation studies (Section 4.3). Thus, the lower the C:N and the higher the application rate, the bigger the stem diameter meaning that compost N influenced the sizes of the maize stalks with more N resulted in larger stems where a positive linear relationship was observed (Fig. 4.30). The bigger stems help the anchorage of the plant in the soil to withstand lodging winds.

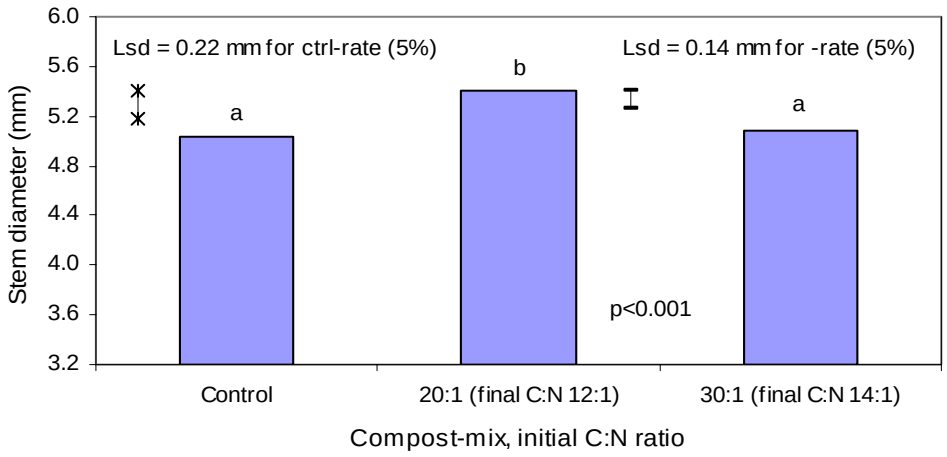

Figure 4.29 Effect of compost-mix on the mean base diameter of maize plants in sandy loam soil during the 25 day period of maize plant growth; the error bar represents LSD at 5%; same letter denotes that the means are not significantly different; n = 24 for control and n = 48 for compost-mix.

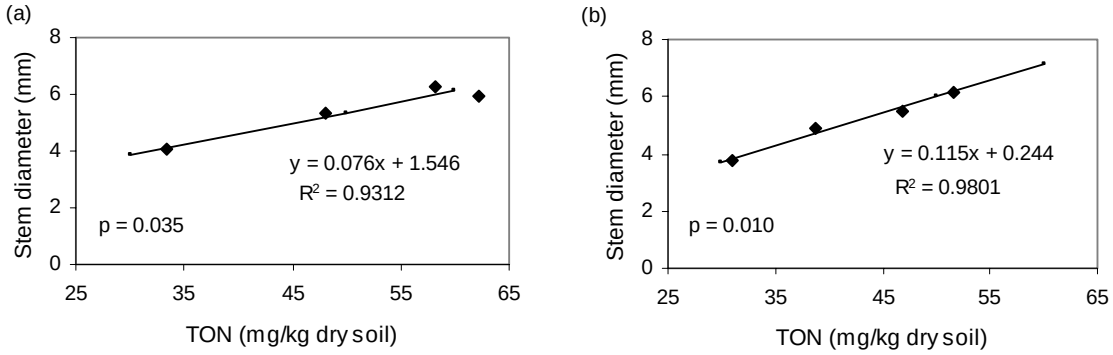

Figure 4.30 Correlation between mean plant diameter and mean TON (mineralization studies) depicting a strong relationship between the two parameters for sandy loam soil for compost from (a) C:N 20:1 and (b) C:N 30:1; R^2 coefficient of determination. The data points are from plant establishment study (*i.e.* stem diameter) and post compost mineralization study (*i.e.* TON).

4.4.1.3 Plant height

In the sand soil, the Changu treatments had plants which were 4% shorter (p = 0.013) than those for the Chimato compost (Fig. 4.31). The Changu and Chimato treatments had plants which were 14% and 17% longer (p = 0.013) than the control respectively. It was

further observed that treatments with 30 t/ha compost application rate had significantly greater plant heights than the control and those of 10 t/ha rate (Fig. 4.32). Treatments with 10 t/ha had equally taller plants than the control. This implies that compost encouraged faster plant growth than when no compost was applied. This is accredited to additional nutrients contributed by the compost. No differences were observed with respect to chop length in the Chimato system, contrary to the Changu system where 10 cm compost produced significantly taller plants than 5 cm compost (Fig. 4.33)

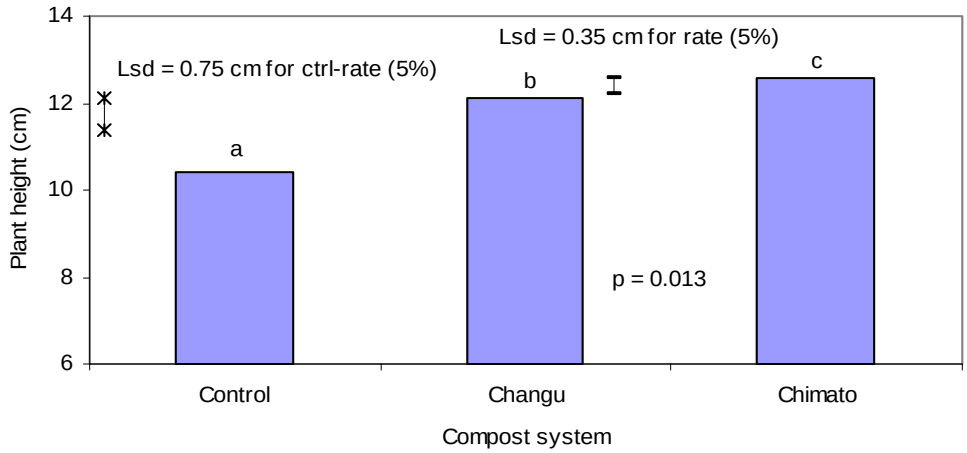

Figure 4.31 Effect of composting system on mean maize plant height in sand soil during the 25 day period of maize plant growth; the error bars are LSD at 5%; same letter denotes that the means are not significantly different; n = 12 for control and n = 96 for the system.

With respect to sandy loam soil, the interaction of different compost-mix and pre-incubation before seed sowing was not significant, except the controls and non-incubated initial C:N 30:1 (final C:N 14:1) treatments (Fig. 4.34a). The compost-mix was effective where treatments with low initial C:N ratio supported significantly taller plants than high initial C:N ratio (Fig. 4.34c). The Chimato treatments had higher plants than Changu treatments at initial C:N 20:1 (final C:N 12:1) and it was vice versa at initial C:N 30:1 (final C:N 14:1) (Fig. 4.34b). No differences were observed between the Changu treatments at initial C:N 20:1 (final C:N 12:1) and 30:1 (final C:N 14:1). For Chimato treatments, initial C:N 20:1 (final C:N 12:1) had higher plants than those of C:N 30:1 (final C:N 14:1).

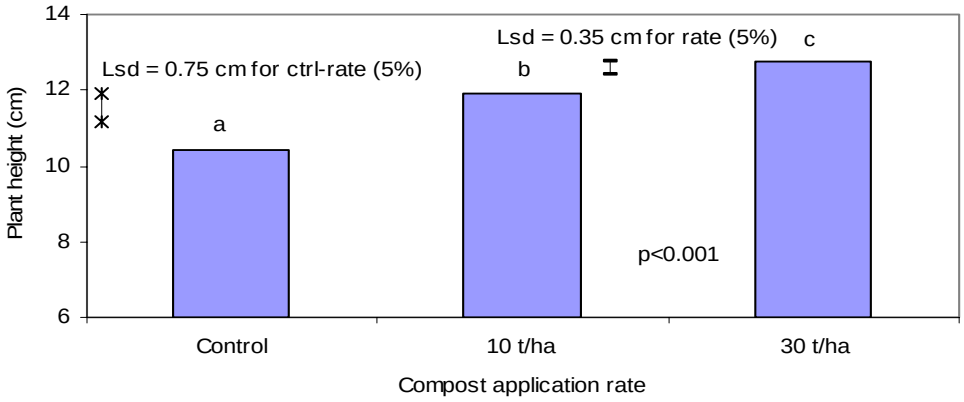

Figure 4.32 Effect of compost application rate on mean maize plant height in sand soil during the 25 day period of maize plant growth; the error bars are LSD at 5%; same letter denotes that the means are not significantly different; n = 12 for control and n = 96 for rate.

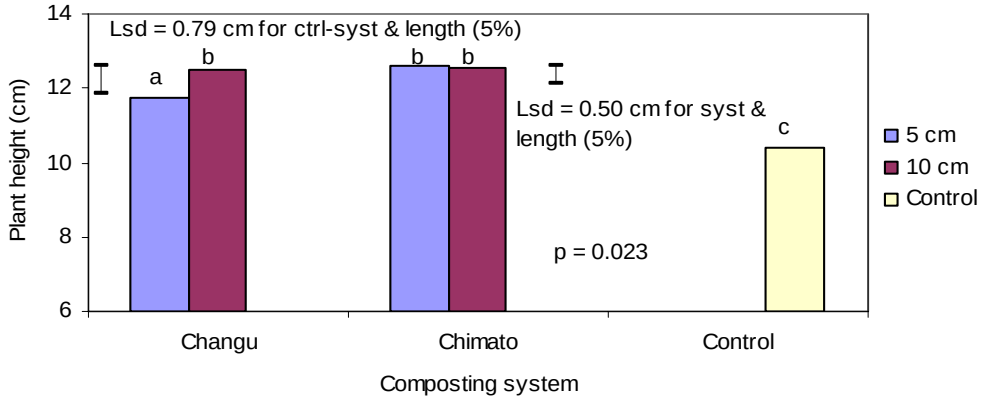

Figure 4.33 Effect of composting system (syst) and chop length (length) on plant height when maize was planted in sand soil mixed with compost during the 25 day period of maize plant growth; the error bars are LSD at 5%; same letter denotes that the means are not significantly different; n = 12 for the control and n = 48 for the system and length interaction.

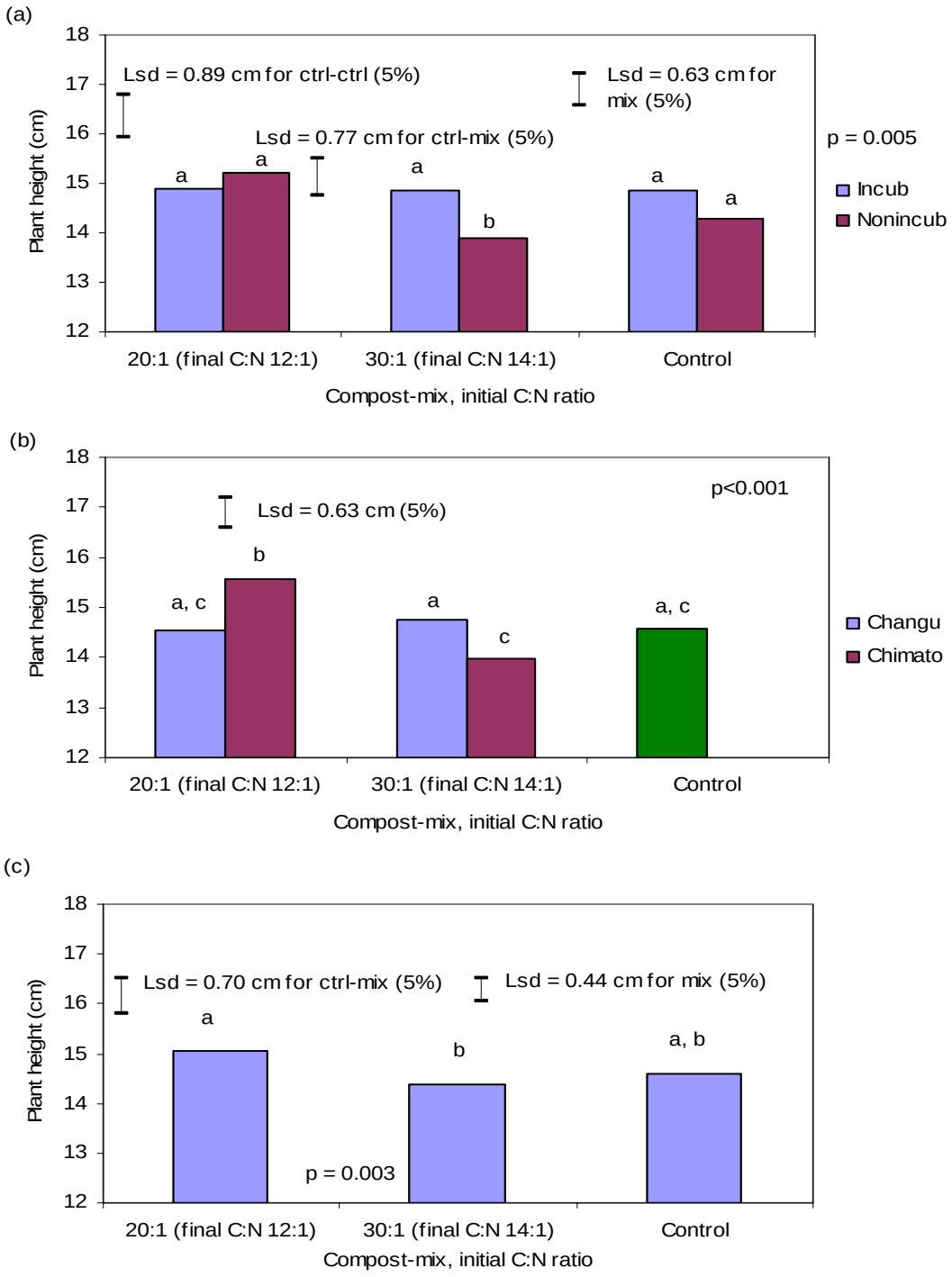

Figure 4.34 Effect of (a) compost-mix and pre-incubation (n = 12 for control, n = 24 for compost-mix) and (b) compost-mix and composting system (n = 24) (c) compost-mix (n = 24 for control, n = 48 for compost-mix) on mean maize plant height in sandy loam soil during the 25 day period of maize plant growth; the error bars are LSD at 5%; same letter denotes that the means are not significantly different.

It was not surprising that Chimato treatments resulted with higher plants than the Changu treatments. But these were associated with higher concentrations of extractable-K during composting and incubation studies (Section 4.2 & 4.3). With respect to application rate effect, the result found here was expected since the higher rate supplied a higher concentration of nutrients required by the plants during establishment. The fact that pre-incubation of the compost prior to seeding was significant when a high C:N ratio (14:1) compost was considered meant that the seed establishment took place when most of the nutrients were released into the soil solution promoting high plant nutrient uptake and plant growth. The lack of differences between pre-incubated and non-pre-incubated treatments at the low C:N ratio (12:1) and the controls was due to the fact that these had enough N which sufficed the needs of the microbes for oxidation of the available C. This agrees with the findings in Chapter 3 when compost from wheat straw and grass/clover was used.

4.4.1.4 Leaf parameters (length, breadth and area)

In Table 4.8 and 4.9 the effect of compost-mix, system, application rate and the interaction of system and compost-mix, compost-mix and pre-incubation is presented. Compost-mix influenced the maize leaf growth characteristics in both the sand and sandy loam soil (Table 4.8 & 4.9). Treatments with initial C:N 20:1 (final C:N 12:1) produced significantly broader leaves than the treatments with initial C:N 30:1 (final C:N 14:1) and the control, but no differences were observed between the compost-mixes for the leaf length and area (Table 4.8). A Similar trend was observed for the interaction of system and compost-mix in the sandy loam soil even though no differences were observed with respect to leaf area (Table 4.9) and that the control had equally larger leaf characteristics.

Table 4.8 The effect of two compost-mix ratios, two composting systems and two application rates of compost on the leaf breadth, length and area during maize establishment when compost made from maize straw and bean residues was used in sand soil

Treatment effect	Breadth (cm)	Length (cm)	Area (cm^2)
Compost-mix effect			
Control	1.70a	35.8a	46.3a
C:N 20:1 (end 12:1)	1.85b	39.5a	54.9a
C:N 30:1 (end 14:1)	1.79c	39.4a	52.6a
LSD	0.10 for control-mix	N/A	N/A
	0.05 for mix		
System effect			
Control	1.70a	35.8a	46.3a
Changu	1.80a	39.2a	52.5a
Chimato	1.84a	39.7a	55.0a
LSD	N/A	N/A	N/A
Application rate effect			
Control	1.70a	35.8a	46.3a
10 t/ha	1.75a	38.1b	50.7a
30 t/ha	1.89b	40.8c	56.8b
LSD	0.10 for control-rate	1.96for control-rate	6.33 control-rate
	0.05 for rate	0.92 for rate	2.98 for rate

Means within the same column and treatment effect followed by the same letters are not significantly different ($p > 0.05$); N/A: where effect had a non-significant F-value

The differences between the compost-mix and the control on leaf growth characteristics in sand soil indicated that the compost amended soils were superior in nutrient contents, especially phosphorus. As established elsewhere, the leaf growth characteristics relate to presence of P. Muchow (1988) found that the average leaf number of maize was not affected by lack of N fertilization. Furthermore, Etchebest *et al.* (1998) found that P deprivation reduced early elongation of maize leaves in a controlled environment. Other researchers determined an influence of soil P on leaf area index (LAI) whereby, the lower the concentration of soil P, the smaller the LAI (Lynch *et al.,* 1991; Colomb *et al.,* 1995;

and Rodriguez *et al.,* 1998a). Therefore, the differences in compost-mixes in this respect can be explained by the differences in the amount of bean residues used which directly influenced the final P content of the compost as observed in Section 4.2 and 4.3. The release of these nutrients promoted higher plant uptake as detailed in the following section (Table 4.10 & 4.11).

Table 4.9 The effect of two composing systems, combined effect of system and mix, and pre-incubation of compost on the leaf breadth, length and area during maize establishment when compost made from maize straw and bean residues was used in sandy loam soil

Treatment effect	Breadth (cm)	Length (cm)	Area (cm^2)
System & mix effect			
Control	1.98a,b	44.5a	67.0a
Changu 20:1 (end 12:1)	2.07a	41.7b	62.0a
Changu 30:1 (end 14:1)	1.94b	45.3a,c	59.4a
Chimato 20:1 (end 12:1)	1.98a	47.2c	62.1a
Chimato 30:1 (end 14:1)	2.07a	44.5a	65.8a
LSD	0.11	1.95	N/A
System effect			
Control	1.98a	44.5a,b	67.0a
Changu	2.00a	43.5a	60.7a
Chimato	2.02a	45.9b	64.0a
LSD	N/A	2.18 for ctrl-method 1.38 for method	N/A
Mix & incubation effect			
Control incubated	2.13a	44.7a	83.4a
Control non-incubated	1.83b,c	44.3a	50.5a
20:1 incubated	2.04a	45.1a	61.8a
20:1 non-incubated	2.00a,c	43.8a	62.3a
30:1 incubated	1.93c	44.2a	57.7a
30:1 non-incubated	2.07a	45.7a	67.6a
LSD	0.14 for ctrl-treatment 0.11 for treatment 0.16 for ctrl-ctrl	N/A	N/A

Means within the same column and treatment effect followed by the same letters are not significantly different ($p > 0.05$); ctrl: control; N/A: where effect had a non-significant F-value

The composting system effect was not significant in both sand and sandy loam soil (except for length), indicating that the compost generated from the two systems had similar contents of P as was realized during post-compost incubation (see Section 4.3). As was expected, the higher rate supported increased sizes of leaf characteristics, the breadth, length and consequently the area (Table 4.8). This was due to the high concentration of the nutrients supplied into the soil as the amount of the compost applied increased per unit area.

The interaction of the compost-mix and pre-incubation was significant ($p = 0.024$), (Table 4.9). The pre-incubated treatments encouraged larger breadth, lengths and area. Contrary to this scenario was the initial C:N 30:1 (final C:N 14:1), where non-incubated treatments influenced larger leaf parameters. This result implies that the pre-incubation process was promising in mitigating immobilization of nutrients during the initial phase of mineralization. This means that adsorbed P was released into the soil and some of the organic P mineralized together with the other nutrients before the seeding reducing the competition for the nutrients. The reverse observed in the high C:N ratio could be due to heterogeneity of the compost.

Comparing the two soils (*i.e.* sand and sandy loam), it was observed that generally sandy loam had larger values of the different leaf parameters than sand soil (Table 4.8 & 4.9). This is accredited to the base soil nutrition (see Chapter 2) in which case sandy loam had relatively higher nutrients (N, P, K) than sand soil at the onset. During plant establishment, under controlled environment, sandy loam soil released more nutrients into the soil compared to sand which increased its concentration hence more plant uptake (see the following section).

4.4.1.5 Plant nutrient content

Table 4.10 and 4.11 presents the effect of compost-mix and application rate on the nutrient plant uptake (N, P, K), when sand soil and sandy loam soil were amended with compost made of maize straw and bean residue. The compost-mix was significant ($p<0.05$) in both soil types. The treatments with initial C:N 20:1 (final C:N 12:1) promoted significantly higher nutrient uptake than initial C:N 30:1 (final 14:1). The control exhibited lower plant nutrient concentrations except in sandy loam soil (plant P). Consideration for the interaction of the compost-mix and pre-incubation in sandy loam soil established no differences at initial C:N 20:1 (final C:N 12:1) and the controls. The only significant difference was observed at initial C:N 30:1 (final C:N 14:1) with pre-incubated treatments supporting high N uptake (Fig. 4.35).

Table 4.10 The effect of two compost-mix and two compost application rates on total plant N, P and K when maize was established in sand soil amended with compost made from maize straw and bean residues

Treatment effect	Plant N (%)	Plant P (g/kg)	Plant K (g/kg)
Compost-mix effect			
Control	1.10a	4.50a	20.7a
C:N 20:1 (end 12:1)	1.26a	5.29b	28.2b
C:N 30:1 (end 14:1)	1.25a	4.78a	24.6c
LSD	N/A	0.51 for ctrl-mix	2.85 for ctrl-mix
		0.24 for mix	1.35 for mix
Application rate effect			
Control	1.10a	4.45a	20.7a
10 t/ha	1.23a	4.82a	25.0b
30 t/ha	1.28a	5.29b	27.7c
LSD	N/A	0.51 for ctrl-rate	2.85 for ctrl-rate
		0.24 for rate	1.35 for rate

Means within the same column and treatment effect followed by the same letters are not significantly different ($p > 0.05$); ctrl: control; N/A: where effect had a non-significant F-value

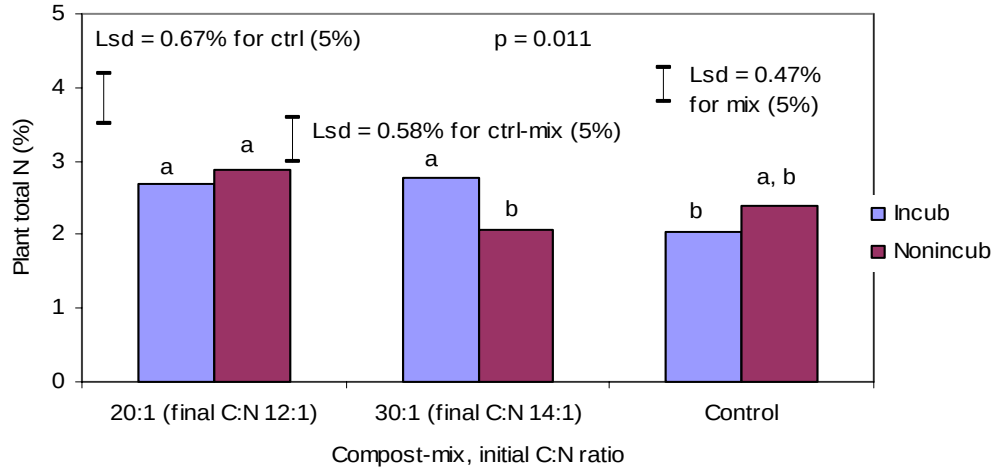

Figure 4.35 Effect of compost-mix and pre-incubation (incub) on the mean total N of the maize plants yielded 25 days after germination in sandy loam soil; error bars LSD at 5%; same letter denotes that the means are not significantly different; n = 3 for control and n = 6 for compost-mix.

The above results are due to the fact that composting experiments and post-compost incubation experiments established that treatments with low initial C:N had higher concentration of N, P, K since their feedstock had more bean residues (had high levels of nutrients). These nutrients were slowly released into the soil through mineralization. This coupled with favourable plant growth conditions (moisture, temperature & oxygen), promoted rapid root proliferation which facilitated the increased uptake of these nutrients. The fact that the control had significantly higher P uptake than the other treatments in the sandy loam soil is due to the reason that sandy loam soil used in this study had inherently high concentration of extractable-P from the beginning (see Section 4.3). This made the plants grown here have advantage over the other treatments where compost was applied in which the mineralization process slowed down the release of the nutrients at the beginning.

As for the rate effect, the 30 t/ha supported significantly higher uptake of the nutrients than 10 t/ha and the control (Table 4.10). This is due to the fact that this supplied higher contents of the nutrients compared to the lower rate as indicated above. Correlations

between extractable-P and plant P, extractable-K and plant K suggest a linear relationship (Fig. 4.36 & 4.37). This meant that the higher the P and K in the compost the greater the uptake of P and K by the plants.

Table 4.11 The effect of two compost-mixes on total plant N, P and K when maize was established in sandy loam soil amended with compost made from maize straw and bean residues

Treatment effect	Plant N (%)	Plant P (g/kg)	Plant K (g/kg)
Compost-mix effect			
Control	2.22a	3.27a	39.7a
C:N 20:1 (end 12:1)	2.79b	2.79b	36.6a
C:N 30:1 (end 14:1)	2.42a	2.81c	36.5a
LSD	0.53 for ctrl-mix 0.34 for mix	0.33 for ctrl-mix 0.21 for mix	N/A

Means within the same column and treatment effect followed by the same letters are not significantly different ($p > 0.05$); ctrl: control; N/A: where effect had a non-significant F-value

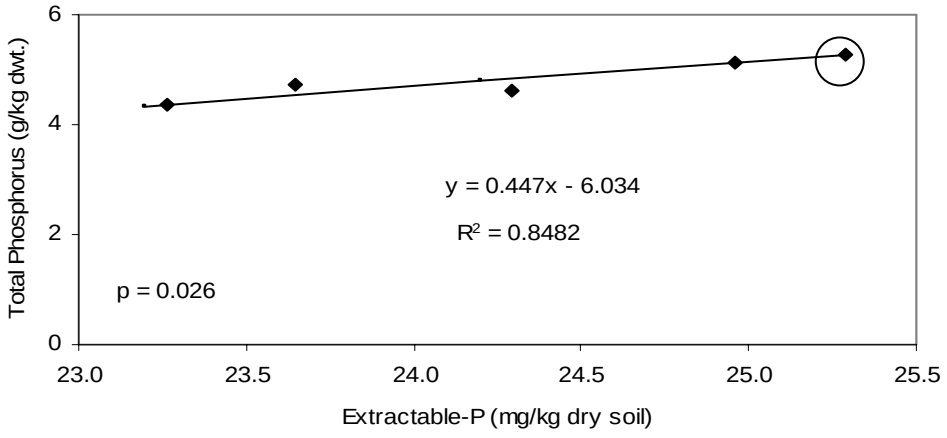

Figure 4.36 Correlation between mean plant total phosphorus and mean soil extractable-P (mineralization studies) depicting a linear relationship between the two parameters for composting system and initial C:N ratio 20:1 (final C:N 12:1) in sand soil. The values used here are from the post compost mineralization study and the maize establishment study. The circle represents control value.

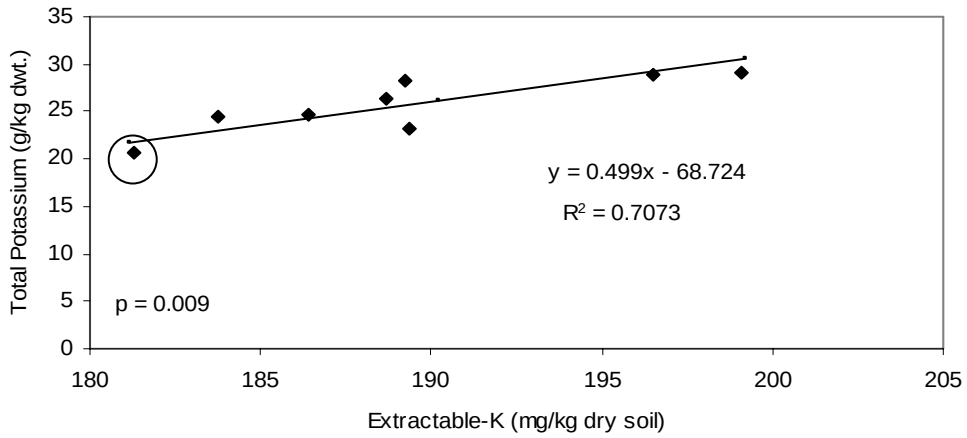

Figure 4.37 Correlation between mean plant total potassium and mean soil extractable-K (mineralization studies) depicting a linear relationship between the two parameters in sand soil. The values used here are from the post compost mineralization study and the maize establishment study. The circle represents control value.

With respect to the interaction of the system, compost-mix and application rate, no differences were observed for total plant N in all the treatments except for Changu 30:1 when 10 t/ha rate had significantly lower plant N than those of 30 t/ha in sand soil (Fig. 4.38). The control had the least plant N compared to the other treatments except Changu 30:1 at 10 t/ha and Chimato 30:1 at 30 t/ha rate. The results indicated that using the compost of final initial C:N 20:1 (C:N 12:1) and initial C:N 30:1 (final C:N 14:1) did not limit N uptake by the plant irrespective of the application rate. The compost introduced extra N which reduced the competition for N between the plants and micro-organisms compared to the control (soil only).

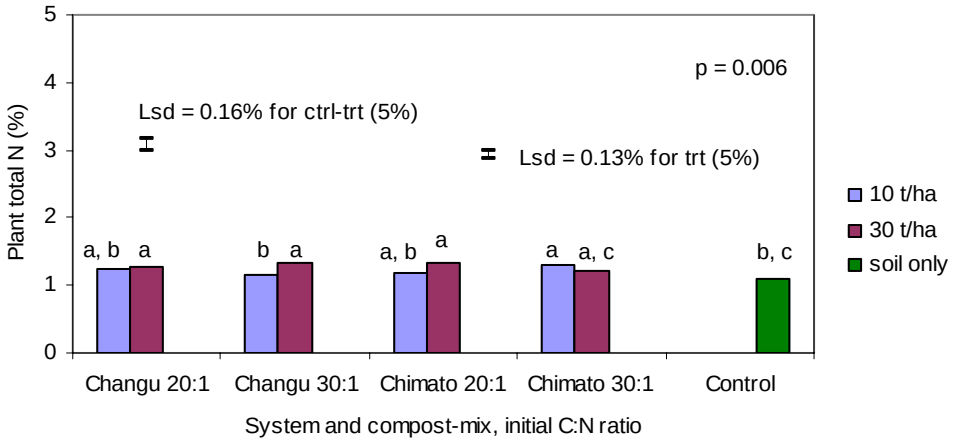

Figure 4.38 Combined effect of compost-mix, system and application rate on the mean total N of the maize plants yielded 25 days after germination in sand soil; error bars LSD at 5%; same letters denote that means are not significantly different; n = 3 for control and n = 6 for the system and mix interaction.

4.4.2 Overall influence of compost on seedling establishment

No differences relating to days to germination, vegetative growth and total plant biomass were determined. No apparent influence was observed due to composting system with regard to maize establishment experiments except for plant height in sandy loam soil when Chimato treatments had significantly taller plants than Changu considering final C:N 12:1 whereas Changu had significantly taller plants at C:N 14:1.

Compost-mix and compost application rate influenced the maize establishment process in both the sand and sandy loam soil. The low final C:N ratio (C:N 12:1) composts produced significantly larger stem diameters and supported higher N and P plant uptake compared to the high C:N ratio (14:1) composts in sandy loam. A similar trend was also observed in sand soil but in this case the low final C:N ratio supported higher K and P plant uptake than the high C:N ratio composts. In the sandy loam soil, the controls (incubated & non-incubated), supported greater P uptake than the two different compost-mixes. This meant that P was not limiting in the soil used.

The 30 t/ha rate produced significantly larger stem diameters (12.8 cm) than 10 t/ha (11.9 cm) and the control (10.4 cm) and the 10 t/ha had significantly larger stems than the control. Similarly, the higher rate supported longer leaf length (40.8 cm) compared to 10 t/ha (38.1 cm) and the control (35.8 cm). This was the case with respect to leaf breadth, leaf area and nutrient uptake especially P and K. Consequently, linear relationships were apparent for P ($p = 0.026$) and for K ($p = 0.009$) indicating that the amount of the nutrient taken up depended on the concentration of the nutrient in the compost. As the concentration of nutrients in the compost increased due to lowering of the C:N ratio or an increase in the compost application rate, the mineralization of the nutrient increased and the uptake increased. The concentration of the nutrients depended on the sources of compost.

The results indicated that the plant establishment was controlled by the quality of the compost, the higher quality of the compost the better the establishment as proposed in Hypothesis 5 (in Chapter 1).

4.4.3 Conclusions

a. Low final C:N ratio (12:1) treatments contained high concentration of nutrients which resulted in high nutrient plant uptake (NPK) and consequently influenced bigger maize stems and leaf parameters (breadth, length and area).
b. Treatments with final C:N 12:1 and 14:1 did not limit the N uptake irrespective of the application rate. This was due to the fact that these were close to the C:N ratio of the soil, thereby they did not supply excess C surpassing the available N required for microbial activity.
c. The high application rate (30 t/ha) supported rapid growth of leaf parameters (leaf length, breadth, area) and larger maize stems and nutrient uptake (P and K) compared to 10 t/ha. The higher rate meant that a high concentration of nutrients

was applied to the soil increasing the plant available nutrients reducing the competition for nutrients between the plant and the microbes.

d. Sandy loam soil contained sufficient concentrations of P required for the establishment of the maize plant. The soil was not limiting in P since the controls produced plants with a higher concentration of plant P than the main treatments.
e. Pre-incubation of the soil amended with compost promised to be an effective way of mitigating immobilization effects of nutrients to maize plant establishment.

4.5 Summary

In the open field, composting of maize straw/bean residues was influenced by the compost-mix and composting system. Low C:N ratio treatments were associated with higher temperatures and significantly longer mesophilic and active composting periods than high C:N ratio treatments. The higher concentration of bean residues presented high contents of organic N which supported increased oxidation of the carbon which consequently determined the final C:N ratio of the compost and the nutrient contents of the compost. The lower the C:N ratio, the lower the final C:N ratio attained and the higher the concentration of NO_3-N, phosphorus and potassium compared to high C:N 14:1 treatments. Phosphorus and potassium were in fact retained in the compost from the feedstock since the watering was controlled and that these are less mobile. This promoted increased concentrations of these nutrients when the compost was applied in the soil.

A direct effect of the compost-mix was realized when compost was incubated in the soil. The low initial C:N ratio which had high nutrients content and final C:N ratio of 12:1 effectively promoted increased mineralization of N, P, K compared to final C:N 14:1 under a controlled environment. This meant that the low C:N ratio had more readily available N required by the microbes to attack the organic forms of N, P, K ending with high levels of the extractable and plant usable forms of nutrients. This was confirmed when the maize established in the soil amended with the low final C:N 12:1 supported

larger plants characteristics (leaf parameter; plant stems, plant height) and higher plant nutrient uptake than the high final C:N ratio 14:1 treatments.

The differences in the management of the two systems used in this study *i.e.* Changu and Chimato, influenced different composting processes due to differences in the microbial activities and length of different composting phases. Consequently, this resulted with predominantly different forms and proportions of N in which case, Changu ended up with significantly more NO_3-N as well as extractable-P compared to Chimato which had more K and NH_4-N. It was expected that compost from the two systems would affect the maize establishment differently. Contrary to this, there was minimal effect of system on the plant establishment. This was the case because the soil used in this study contained high amounts of extractable-P and K, and that N of the compost from the two systems was similar since these had similar final C:N ratios. This coupled with the short period over which the maize establishment experiment was run, made it such that, the plant growth did not reach the critical period when it demands excess nutrients for the increased plant demands.

All the objectives set in Chapter 1 have been achieved by the research approach followed in this research.

CHAPTER FIVE: Overall discussion

5.1 Synthesis of experimental results

The results from Chapters 3 and 4 established that quality of the compost is controlled by the type of the feedstock and modulated by the composting system, due to differences in the status of the composting factors. Composting for agricultural production is primarily intended to transform the organic material into mineralizable fertilizer or for utility as a soil amendment (Domínguez *et al.,* 1997). Technically, this is engineered by manipulating the feedstock and controlling the composting factors in order to enhance bio-oxidation processes which degrade and stabilize the organic material (Avnimelech *et al.,* 2004; Kadir *et al.,* 2004; Shaw *et al.,* 1999).

5.1.1 Effect of composting system

Many different composting systems exist (de Bertodi 1993; Stentiford 1996). These are purposely developed to control moisture, temperature and aeration during composting. Commercially, the composting process is typically monitored closely and composting factors are controlled throughout. However, for low-resource farmers, the situation is somewhat different. The farmers are limited in their capacity to control the processes due to lack of resources. The Changu and the Chimato systems fall in this category. The two systems differ in their aeration, temperature and moisture control. The status of these factors in each system were responsible for the composting process observed. For instance, the differences in the temperature profiles between the two systems (especially in the field) are a reflection of the differences in aeration and temperature control. This is due to the fact that Changu is open and loses heat and moisture to the surrounding area, but the turning and watering activities sustain microbial activity. In Chimato, the heat loss is reduced by the coating, but it is deprived of the watering and aeration activities except by the one hole created during heap formation. Evidently, microbial activity in the Chimato was limited by the oxygen depletion in this study and elsewhere (Avnimelech *et al.,* 2004), and in addition by low moisture content (presence of dry pockets observed)

which was not the case in the Changu system (see Fig. 4.1). Lack of moisture hindered diffusion of soluble molecules and microbial mobility and hence microbial activity. The more limited zone was the outer region surrounded by the mud coat where the partially decomposed material was found. This meant that a lower amount of matured compost was derived from the Chimato system (78 kg dwt./heap) compared to the Changu system (91 kg dwt./heap). But the mud coat was more influential in the field, Malawi (cooling dry winds) than in the glasshouse, UK experiments (stable, lack of winds). In Malawi Chimato treatments rapidly attained a thermophilic phase (within 2 days) whereas there was a delay of up to 8 days in the Changu whilst in the UK, both Chimato and Changu treatments attained thermophilic phase by Day 5 of composting. In the field, the situation could be improved by introducing a coat in the Changu system *e.g.* a plastic sheet or banana leaves which can be taken out during turning and watering of the compost heap.

The consequences of the differential oxygen diffusion into the compost matrix, and the different moisture contents were that the Changu system resulted in a longer composting time than Chimato as follows: the Changu had 17 and 19 days of mesophilic phase for the UK and Malawi experiments respectively whilst Chimato had 14 and 11 days for same phase for the UK and Malawi studies. Similarly, the Changu had 24 and 22 days of active composting for the UK and Malawi experiments respectively contrary to 22 and 17 days for the same phase in the Chimato system. The Chimato system had a longer thermophilic phase attributable to the mud coat. Since this is a manifestation of the bio-oxidation of the composts, the Changu ended up with higher concentrations of TON or NO_3-N (61 and 12% higher than Chimato for UK & Malawi trials) while the Chimato retained a greater concentration of NH_4-N (87 and 7% higher than that of Changu for the UK and Malawi trials respectively). The big differences in the concentration of mineral N forms in Changu and Chimato systems for UK treatments as compared to Malawi could be due to microbial colonization and succession combined with the differences in the nature of the feedstock and ambient temperatures (consistently higher ambient temperatures in Malawi than UK). These controlled the differences in the concentration of the NO_3-N relative to NH_4-N in the two localities.

The fact that Changu had a higher concentration of TON or nitrates while Chimato had a higher concentration of NH_4-N both in the UK and Malawi experiments emphases the importance of management on the composting processes. This meant that the difference in aeration affected the amount of oxygen available in the systems which eventually had implications on the ammonification and nitrification processes. *Nitrosomonas* and *Nitrobacter*, the nitrification bacteria are obligate aerobes and cannot multiply or convert ammonia or nitrites into nitrates in absence of oxygen. Thus, turning process in Changu promoted the nitrification process due to increased amount of oxygen in contrast to Chimato, hence the higher concentration of TON or nitrates in Changu and NH_4-N in Chimato. Furthermore, the mud coat in the Chimato systems protected the loss of NH_3 increasing the concentration of NH_4-N in this system. This means that the composting processes in the Chimato could be enhanced by improving the aeration and moisture content during composting. It is suggested here that more holes be created during formation of the Chimato compost heaps which should be used for aeration and moisture adjustment. The holes should be opened and sealed accordingly to control the air flow and temperature build up. This can be achieved by inserting a number of poles during heap formation creating a network of air passages. These can be retained in the heap for at least 2 days until the heap has stabilized. The poles can be removed from the heap leaving void spaces for air. The open ends left by the removal of the poles could be temporarily closed by stones.

5.1.2 Effect of compost-mix, feedstock

As much as the composting systems controlled the composting factors, and affected the composting process, the feedstock (compost-mix) quality had an impact on the composting process. The lower C:N ratio (20:1 & 25:1) material supported increased microbial activity and resulted in higher temperatures (up to 60^{o}C) and longer active composting (as high as 23 days) than higher C:N ratio (30:1 & 60:1) materials due to the presence of more and easily decomposable substrate. It is notable that the low C:N ratio treatments were also associated with higher mineral N and extractable P and K contents compared to high C:N ratio treatments since these depended on the quality of the

feedstock. The exception to this was extractable K for the UK composting which was not significantly different. The presence of easily mineralizable organic nutrients promoted high microbial activity and release of these nutrients into the composts. When using straw for composting (wheat & maize), anything with initial C:N ≥ 60:1 would create problems *i.e.* the microbial oxidation of the organic material would be arrested due to limitations of the nitrogen. Since the final C:N ratio of the compost was controlled by the initial C:N ratio, whereby the lower the initial C:N ratio, the lower the final C:N ratio, it is unlikely that feedstock mixes with C:N ≥ 60:1 would end up with final C:N < 20:1. Such composts are not ideal for crop production because they induce immobilization of N when applied into the soil (Iglesias-Jimenez & Perez-Garcia, 1989). In this study, composts from feedstock with initial C:N 60:1 (final C:N 31:1) immobilized 20 mg/kg dry soil of TON while that from initial C:N 30 (final C:N 19:1) immobilized 6 mg/kg dry soil of TON relative to soil alone when they were applied to the soil and incubated at 30^{o}C for 42 days for the UK resultant compost. Nonetheless, no immobilization was observed for the Malawi compost for all treatments but the treatments with initial C:N 20:1 (final C:N 12:1) mineralized more N than treatments with initial C:N 30:1 (final C:N 14:1) and the control.

The chop length of 5 and 10 cm did not significantly influence the composting process. As much as surface area exposed for microbial attack stimulates increased activity, the difference was not significant using the maize straw at such lengths. Ndung'u *et al.,* (2005) used lengths of 30-45 cm of maize straw when producing fortified composts and managed to get matured compost. The results of this study imply that with proper management, the chop length of the maize straw can be extended to at least 10 cm without negatively affecting the composting process when all other conditions are conducive as was observed in this current study.

There were also similarities on the mineralization of P and K during composting of wheat straw and grass/clover and maize straw and bean residues *i.e.* UK and Malawi experiments. The low initial treatments contained a higher concentration of extractable P than high initial C:N treatments both in the UK and Malawi study. For instance

treatments with initial C:N 20:1 had 8% more extractable P than those from C:N 30:1 in the Malawi case. This was due to the fact that these were made of high contents of bean residues which contained high organic P than the high C:N feedstock and this was eventually released during mineralization. Similar argument can be advanced for the UK study where treatments with initial C:N ratio had low extractable P than the other treatments (C:N 20:1; 25:1 & 30:1). Changu system had 6% more extractable P than Chimato in Malawi due to prolonged microbial activities which released more P than in Chimato. No differences were observed in the UK. As for extractable K, Compost-mix (initial C:N ratio) and system were significant in Malawi composting where treatments with initial C:N 20:1 had 3% more extractable K than C:N 30:1. On the other hand Chimato system had 6% more extractable K than Changu system. In the UK an interaction of system, compost-mix and time was observed where treatments with low initial C:N ratios attained higher concentration of extractable K than the high initial C:N ratios. For the initial C:N ratios the differences are due to the feedstock quality as presented above whereas for the Changu system, the high microbial activities demanded more K (fixation as alluded to later in this section) thereby less amount of extractable K was released in the solution compared to Chimato. There was a general decline in the P and K profiles in both UK and Malawi indicating that the composting process requires P and K in addition to N, agreeing with the findings of Felton *et al.,* 2004. Some reduction in P and K concentrations were observed in the earlier part of composting followed by a release despite the fact that the pH of the material ranged between 6.8 and 8.8 in the first 28 days suggesting that mineral complexes between P and Mn, Al, Fe or Ca were unlikely to be formed. Similarly, this was also observed during post-compost incubation (see later). Precipitation occurs when phosphate ions react with other soluble ions (***e.g.*** Al, Fe or Ca) to give insoluble salts. Under acid conditions (pH < 5.5), Mn, Al, and Fe phosphates are formed, all of which are unavailable to the plant. In alkaline conditions (pH ≥ 8.0), Ca-phosphate is formed which is less soluble (PPI, 1998).

The development of the pH during composting was somehow different when the processes were done under glasshouse (UK) and field (Malawi). In the UK, the pH of most of the treatments was declining the first 28 days indicating the production of organic

acids (Beck-Friis *et al.,* 2003) which is normal when the composting processes have been initiated. This creates conducive environment for the growth of fungi and breakdown of lignin and cellulose. Contrary to this, in Malawi the pH was increasing the first 21 to 28 days which was due to ammonification process followed by the release of the organic acids (a declining phase up to Day 35). This difference between UK and Malawi pH behaviour at the initial phase symbolizes the differences in the succession of the micro-organisms in the compost matrix due to differences in the ambient temperatures (Fig. 3.1 & 4.1) and the feedstock used between the two places. Nonetheless, the later part of the composting was characterized by a decline in the pH both in the UK and Malawi due to the nitrification process. The decline was great in Malawi (between Day 49 & Day 56) as compared to UK (between Day 70 & Day 112) *i.e.* a range of 0.7 units and 0.2 units for the Malawi and UK experiments respectively. This difference could be due to the differences in the environment within the compost heaps and the microbial succession as indicated earlier on. Generally, the composting processes of the feedstock used in the UK and Malawi was done across a similar range *i.e.* cross 1.8 unit and 1.7 units for UK and Malawi experiments respectively.

5.1.3 Compost usage

Producing a better quality of compost is not an end in itself. What is important is getting the best out of the compost made. Thus, one aims at creating the processes which can retain as many nutrients as possible which can then be released in the soil for plant uptake. No differences were observed with respect to decline of total N during composting using Changu and Chimato systems both in the UK and Malawi. Nonetheless, differences were observed with respect to the forms of mineral N whereby Chimato treatments contained significantly high concentration of NH_4-N while Changu contained high concentration of nitrates both in the UK and Malawi experiments as elaborated in Section 5.1.1. Despite the lack of differences in the decline of total N for both Malawi and the UK composting experiments using Changu and Chimato systems, a temporal difference was observed when the resultant compost from the two systems was incubated in the soil. The Changu treatments showed higher level of total N (%) on Day

28 and 63 than Chimato for the Malawi study. This was reflected in the mineralization study whereby Chimato treatments contained significantly higher concentration of TON than Changu treatments on Day 28 and 63. This was due to the fact that a greater amount of total N was mineralized into TON in Chimato compared to Changu. Nonetheless, there was no clear pattern since this was temporal difference. With respect to post-compost mineralization of the UK resultant compost, no direct effect of the system was observed, but an interaction of the system, compost-mix and rate of application was significant. Just as for Malawi experiments, the differences were variable in which case Chimato 30t/ha treatments contained least concentration of TON than the other treatments during incubation when resultant compost from feedstock with initial C:N 30:1 and 60:1 were used. The differences for initial C:N 60:1 was only observed on Day 28 and 42. On the other hand Changu 30t/ha treatments had higher concentration of TON than the other treatments when resultant compost from initial C:N 20:1 was used. The lack of consistent differences is due to the fact that composts release nutrients slowly, it is likely that consistent outright differences could be manifested in the long run and especially when the plant nutrient demand from the soil increases with increased plant growth. What was evident though was that treatments with high final C:N (*i.e.* C:N 19:1 & 31:1) ratio immobilized N due to limitation of N to meet the demands of microbes whereas the low final C:N (C:N 12:1) mineralized N (UK resultant compost). No immobilization was observed when Malawi resultant compost was used (see Section 5.1.2). The treatments that started with initial C:N 30:1 ended up with different final C:N ratios when they were composted in the glasshouse (UK) and in the field (Malawi). Even though the total composting period in the field was short (77 days), the final C:N was 14:1 compared to the glass house (112 days) which ended at 19:1, evidence for the influence of environmental conditions affecting composting process as well as that of different use of feedstock. This glasshouse (UK) compost was limited in N and immobilized N despite starting at the same initial C:N while the field (Malawi) compost was mineralizing throughout the post-compost mineralization study.

No apparent differences were observed with respect to P and K during post-compost mineralization for both the UK and Malawi resultant compost. For instance, treatments with initial C:N 20:1 (final C:N 12:1) had significantly higher concentration of extractable P than treatments with initial C:N 30:1 and 60:1 for the UK compost on Day 0 only whereas treatments with initial C:N 30:1 (final C:N 19:1) contained higher concentration of extractable P than the control on Day 7 only. For Malawi compost, low initial C:N 20:1 (final 12:1) treatments showed significantly higher concentration of extractable P than the high initial C:N (final 14:1) and the control for the first 14 days only. Similarly, the system's differences were observed the first 14 days where Changu had high concentration of extractable P than Chimato for the Malawi compost. A similar trend was observed with respect to extractable K. Unlike for P there was no system effect on K. As established earlier, the effect of the compost-mix (initial C:N ratio) depended on the feedstock quality and source whereas for the system the treatments contained similar amounts of organic K and with similar incubation conditions no differences could be manifested. As was the case with composting studies, fixation of P was observed for the at least first 7 days for treatments with initial C:N 20:1 and 30:1 for UK studies and the first 14 days for the Malawi study. Fixation of K was only observed in the Malawi study the first 14 days followed by release. The fixation observed here was not due to a chemical process since the pH of the soil during incubation was between 6.3 and 6.9, thereby no complexes could be formed between P or K and other elements as indicated earlier. This meant that microbes required P and K for their metabolism.

The contents of N, P and K increased with application rate since these were as a result of the compost-mix quality. The feedstock controlled the mineralization process of the compost. It is clear here that every effort and attention should be made when preparing the feedstock for composting since the quality of the feedstock directly influences the final compost product and its behaviour when it is incorporated into the soil. The straw should be mixed with a nitrogen source e.*g.* leguminous crop residues in order to reduce the initial C:N ratio to $\leq$ 30:1. The feedstock should be chopped to approximately 10 cm to promote microbial activity.

5.1.4 Plant establishment

The importance of the feedstock needs special emphasis with respect to its effect on plant establishment and growth for both UK and Malawi experiments. Plant growth parameters were affected by the compost addition into the soil. The effect of compost-mix on the plant growth was similar for both UK and Malawi resultant compost. Treatments with initial C:N 20:1 (final C:N 12:1) produced plants with 7% larger maize stalks than those from initial C:N 30:1 (final C:N 19:1) and 15% larger than those from initial C:N 60:1 (31:1) for the UK compost. The difference in plant stem diameter between treatments with initial C:N 20:1 (final C:N 12:1) and initial C:N 30:1 (final C:N 14:1) was 6% where C:N 20:1 (final C:N 12:1) had larger plant stalks for Malawi compost. This scenario was also observed for the leaf area and plant biomass using UK resultant compost whereas this was observed for plant height and plant breadth for the Malawi resultant compost. The lower the final C:N, the greater the value of each parameter. As indicated above, the final C:N was directly as a result of the initial C:N ratio and the nutrient content of the compost depended on the initial feedstock. This trend was also noted with regard to plant nutrient uptake. For instance treatments with initial C:N 20:1 (final C:N 12:1) and initial C:N 30:1 (final C:N 19:1) supported 21% more plant N uptake than treatments with initial C:N 60:1 (final 31:1) for the UK experiments. Similarly, treatments with initial C:N 20:1 (final C:N 12:1) supported 13% more plant N uptake than C:N 30:1 (final C:N 14:1) for the Malawi resultant compost. Similar trend was observed for plant P and K for the UK and Malawi experiments. No relationships were found between nutrient concentration in the soil/compost mixtures and the plant parameters for the UK treatments whereas correlations were established for the Malawi experiments. This was evident for the plant stem diameter and total plant P and K. The higher the concentration of the nutrient in the soil, the bigger the plant stem diameter or the higher the total plant P or K. Despite the relationship not being evident in the UK experiments, this demonstrates that the composting processes as controlled by the compost-mix, were influential to crop establishment, and the concentration of the nutrients was related to the application rate (for both Malawi and UK experiments).

The effect of the composting system on plant establishment was different for the UK and Malawi resultant compost. The Changu system supported significantly larger plant stem diameters (7% larger), more plant N (16% more) and plant K (9% more) uptake which resulted in a larger plant biomass (14% larger) compared to Chimato treatments. Contrary to this, Chimato treatments supported longer plants (4% longer) and wider leaves (5% wider) than Changu treatments for the Malawi resultant compost. In either case (*i.e.* UK or Malawi study) the system which supported bigger plant growth characteristics than the other was associated with a higher concentration of TON during the post-compost mineralization. This means that the post-compost mineralization characteristics were affected by the composting processes through which the feedstock went through. The differences in the impact of the system between UK and Malawi could be due to the effect of the environment (glasshouse (UK) compared to field (Malawi)) under which the feedstock was composted. As for pre-incubation of the compost in a soil prior to planting, this illustrated potential in improving the nutrient release and mitigating immobilization. As established in the sandy loam soil, the pre-incubated treatments supported higher N uptake. This means that incorporation of the compost a few weeks before seed sowing would promote seed establishment process and may be beneficial in terms of plant performance.

5.2 Cost-benefit analysis of the composting systems and its utilisation

5.2.1 Cost-Benefit Analysis model

The Cost-Benefit Analysis of the composting systems and the compost produced under smallholder farmer was estimated using the model outlined in Fig. 5.1. A number of assumptions were made to represent realistically the smallholder farmers who reside in bean production areas. These included: a) the maize straw and bean residues are produced by the composting farmer; b) feedstock is produced close to the composting site; c) water availability is not a constraint (*i.e.* near the production site).

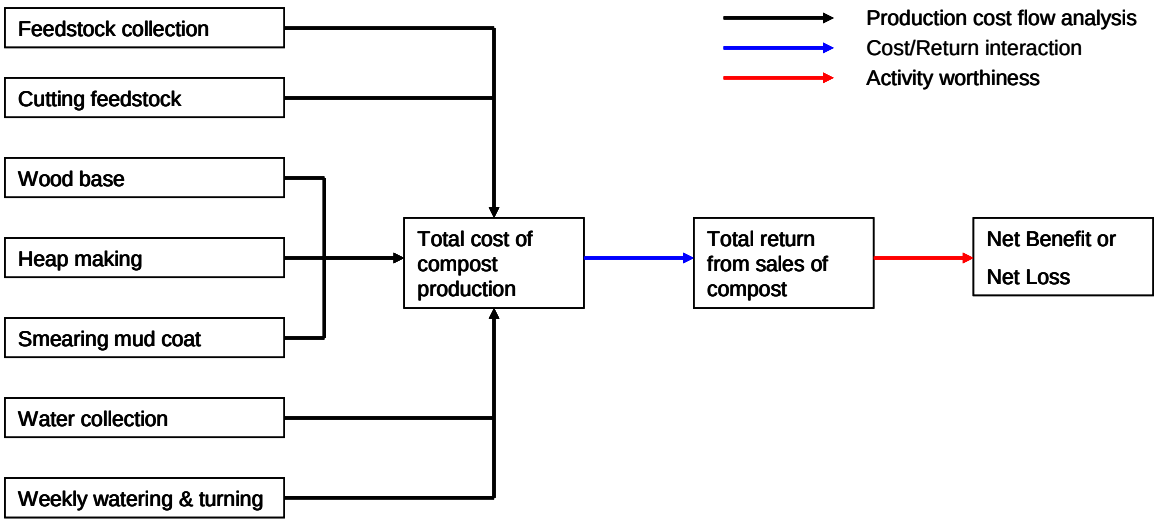

Figure 5.1 The Cost-Benefit Analysis model used in comparison of the overall worthiness of composting exercise by smallholder farmers using maize straw and bean residues in the Changu and Chimato system

Typically, the smallholder farmer produces compost for their own use. This arises from the simple reason that most of these farmers are subsistence farmers and rely on the extended family for remittances to survive. Consequently, this sector of farmers rarely uses chemical fertilizer which is very expensive. Due to the fact that most of the farmers have low-quality feedstocks for their compost, other researchers are proposing fortification of this compost to improve the processes and end chemical content (Ndung'u *et al.*, 2005; Kadir *et al.*, 2004). Analysis in this chapter also considers a situation where nitrogen fertilizer (calcium ammonium nitrate; CAN) was used to fortify the compost to evaluate its effect on the practice based on the research of Ndung'u *et al.*, 2005.

5.2.2 Comparison of composting scenarios

As much as research suggests some possible correlations between some maize growth characteristics and yield (Ma *et al.*, 1996; Léon *et al.*, 1989), there is no direct relationship between the plant growth stage and yield. Due to this, no attempt was made to estimate the final grain yield of the maize crop based on the 25 day establishment study, in order to avoid over/under estimating the overall yield. An opportunity cost

(market value of the smallholder compost) was used to accomplish the Cost-Benefit Analysis (see the following examples). Appendix 5 is presented in Annex on a CD-ROM.

Table 5.1 The cost of different materials and activities required to compost maize straw/bean residues using feedstock of initial C:N 20:1 or 30:1, chopped 5 and 10 cm long under Changu system

Material	Treatment type			
	Changu 20:1, 5 cm	Changu 20:1, 10 cm	Changu 30:1, 5 cm	Changu 30:1, 10 cm
	Cost (MK)	Cost (MK)	Cost (MK)	Cost (MK)
Feedstock collection	100	100	100	100
Chopping feedstock	165	140	175	150
Wood base	0	0	0	0
Water collection	150	150	150	150
Heap making	350	350	350	350
Smearing mud coat	0	0	0	0
Weekly watering & turning	800	800	800	800
Total cost	**1565**	**1540**	**1575**	**1550**

Weekly watering & turning is fixed at MK100/week for 8 weeks; MK = Malawi Kwacha; Source of data: Extension services, Lilongwe, Mulanje & Nsanje ADD (personal communication); U$1 = MK139.44; £1 = MK274.18, exchange rate as of 16/01/07 (National Bank of Malawi).

Table 5.2 The cost of different materials and activities required to compost maize straw/bean residues using feedstock of initial C:N 20:1 or 30:1, chopped 5 and 10 cm long under Chimato system

Material	Treatment type			
	Chimato 20:1, 5 cm	Chimato 20:1, 10 cm	Chimato 30:1, 5 cm	Chimato 30:1, 10 cm
	Cost (MK)	Cost (MK)	Cost (MK)	Cost (MK)
Feedstock collection	100	100	100	100
Chopping feedstock	165	140	175	150
Wood base	200	200	200	200
Water collection	300	300	300	300
Heap making	350	350	350	350
Smearing mud coat	250	250	250	250
Weekly watering & turning	0	0	0	0
Total cost	**1365**	**1340**	**1375**	**1350**

Weekly watering & turning is fixed at MK100/week for 8 weeks; MK = Malawi Kwacha; Source of data: Extension services, Lilongwe, Mulanje & Nsanje ADD (personal communication); U$1 = MK139.44; £1 = MK274.18, exchange rate as of 16/01/07 (National Bank of Malawi).

Tables 5.1 and 5.2 illustrate the costing involved in the production of the compost on smallholder sector for different initial C:N ratios, systems and chop lengths (treatments). The major differences in the costs between Changu and Chimato treatments are the cost for the wood base, water collection and weekly turning (Table 5.1 & 5.2). The Changu system does not require the wood base whereas the Chimato system does not need

weekly turning. Overall, the construction of the Changu system costs MK200 more than Chimato system for the same compost-mix ratio and chop length (Table 5.1 & 5.2).

Table 5.3 Benefit calculations for different treatments made of feedstock of initial C:N 20:1 or 30:1, chopped 5 and 10 cm long under Changu system

Parameter	Treatment type			
	Changu 20:1, 5 cm	Changu 20:1, 10 cm	Changu 30:1, 5 cm	Changu 30:1, 10 cm
	Calculations & values			
Total compost produced (kg)	= 130	130	124	124
Value (MK/kg)	= 15	15	15	15
Estimated total sales (MK)	= 15 x 130 = 1950	15 x 130 1950	15 x 124 1860	15 x 124 1860
Total benefit (MK)	= **385**	**410**	**285**	**310**

MK = Malawi Kwacha; U$1 = MK139.44; £1 = MK274.18, exchange rate as of 16/01/07 (National Bank of Malawi).

Table 5.4 Benefit calculations for different treatments made of feedstock of initial C:N 20:1 or 30:1, chopped 5 and 10 cm long under Chimato system

Parameter	Treatment type			
	Chimato 20:1, 5 cm	Chimato 20:1, 10 cm	Chimato 30:1, 5 cm	Chimato 30:1, 10 cm
	Calculations & values			
Total compost produced (kg)	= 111	111	106	106
Value (MK/kg)	= 15	15	15	15
Estimated total sales (MK)	= 15 x 111 = 1665	15 x 111 1665	15 x 106 1590	15 x 106 1590
Total benefit (MK)	= **300**	**325**	**215**	**240**

MK = Malawi Kwacha; U$1 = MK139.44; £1 = MK274.18, exchange rate as of 16/01/07 (National Bank of Malawi).

Worthy noting is the fact that the chopping costs differ for the treatments made of materials with different chop lengths due to differences in the labour demands. Composting of materials with chop length of 5 cm costs MK25 more than that of 10 cm length *e.g.* Changu 20:1, 5 cm versus Changu 20:1, 10 cm (Table 5.1). There is also a difference of MK10 due to chopping costs in formation of different compost-mixes where

treatments with initial C:N 20:1 costs less than C:N 30:1 *e.g.* Chimato 20:1, 5 cm versus Chimato 30:1, 5 cm (Table 5.2). This is due the use of more biomass of maize residues in treatments with initial C:N 30:1 than C:N 20:1. Chopping of maize residues requires more labour than bean residues. The sample calculations used for the benefits for different treatments are shown in Tables 5.3 and 5.4 for associated costs in Table 5.1 and 5.2 respectively.

A summary of the benefits for all the treatments are presented in Table 5.5. Despite the Changu treatments costing more than Chimato treatments, Changu treatments had higher benefits than Chimato. This was due to the fact that Changu treatments produced comparably more matured mass of compost than Chimato treatments since Chimato had some patches of partially decomposed material as established in Chapter 4, Section 4.2.1.7. The treatments made from C:N 20:1 feedstock in this study also yielded more mass than treatments made of C:N 30:1 due to the differences in the initial dry matter at the on set of composting (Table 5.3 & 5.4).

With reference to the compost produced in this research, the treatment Changu 20:1, 10 cm produced the highest benefit (MK410) compared to MK325 for the same treatment under the Chimato system (Table 5.5). This was due to the favourable conditions created in the Changu system which composted all the material and resulted in higher mass of resultant compost than in the Chimato where there was an outer layer material which was partially composted due to limitations of the oxygen and moisture. The worst scenario was the production of the compost using Chimato 30:1, 5 cm where a least benefit was incurred (MK215) (Table 5.5). This emphasizes the importance of the need to improve processes in the Chimato system to maximize the amount and quality of the compost produced in order to increase the benefits which can be attained.

Table 5.5 The benefit evaluation for different treatments tested for the smallholder composting practice using maize straw and bean residues

Treatment type	Benefit (MK)/heap
Changu 20:1, 5 cm	385
Changu 20:1, 10 cm	410
Chimato 20:1, 5 cm	300
Chimato 20:1, 10 cm	325
Changu 30:1, 5 cm	285
Changu 30:1, 10 cm	310
Chimato 30:1, 5 cm	215
Chimato 30:1, 10 cm	240
Changu 5 cm	335
Changu 10 cm	360
Chimato 5 cm	265
Chimato 10 cm	290
Changu 20:1	397
Chimato 20:1	312
Changu 30:1	297
Chimato 30:1	227
Changu	347
Chimato	277

U$1 = MK139.44; £1 = MK274.18, exchange rate as of 16/01/07 (National Bank of Malawi).

5.2.3 Comparison of normal composting and fortified composting

The fortification practice advocated by other researchers pushes up the production cost of the smallholder composting by MK20 (the cost of the fertilizer incorporated per heap). This reduces the monetary benefits compared to normal compost production, but could result with high yield than unfortified compost. The incorporation of compost in the soil has several intangible benefits. These include the improvement of the soil physical fertility and the gradual release of the nutrients over time. Both, the normal compost and fortified compost fulfil these benefits. Note that the fortified compost utilizes chemical nitrogen fertilizer which is not necessarily friendly to the environment. Excess use of this may lower the air, soil and water quality. This coupled with the fact that the smallholder

sector can rarely afford fertilizer means that improvement of the compost quality using the organic sources is of paramount importance.

5.3 Application of the results findings in low resource farmers (*e.g.* Malawian context).

5.3.1. The current situation in Malawi

There is little use of chemical fertilizers and organic-matter technology by the smallholder farmers (Kumwenda *et al.,* 1997). Fertilizers are sold at prices that are too high for the smallholder farmer uses (Kumwenda *et al.,* 1996, 1997; Sanchez *et al.,* 1997) whereas there is minimal support from the government on use of organic sources of nutrients in crop production. This has led to a situation where farmers collect dry maize stover, grass and if available chicken manure and put these in the pit or heap and add some soil and water to create compost. A survey carried out in 2002 (Maliro *et al.,* 2002), uncovered a number of short-comings with the way the practice is being currently conducted. These include:

a. not many farmers understand what composting encompasses (requires)
b. there is lack of nitrogenous material in the rural areas which can be used to improve the quality of the feedstocks mainly comprising maize stover
c. lack of knowledge on the composting systems being currently employed
d. lack of extension services relating to composting technologies

Due to the foresaid, some farmers were observed literally mixing dry grass and soil and adding water hoping to generate compost. The consequence of this is that farmers tend to lose interest in the technology when they realise no benefit from what they perceived as compost.

5.3.2. Applying this research

The results showed that feedstock quality is critical, maize straw can be turned into a fertilizer or soil amendment by adding an organic source of N *i.e.* green bean residues or grass with some clover. The target should be to reduce the C:N ratio of the feedstock to ≤ 30:1. With proper management of the composting process, this material can be oxidized and stabilized at low final C:N which can easily be incorporated into the soil for crop production. To make this work in the context of the smallholder sector, there is need to characterize different feedstocks and develop a guide for mixing different types of feedstocks to desired initial C:N ratios. During characterization of the feedstocks, the development of the use of colour as a means for determining the status of the feedstock would be of great use to the smallholder farmer. This can then be linked to the organic resource database (ORD) currently under construction (Palm *et al.,* 2001) as an input to the expansion of the ORD as well as a source to prediction of the quality of the different materials whether fresh or dry before feedstock formulation.

The initial compost-mix is crucial to the composting process undertaken and the quality of the final compost and its mineralization and plant support depends on it. A deliberate effort should be made to characterize different materials which exist in rural areas and are potentially compost feedstock, so that guideline mix ratios could be used by farmers to create ideal C:N ratios before they proceed with composting activity. To reduce labour requirements, the farmers can work with equivalent to 10 cm chop length of maize straw rather than cutting them very short.

It was also found that the systems differ in the way they control the composting factors hence the processes and the quality of the end product. An attempt should be made to impress upon farmers how these operate so that farmers can make an informed choice on which system to use, based on required output, social factors and economic status. As was established, there is a potential for further optimising the two systems that were studied here. Mainly this is to do with manipulation of the aeration procedures, moisture control and feedstock formulation. The Chimato system requires modification whereby

the number of holes is increased to efficiently aerate the system but these should also be used to improve the moisture content of the system with time. Technical support in these issues would be paramount in improving the quality of the compost farmers can expect from such systems.

The composing processes studied here can also be replicated in a longer heap (windrow). This can be achieved by only extending the length and maintaining the same height to avoid compaction, which can drastically reduce the porosity of the material hence the oxygenation of the heap. This is because the Changu system is turned regularly exposing much of the material to air and moisture facilitating the composting process. On the other hand, in a Chimato system with increased holes, more air can enter into the heap and promote microbial activity, but there is need to find a mechanism to reduce the compaction effect of the mud coat on the feedstock.

5.4 Publishable material from this research: a proposed framework

5.4.1. Understanding the composting processes of the Changu and the Chimato systems practiced by smallholder farmers in Malawi

This work pioneers and establishes the base of the knowledge of the processes undertaken by the two composting systems being practiced by smallholder farmers in Malawi. The Chimato system is characterized by a rapid build up of microbial activity which sharply declines within a few days while the microbial activity in the Changu system builds up gradually and is sustained for a longer period with proper management. The differences in the composting processes resulted with a high concentration of NH_4-N in the Chimato system and a high concentration of NO_3-N in the Changu system. Even though there was a divergence in nutrient contents with respect to the same compostable substrate, overall, the quantity of the final nutrient content tended to converge as composting proceeded. It is proposed to submit this component of work to the *African Journal of Biotechnology.*

5.4.2. Post-compost mineralization of straw-based compost in relation to the composting systems

Under a controlled environment, only TON was observed when compost from the Changu and the Chimato systems was incorporated into the soil. Overall, the effect of the compost from the two systems was not significantly different, but the compost-mix influenced the mineralization processes. There was minimal variation in the dynamics of the extractable-P and K with microbial fixation of the nutrients in the initial phase. Despite the short duration of the mineralization tests, this work supported the influence of the use of compost on the elevation of CEC. It is proposed to submit this component of work to *Biology and Fertility of Soils.*

5.4.3. Agronomic impact of compost from different systems during maize establishment

The compost made from the maize/wheat straw with organic sources of N using smallholder composting systems is an effective soil fertilizer. The compost systems had variable effects on maize growth characteristics. The treatments made from the low compost-mix (C/N ratios) supported significantly larger growth parameters and higher nutrient plant uptake than the high C/N compost due to increased availability of the nutrients accredited to the feedstock quality. It is proposed to submit this component of work to the *Journal of Plant Nutrition and Soil Science* or *Field Crops Research.*

5.5 Summary

1. Smallholder farmers can compost maize straw using locally-available green sources of N (grass/clover or bean residue), to produce an effective product.
2. Compost-mix (feedstock C:N) predominantly controls the composting process, compost quality and mineralization characteristics. The lower the initial C:N, the higher the microbial activity (high temperatures e.g. 60^{o}C attained during composting from treatments with initial C:N 20:1), the higher the concentration of mineral N and the lower the final C:N ratio.

3. The composting system affects the status of the composting factors and consequently modulates the composting processes *i.e* Changu system promotes aeration (oxygen) and moisture content for a longer period which results in longer microbial activity than in Chimato.
4. There is potential to further improve the composting processes and quality of compost produced from the composting systems reported in this thesis. This can be achieved by improving the aeration and moisture regimes of the Chimato system. On the other hand there is need to reduce the loss of heat from the Changu system by introducing the coat. In both systems the feedstock quality should be controlled and the initial C:N ratio should be ≤ 30:1.

CHAPTER SIX: Conclusions and recommendations

6.1 Conclusions

This thesis aimed to develop techniques to optimise composting systems and quality of compost produced by resource poor farmers of Malawi for increased crop production.

The original objectives were:

1. To study and characterise two composting systems practised in Malawi using straw/green organic material feedstock under different agro-ecological zones.
2. To determine optimum conditions required for production of well matured and quality compost under these systems.
3. To investigate the nutrient release characteristics of composts in soils from different composting systems.
4. To determine the establishment pattern of maize seedlings in relation to different composting systems.
5. To evaluate the cost and benefit of the two composting systems with respect to the smallholder sector in Malawi.

The following conclusions of this thesis are based on the results from the experiments characterizing the Changu (turned and watered regularly) and Chimato (covered with mud and static) composting systems practiced in Malawi, mineralization of compost and maize seedling performance in the soil amended by the resultant composts and the cost benefit analysis of the systems is presented:

1. Composting crop residues using smallholder systems was an effective way of converting high C/N ratio materials (maize straw/wheat straw) into a fertilizer and soil organic matter amendment. The Changu and Chimato systems transformed maize straw when mixed with bean residue into an organic fertilizer with as much as 1.1% total N.

2. The Changu system was characterized by significantly longer mesophilic (18 days) and active composting periods (24 days) in contrast to the Chimato system which had a longer thermophilic phase (7 days) due to influence of the mud coat, but had overall short active composting period (19 days). This resulted in a longer period of higher microbial activity in the Changu compared to the Chimato. The major limitation to composting processes in Chimato was apparently lack of oxygen and moisture, which was exacerbated by the compressive effect of the mud coat, reducing the total yield of compost from this system *i.e.* the mass of matured compost.

3. The different composting processes generated by the Changu and Chimato systems influenced the final mineral nitrogen forms. The longer composting time in the Changu system resulted in greater concentrations of TON (61 mg/kg dwt.) or nitrates (406 mg/kg dwt.) than NH_4-N (24 and 359 mg/kg dwt.) for UK and Malawi experiments respectively. Whilst the Chimato system produced greater concentrations of NH_4-N (61 and 36 mg/kg dwt.) than TON (8 and 34 mg/kg dwt.) for UK and Malawi experiments respectively.

4. The feedstock quality affected the composting process and determined the final quality of the compost. When compost was made from different compost mixes, the lower initial C:N ratio (C:N 20:1) resulted in higher microbial activity (reached a temperature of 60^{o}C) and the lowest final C:N ratio (final C:N 12:1) compost and the higher nutrient concentration compared to the high initial C:N feedstock (C:N 60:1). This reached only 43^{o}C and a final C:N of 31:1. It was not possible to efficiently compost feedstock with initial C:N ratio ≥60:1 using the smallholder systems since this could not reach the minimum required C:N (≤ 20:1) which can allow the resultant compost to be applied into the soil without immobilization of mineral nitrogen or phytotoxic effects.

5. Smallholder farmers can chop the maize straw and bean residue to 10 cm when preparing for composting. When feedstock with chop lengths of 5 and 10 cm were used, no significant differences were observed in the composting process indicating that the farmers can safely use a 10 cm chop length without adversely affecting the composting process, consequently saving labour costs.

6. Post-compost mineralization processes were influenced more by the compost-mix (C:N ratio) than the composting system (these had not significantly different concentrations of total N). Treatments with low initial C:N ratio (20:1) mineralized more N (TON) during incubation while those with high initial C:N 30:1 and 60:1 (especially for wheat straw/grass clover compost) were immobilizing N compared to the no-compost control due to limitation of N. There is potential that pre-incubating the compost into the soil prior to maize seed sowing will mitigate the detrimental effects of immobilization on maize plant establishment.

7. The use of compost elevated the CEC of the soil by 2.1 cmol/kg, suggesting that use of compost made from the maize straw would improve the nutrient retention capacity of the soil. This will help smallholder farmers to prevent limited nutrient supplies from leaching in times of rain.

8. The compost made from the maize or wheat straw and bean residue or grass/clover promoted maize seedling establishment compared to an un-amended soil control. Low final C:N ratio composts (12:1 & 14:1 from initial C:N 20:1 and 30:1) supported more uptake of N, P and K and consequently produced plants with larger stems, leaf parameters and biomass compared to higher final C:N ratio composts (19:1 & 31:1) emphasizing the importance of the feedstock quality. The composting system was also significant during maize establishment, but the differences varied between UK and Malawi experiments for plant growth parameters. The Changu system supported larger plant growth characteristics compared to Chimato for the UK experiments whereas it was *vice versa* for the

Malawi resultant compost. No differences were observed with respect to plant nutrient uptake for the Malawi experiment whereas Changu treatments supported more plant N and K uptake than Chimato for the UK experiments.

9. There is an opportunity for optimizing the compost, and composting systems used by smallholder farmers in Malawi:
    a. The compost produced could be improved by promoting production of green leguminous crops which can be mixed with the maize straw to improve its quality before composting processes commence.
    b. The Chimato system requires some modifications to promote aeration (oxygen supply) and moisture adjustment to sustain microbial activity over time. There is a need to modify the formation of the mud coat whereby it should not be put directly on the feedstock to reduce the compression effect from the weight of the wet mud. For example, a protective mesh could be created using locally-available shrubs, bamboos or maize stover that is not chopped. The Changu can be improved by introducing a movable coat which would help to reduce the excess loss of moisture and heat thereby retaining higher temperatures and moisture for longer periods. This would reduce the labour costs and speed up the composting process. Based from the findings in this research, Changu system is recommended than Chimato since it offers an opportunity to control the composting factors thereby promoting composting processes and resulting in higher biomass of mature compost.

10. The cost benefit analysis showed that it is profitable to compost feedstock with low initial C:N ratio and long chop length using the Changu system (Changu 20:1, 10 cm) where the highest net-benefit is obtained (MK410). It is not advisable to produce compost using the Chimato system, with a 30:1 feedstock, and a chop length of 5 cm, since this result in a least benefit (MK215).

6.2 Recommendations for further study

1. A study is required to determine the aeration system (*e.g.* number of holes) needed to effectively improve the compost process and amount of the compost produced from the Chimato system. There is also a need to investigate the possibility of adjusting the moisture of the heap without breaking up the mud coat.

2. Observations from this study noted the need to modify the formation of the mud coat so that it does not rest on the feedstock and observe the consequences of absence of compression (improved porosity) and lack of turning on the composting process and compost quality.

3. There is a need to determine the maximum chop length where maize straw effectively composts when mixed with bean residue in order to ensure minimum labour costs associated with this step are incurred during compost preparation.

4. In this study, the maize establishment experiments ran for 25 days only. During this period the maize plants were still small, such that they never reached a stage when they demanded more nutrients from the soil. This made it difficult to assess the full impact of the composting systems on the maize growth performance. A complete maize growth trial should be conducted in the field using compost from Changu and Chimato systems (made of maize straw and green organic source of N) to determine the maize grain yield from these compared to no compost application trial and fertilizer trials.

5. To promote good composting practice (controlling the initial C:N ratio), there is need for a country-wide study where a comprehensive range of potential feedstocks for composting can be characterized and a guide be developed on how smallholder farmers can create ideal compost mixes. This study needs to be divided into the different agro-ecological zones and be streamlined by the

common sources of nitrogen which can be incorporated into the feedstock to improve the initial C:N ratio. Once the feedstocks have been characterized, the mix ratio should be determined as mass or volume of each organic material (*i.e.* number of buckets of each material to be mixed) to obtain a desired C:N ratio. This should be followed by composting trials in each of the agro-ecological zones to assess the developed compost feedstock proportion mixing technique.

6. Peri-urban agriculture has grown in the recent past and supplies most of the city with vegetable and green maize. The city assemblies (*e.g.* Lilongwe City Assembly) discard tonnes of food wastes from the city markets into land fill sites which are 30 km away from the city. This is a potential source of compost feedstock for the farmers who produce for the city. There is need to develop composting guidelines of these materials alone and when they are mixed with straw. Composting farmer groups can be formed, and links with the city assemblies forged, so that these wastes can be managed and composted by the farmer groups instead of going into land fill sites. This will improve the household food security in peri-urban areas.

7.0. References

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8.0 Appendices

8.1 Appendix 1: Maps presented here relate to Chapter 1

Figure A1.1 Map of England and Wales showing the site (Silsoe) where the UK composting experiments and subsequent post-compost mineralization and maize establishment experiments were conducted.

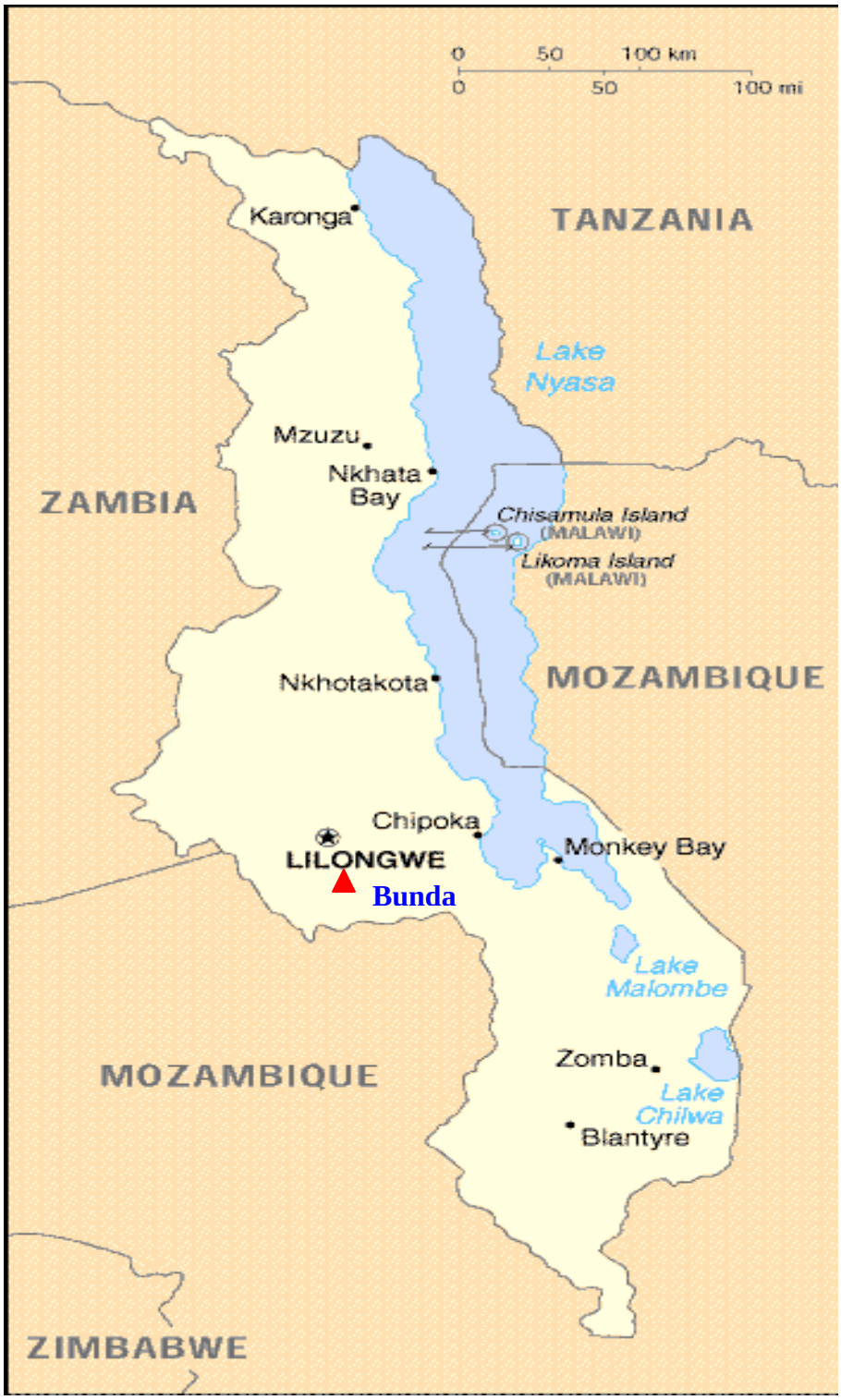

Figure A1.2 Map of Malawi showing the site (Bunda College) where the Malawi composting experiments were conducted.

8.2 Appendix 2: Methods and principles presented here relate to Chapter 2

Appendix 2.1a Recipe formulation methodology; Blending materials to the desired C:N ratio using weight basis

Parameters required for the calculations include moisture content, weight of water in the material, dry weights, nitrogen contents, and carbon contents. The primary formulas for individual ingredients are as follows:

Moisture content = % moisture content ÷ 100

Weight of water = total weight x moisture content

Dry weight = total weight – weight of water

= total weight × (1 – moisture content)

Nitrogen content = dry weight × (%N ÷ 100)

% carbon = %N × C:N ratio

Carbon content = dry weight × (%C ÷ 100)

= N content × C:N ratio

The formulas for mixing materials for composting used were as follows:

C:N ratio =

$$\frac{\left[\%C_a \times a \times \left(1-m_a\right)\right]+\left[\%C_b \times b \times \left(1-m_b\right)\right]+\left[\%C_c \times c \times \left(1-m_c\right)\right]}{\left[\%N_a \times a \times \left(1-m_a\right)\right]+\left[\%N_b \times b \times \left(1-m_b\right)\right]+\left[\%N_c \times c \times \left(1-m_c\right)\right]}$$

This is followed by moisture content check up. Moisture content of the ingredients can be checked as follows:

Moisture content = weight of water in ingredient a + water in b + water in C ÷ total weight of all ingredients

$$\text{Moisture content} = \frac{(a \times m_a) + (b \times m_b) + (c \times m_c)}{a + b + c}$$

Where: a = total weight of ingredient a

b = total weight of ingredient b

c = total weight of ingredient c

m_a, m_b, m_c = moisture content of ingredients a, b, c

% N_a, N_b, N_c = % nitrogen of ingredients a, b, c (% dry weight)

% C_a, C_b, C_c = % carbon of ingredients a, b, c (% dry weight)

(Adopted from Dougherty, 1999)

Appendix 2.1b Incubation sample calculation formulas; mixing soil and compost to a desired application rate

a) Quantification of the soil in a hectare

Working depth = 0.30 m

Area, hectare = 10, 000 m^2

Bulk density of soil used = 1,500 kg/m^3

Calculating for the total soil in 1 hectare:

Weight of soil in 1 ha = Depth x Area x Bulk density

$$\text{Weight of soil in 1 ha} = 0.30m \times 10{,}000m^2 \times \frac{1{,}500kg}{m^3}$$

Weight of soil in 1 ha = 4,500,000 kg

b) Calculating for the compost required for each application rate *i.e.* 10 t/ha and 30 t/ha:

$$\text{Amount of compost applied (g)} = \frac{\text{Weight of soil in a pot}}{\text{Total weight of soil in 1 ha}} \times \text{Application rate}$$

Appendix 2.1c Method used for analysis of total carbon and total Nitrogen for organic material used in the United Kingdom

Carbon determination by CNS analyser (VARIO EL II)

General measuring principle

The elementary analyser Vario EL is fully automatic instrument for the quantitative determination of Carbon, Nitrogen and Sulphur. It works according to the principle of catalytic tube combustion in an oxygenated CO_2 atmosphere and high temperatures. The combustion gases are freed from foreign gases (*i.e*. volatile halogen). The desired measuring components are separated from each other with the help of specific adsorption columns and determined in succession with a thermal conductivity detector (TCD). Helium (He) serves as flushing and carrier gas. The automatic control of the analysis procedure is accomplished through the software.

Sample loading

The homogenized sample is packed in tin foil, weighed and placed into the carousel of the automatic sample feeder. The sample name and the matrix specific oxygen dosing are allocated to the sample weight. At the start of an analysis, the "auto-zero adjust" of the measuring signal is carried out through the detector. Thereafter the ball valve opens through a 180º turn of the blind hole ball. The carousel moves up one position and the sample drops into the ball valve. The ball valve turns 90º into flushing position and seals the apparatus. The atmospheric nitrogen that had entered is flushed out and the sample drops into the ash finger of the combustion tube through another 90^o turn of the ball valve.

Sample digestion and removal of foreign gases (CN-mode)

Parallel to the sample feeding procedure, the oxygen dosing in the ash finger begins, so that the sample drops into a highly oxygenated atmosphere and combusts explosively. During oxidised combustion the elements C and N produce, in addition to the molecular nitrogen (N_2), the oxidation products CO_2, NO_X.

A copper oxide filling inside the combustion tube works as catalyst for quantitative oxidation of higher carbon oxide and samples that are difficult to combust. Volatile Fluor compounds are chemically bound on a layer of ceroxide and the lead chromate filling absorbs the sulphur compounds (SO_2 / SO_3). A copper filling in the reduction tube quantitatively reduces nitrogen oxides (NO_X) to N_2 and binds excess oxygen. The volatile halogen compounds are removed from the gas stream at the exit of the reduction tube with silver wool. The remaining gas stream contains only CO_2, H_2O and N_2 in the carrier gas (He). In the CN-mode the gas stream is freed of H_2O with a built in absorption U-tube and guided to a modified separation system.

Separation of the measuring components (CN-mode)

The separation of measuring components is carried out through specific adsorption on heatable columns. In each mode of operation only the necessary adsorption columns are built into the gas path. This column adsorbs the CO_2 and the measuring gas stream contains only N_2, which is measured directly in the thermal conductivity detector (TCD). After the N-measurement, the CO_2 is likewise thermally desorbed and measured. When the integration of a component is concluded, the integral value is stored, an integrator reset is carried out and the next component is desorbed by the adsorption column and measured.

Detection

The thermal conductivity detector consists of two measuring chambers. The gas flows through them at constant rate of flow. During measuring operation the reference measuring chamber is flushed with pure carrier gas He while the measuring gas flow, ***i.e.*** the respectively desorbed fraction of the reaction gas (e.g. He/N_2 – or He/CO_2 – mixture) passes through the other one. The detector output voltage is recorded as a function of time and digitized.

Through the calibration for each element the integral is allocated to an absolute element content of the sample. From the resulting content and the sample weight, the percentage of the element content is calculated.

Appendix 2.1d Method used for analysis of total carbon for organic material used in Malawi

The total carbon analysis used wet oxidation of the organic carbon by acidified dichromate. The reaction is as follows:

$$2Cr_2O_7^{2-} + 3C^0 + 16H^+ = 4Cr^{3+} + 3CO_2 + 8H_2O$$

The temperature of the reaction is increased by heating the sample at 150^{o}C for 30 minutes to completely oxidize the organic carbon. The amount of chromic (Cr^{3+}) produced in the reaction was determined colorimetrically.

Reagents

1. Barium chloride, 0.4%: dissolve 4 g bariun chloride in 1000 mL water
2. Potassium dichromate, 5%: dissolve 50 g in 1000 mL water
3. Sucrose
4. Sulphuric acid, concentrated (H_2SO_4, 36 N)

Standards

1. Dry 15 g sucrose at 105^{o}C for 2 hours. Cool in a desiccator
2. Dissolve 11.886 g dry sucrose in water and make up to 100 mL in a volumetric flask. This gives 50 mg/mL C solution
3. Using a pipette transfer 0, 5, 10, 15, 20, 25 mL of the 50 mg/mL C stock solution into labelled 100 mL volumetric flasks and make up to the mark with water. Mix well. These constitute working standards and contain 0, 2.5, 5.0, 7.5, 10.0, 12.5 mg/mL C
4. Pipette 2 mL of each working standards into labelled 100 mL conical flasks, and dry at 105^{o}C. These contain 0, 5, 10, 15, 20, 25 mg C

Procedure

1. Weigh 1 ± 0.001 g ground sample (< 1 mm) into labelled 100 mL digestion tube. Record the weight of the sample used as W
2. Add 2 mL water
3. Add 10 mL 5% potassium dichromate solution and allow it to completely wet the sample or dissolve the standards
4. Slowly add 5 mL H_2SO_4 with a burette and gently swirl the mixture (CAUTION on handling the acid)
5. Digest at 150^{o}C for 30 minutes
6. Allow to cool, then add 50 mL 0.4% barium chloride, swirl to mix thoroughly, and allow to stand overnight, so as to leave a clear supernatant solution
7. Transfer aliquot of the supernatant solution into a colorimeter cuvetted, and measure and record each standard and sample absorbance at 600 nm

Calculation

Plot a graph of absorbance against standard concentration. Determine solution concentrations for each sample and the blanks. Subtract the mean blank values from the sample value, the corrected concentration are designated K. The weight of sample used is designated W

% organic carbon = (K * 0.1) / W

(Adopted from Anderson & Ingram, 1993)

Appendix 2.1e Method used for extraction of total nitrogen and phosphorus of organic material used in Malawi

Wet oxidation of organic matter based on Kjeldahl was used for analysis of total nitrogen. Hydrogen peroxide was used as an additional oxidizing agent along aside selenium and lithium sulphate raised the boiling point of the sample. Only one digestion is required to bring nearly all of the nutrients into solution, no volatilization of metals, nitrogen or phosphorus takes place.

Reagents

1. Hydrogen peroxide, 30%
2. Lithium sulphate
3. Selenium powder
4. Sulphuric acid, concentrated (H_2SO_4, 36 N)
5. Digestion mixture: Add 0.42 g selenium powder (handled in a fume cupboard) and 14 g lithium sulphate to 350 mL 30% hydrogen peroxide and mix well. Slowly add with care 420 mL concentrated H_2SO_4 while cooling in an ice bath. The mixture is stable for 4 weeks when stored at 2^oC.

Procedure

1. Weigh about 0.2 ± 0.001 g ground sample (< 1 mm) into a numbered digestion tube. Record the weight
2. Add 4.4 mL digestion mixture to each tube.
3. Digest at 360^oC for 2 hours. The solution should now be colourless and any remaining solids white. If colour can still be seen, heat for a further 1 hour
4. Allow to cool
5. Add 50 mL water and mix well and allow to cool
6. Volumetrically make up to 100 mL with water and mix well
7. Allow to settle so that a clear solution can be taken for analysis

Colorimetric determination of total N

Reagents

1. Sodium citrate
2. Sodium hydroxide
3. Sodium hypochlorite solution, 5% available Cl^-
4. Sodium nitroprusside (CAUTION: poison)
5. Sodium salicylate
6. Sodium tartrate

7. Reagent N1: Dissolve 34 g sodium salicylate, 25 g sodium citrate and 25 g sodium tartrate together in 750 mL water. Add 0.12 g sodium nitroprusside and when dissolved make up to 1000 mL with water. Mix well
8. Reagent N2: Dissolve 30 g sodium hydroxide in 750 mL water. Allow to cool, add 10 mL sodium hypochlorite solution and make up to 1000 mL with water. Mix well.

Note: Reagent N1 and N2 should be made at least 24 hours before use and stored in the dark

Standards

1. Dry 7 g ammonium sulphate at 105^{o}C for 2 hours. Cool in desiccator
2. Dissolve 4.714 g dry ammonium sulphate in water and make up to 1000 mL in a volumetric flask. This is 1000 µg/mL NH_4^+-N stock solution
3. Pipette 50 mL of 1000 µg/mL NH_4^+-N solution into a 500 mL volumetric flask and make up to the mark with water. This is a 100 µg/mL N solution
4. Pipette 0, 5, 10, 15, 20 and 25 µg/mL NH_4+-N solution into labelled 100 mL volumetric flasks. The standards must be made up in exactly the same solution as the final samples, excluding the sample. These working standards contain 0, 5, 10, 15, 20 and 25 µg/mL NH_4^+-N

Procedure

1. Using pipette transfer 0.100 mL of each standard and sample into marked test tubes
2. Add 5.00 mL of reagent N1 to each test tube, mix well and leave for 15 minutes
3. Add 5.00 mL of reagent N2 to each tube mix well and leave for 1 hour for full colour development. The colour is stable for 1 day only
4. Read each standard and sample absorbance at 655 nm

Calculation

Plot a graph of absorbance against standard concentration. Determine solution concentrations for the sample and the blanks. Subtract the mean blank value from the sample; this gives absorbance value for the corrected concentration, C. The weight of the sample is presented by W.

Nitrogen (%) = (C/W) * 0.01

(Adopted from Anderson & Ingram, 1993)

Appendix 2.1f Method used for extraction of total potassium and phosphorus of organic material used in the United Kingdom (NSRI/AL/SOP 18/Version 1)

Principle

The organic mater of the sample is destroyed by dry combustion and the soluble mineral constituents in the ash are dissolved in hydrochloric acid. Any silica present is dehydrated and hence made insoluble.

Reagents

1. Hydrochloric acid; 36 % m/m HCL
2. Hydrochloric acid; 6 M (RSPUR 64)

Procedure

1. Transfer 2.0 ± 0.004 g of ground sample ((< 1 mm) into a labelled evaporating basin (shallow form with round bottom and spout)
2. Include a blank with each batch of samples
3. Place a basin in a furnace and heat the sample at 500^{o}C. Maintain this temperature overnight – until a whitish-grey ash remains. (If difficulty is experienced in obtaining a carbon-free ash, remove the basin from the furnace, moisten the cold ash with deionised water, dry thoroughly at 102^{o}C and reheat at 500^{o}C)
4. When all the organic matter has been destroyed remove the basin from the furnace, cool and cover with a watch glass

5. In the fume cupboard add 10 mL of 6 M hydrochloric acid by pipette, to the ash in the basin, taking care that losses due to effervescence do not occur. Remove and rinse the watch glass, collecting the washing in the basin
6. Place the basin on a boiling water bath in the fume cupboard, and evaporate the solution to dryness – this will take one hour
7. When dry, continue heating for one hour on the boiling water bath
8. Moisten the residue with 2 mL of hydrochloric acid (36 % m/m HCL), place the basin on a hotplate in the fume cupboard, cover with a watch glass and gently boil for 2 minutes
9. Add 10 mL of hot deionised water and allow to boil
10. Remove and rinse the watch glass, collecting the washings in the basin
11. Transfer the entire contents of the basin into a 50 mL volumetric flask and dilute to 50 mL
12. Filter through a No. 4 filter paper and retain the filtrate in a plastic bottle for analysis. Refrigerate the samples if the analysis is not to be carried out immediately

(Adopted from MAFF, 1986; NSRI/AL/SOP 14/Version 1)

Appendix 2.1g Method used for determination of total potassium of organic material used in the United Kingdom (NSRI/AL/SOP 20/Version 1)

Potassium in the sample solution remaining after the destruction of the organic matter of the sample (NSRI/AL/SOP 18) is dissolved in hydrochloric acid. The concentration of potassium in the solution is determined by flame photometry.

Reagents

1. Potassium stock standard solution, 1000 mL/L K (RSPUR 47)
2. Potassium working standard solutions, 0-50 mg/L K (RSPUR 130)

Preparation of standard graph

1. Set up the flame photometer according to (NSRI/AL/SOP E14) and calibrate to produce zero and maximum readings whilst aspiring the 0 and 50 mg/L of potassium standard solutions
2. Aspirate the intermediate standard solutions and construct a graph relating meter readings to mg/L of potassium

Determination of potassium

1. Aspirate the blank and sample extracts and record the meter readings
2. If the meter readings are greater than 100 dilute the sample and call the dilution factor D

Calculations

1. Read from the standard graph the mg/L of potassium equivalent to the meter readings of the blank and sample extracts
2. The sample minus blank value (V) gives the mg/L of potassium in the extract
3. 2 g of sample is extracted and diluted to 50 mL; Therefore, the total potassium in the extract = 50/1000 * V mg
4. And the total potassium in the sample = 50/1000 * V * 1000/2 mg/kg
   = V * 25 mg/kg
5. If the sample has been diluted the total potassium = V * 25 * D mg/kg

Appendix 2.1h Method used for determination of extractable potassium of soil used in the United Kingdom (NSRI/AL/SOP 14/Vesrion 1)

Potassium was extracted from the soil with 1 M ammonium nitrate. The concentration of potassium in the extract was determined by flame photometry (NSRI/AL/SOP E14). The analysis was done in triplicate.

Reagents

1. 1 M ammonium nitrate solution (RSPUR 46)
2. Potassium stock standard solution, 1000 mg/L potassium (RSPUR 47)
3. Potassium working standard solution, 0-50 mg/L potassium (RSPUR 48)

Extraction

1. Weighed 5 g of ground air dried soil (< 2 mm) into a 100 mL plastic bottle
2. Added 25 mL of 1 M ammonium nitrate solution to each bottle
3. Carry out the blank extraction, omitting the soil, with each batch of samples
4. Shake for 30 minutes (NSRI/AL/SOP E15)
5. Filter through Whatman No. 2 filter paper and retain the extract in a refrigerator for no longer than one week

Preparation of standard graph

1. Set up the flame photometer as in (NSRI/AL/SOP E14) and calibrate to produce zero and maximum readings whilst aspiring the 0 and 50 mg/L of potassium standard solution
2. Aspirate the intermediate standard solutions and construct a graph relating meter readings to mg/L of potassium

Determination

1. Aspire the blank and sample extract and record the meter readings
2. If the meter reading is greater than 100, dilute the sample using volumetric glassware. Call the dilution factor D

Calculations

1. Call sample value V_S and blank value V_B
2. $V = (V_s - V_b)$
3. 5 g of sample was extracted in 25 mL solution
4. Read from the standard graph the mg/L potassium equivalent to the meter readings for the blank and sample extracts

5. Multiply the sample minus blank value by 5 to give the results in mg/kg of extractable potassium in the sample (*i.e*. 5 g extracted in 25 mL)
6. If the sample has been diluted, multiply the result by D
7. Thus, mg/kg extractable potassium = $(V_s - V_b) * 5 * D$

Appendix 2.1i Methods used for determination of available nitrogen (NH_4-N and TON), phosphate P, and potassium of the compost used in the United Kingdom (NSRI/AL/SOP 23/Vesrion 1)

The finished compost samples was extracted immediately or refrigerated to arrest the microbial activities. The extraction was done by calcium chloride/DTPA (CAT) solution. The samples were extracted in an extraction volume ratio of 1 + 5. Ammonium-N was determined by an automated phenate method (NSRI/AL/SOP 8) while total oxides of nitrogen - TON (nitrate-N and nitrite-N) was determined by an automated hydrazine reduction method (NSRI/AL/SOP 7). Phosphorus was determined by an automated ascorbic acid reduction method (NSRI/AL/SOP 9). All these were run through Segmented Flow Analyser (NSRI/AL/SOP E10). Potassium was determined by flame photometer (NSRI/AL/SOP E14).

Reagents for extraction
1. Concentrated extracting solution $CaCl_2$/DTPA (CAT), (RSPUR 130)
2. Extracting solution $CaCl_2$/DTPA (CAT), (RSPUR 131)

Extraction
1. Transfer a weight equivalent to 30 mL of sample volume, weighed to the nearest 1 g of wet compost (prepared in accordance with EN 13040:1999) into a 250 mL wide mouth plastic bottle with a screw top
2. Take a small sample of the wet compost and determine the moisture content
3. Add 150 mL of extracting solution to each bottle
4. Carry out a blank determination with each batch of sample
5. Cap the bottles and shake on the machine for 1 hour (NSRI/AL/SOP E 15)

6. Filter through a Whatman No. 2 filter paper discarding the first 10 mL. Retain the filtrate for the determination of potassium. Phosphate-P, ammonium-N and TON
7. The filtrate extract is stable for three days in a closed polyethylene bottle stored in a refrigerator at 0 to 5^{o}C, and may be stored longer in a freezer at about -18^{o}C

Reagents for analysis

Phosphate-P

1. 2% Sulphuric acid (RPU 96)
2. Ammonium molybdate (RPU 97)
3. Ascorbic acid (RPU 98)
4. Stock standard, 1000 mg P/L (RPU 95)

TON

1. Sodium hydroxide, 0.4M (RPU 71)
2. Sodium hydroxide, 0.2M (RPU 72)
3. Stock copper sulphate solution (RPU 73)
4. Hydrazine-copper reagent (RPU 74)
5. Sulphanilamide (RPU 75)
6. Stock TON standard, 1000 mg N/L (RPU 64)

Ammonium-N

1. Sodium salicylate (RPU 94)
2. D.I.C. (RPU 88)
3. Citrate buffer (RPU 89)
4. Stock ammonium standard, 1000 mg N/L (RPU 90)
5. Extracting solution $CaCl_2$/DTPA (CAT), (RSPUR 131)
6. Standard in $CaCl_2$/DTPA (CAT), (RSPUR 132)

Potassium

1. Potassium stock standard solution, 1000 mg/L (RSPUR 47)
2. Potassium working standards in $CaCl_2$/DTPA solution (RSPUR 132)

Analysis

1. Phosphate-P, ammonium-N, TON – Segment flow analyser (NSRI/AL/SOP E10)
2. Potassium – using flame photometer (NSRI/AL/SOP E14)

Calculations

1. Call sample value V_s and blank value V_b
2. $V = (V_s – V_b)$ mg/L
3. V/1000 converts to mg/mL
4. Total solution = (150 mL of extracting solution + mass of water in sample)
5. mg/kg potassium, phosphate-P, TON or ammonium-N = (V/1000) * (total solution/dry mass of compost) * 1000

(Adopted from MAFF, 1986; Faithfull, 2002; BS EN 13651:2001)

Appendix 2.1j Method used for determination of extractable potassium of compost used in Malawi

Mehlich 3 method

Reagents

1. Ammonium fluoride (NH_4-F)
2. Ammonium nitrate (NH_4NO_3)
3. Acetic acid (CH_3COOH), 99%;
4. Nitric acid (HNO3), 70%
5. Ethylenediaminetetraacetic acid (EDTA), [$(HOOCCH_2)2NCH_2N(CH_2COOH)_2$]
6. 1000 ppm K stock solution
7. 1000 ppm strontium: Dissolve 6.08 g of $SrCl_2.6H_20$ to 2 L in a volumetric flask

Mehlich 3 Stock Solution (3.75 M NH_4F + 0.25 M EDTA)

- Mix 277.8 g NH_4F with ~1200 mL distilled water in a 2 L volumetric flask. Add 146.1 g of EDTA. Dilute to volume with distilled water and mix well. This is enough stock solution for ~10,000 samples

Mehlich 3 Extractant: (0.2 N CH_3COOH + 0.25 N NH_4NO_3 + 0.015 N NH_4F + 0.013 N HNO_3 + 0.001 M EDTA)

- Dissolve 500 g NH_4NO_3 in ~ 20 L of distilled water in a 25 L calibrated plastic container. Add 100 mL of the Mehlich 3 stock solution and mix well. Add 287.5 mL of glacial acetic acid (CH_3COOH) and 20.5 mL of concentrated nitric acid (HNO_3). Dilute to 25 L final volume with distilled water and mix thoroughly. The solution pH should be 2.5 +/- 0.1.

Finally prepare the potassium standards from the stock solution to develop the standard graph

Procedure

1. Weigh 2.5 g of compost into a 100 mL extraction bottle
2. Add 25 mL of the Mehlich 3 extracting solution to each bottle
3. Shake the solution on the shaker for 5 minutes and let it stand for 10 minutes
4. Centrifuge and filter through Whatman No. 2 filter paper
5. Prepare the blanks following the same procedure, but exclude the sample
6. Run the standards first to prepare a standard graph
7. Draw 0.5 mL of sample and blanks and mix with 25 mL of strontium chloride and analyze at 766 nm on atomic absorption spectrophotometer

(Adopted after (Mehlich, 1984)

Appendix 2.1k Method used for determination of total phosphorus of organic material used in the United Kingdom (NSRI/AL/SOP 19/Version 1)

The phosphorus in the sample solution remaining after destruction of the organic matter of the sample (NSRI/AL/SOP 18) is dissolved in hydrochloric acid. The concentration of phosphorus in the solution is determined as the yellow phosphor-vanado-molybdate complex on a spectrophotometer.

Reagents

1. Ammonium molybdate-ammonium metevanadate reagent (RSPUR 65)
2. Hydrochloric acid, 5 M (RSPUR 66)
3. Phosphorus stock standard solution, 1000 mg/L P (RSPUR 67)
4. Phosphorus working standard solutions, 0-50 mg/L P (RSPUR 68)

Preparation of standard graph

1. Pipette 10 mL of each phosphorus working standard solution into labelled 50 mL volumetric flasks
2. To each flask add 5 mL of 5 M hydrochloric acid and 5 mL of ammonium molybdate-ammonium metevanadate reagent
3. Dilute to 50 mL with deionised water and allow to stand for 30 minutes
4. Measure the concentration at 400 nm (NSRI/AL/SOP E4 or NSRI/AL/SOP E6)

Calculations

1. V_s = reading from spectrophotometer of sample solution in mg/L of phosphorus
2. V_b = reading from spectrophotometer of blank solution in mg/L of phosphorus
3. $V = (V_s - V_b)$
4. 2 g of sample is extracted and diluted to 50 mL
5. 2 mL of extract is used to produce V in mg/L phosphorus
6. Concentration of phosphorus in the extract = V/2 * 10 mg/L
   = 5V mg/L

Therefore, the total phosphate in 50 mL of extract = 5V * 50/1000 mg; and the total phosphate in the sample = 5V * 50/1000 * 1000/2 mg/kg

= V * 125 mg/kg

If there was dilution, then the dilution factor should be multiplied to get the final total phosphate

Appendix 2.1l Method used for determination of total phosphorus of organic material used in Malawi

The digestion procedure for organic material is described in Appendix 2.2d. The determination of phosphorus was done colorimetrically.

Reagents

1. Ammonium molybdate
2. Antimony sodium tartarate
3. Sulphuric acid, concentrated
4. Ascorbic acid, 1%: Dissolve 1 g ascorbic acid in 100 mL water; make a fresh solution every day
5. Molybdate reagents: Dissolve 4.3 g ammonium molybdate in 400 mL water in a 1000 mL measuring cylinder. Add carefully with stirring, 54 mL H_2SO_4. Allow to cool and make up to 1000 mL water. Mix well. This is stable for 4 weeks at 2^oC

Standards

1. Dry 7 g KH_2PO_4 at 105^oC for 2 hours. Cool in a desiccator
2. Dissolve 4.394 g dry KH_2PO_4 in water and make up to 1000 mL in a volumetric flask. This is a 1000 µg/mL stock solution
3. Pipette 10 mL of the 1000 µg/mL P solution into 500 mL volumetric flask and make up to the mark with water. This is a 20 µg/mL P solution
4. Pipette 0, 5, 10, 15, 20 and 25 mL of the 20 µg/mL P solution into labelled 100 mL volumetric flasks. Make up to the mark with water and mix well. These are the working standards and contain 0, 1, 2, 3, 4 and 5 µg/mL P

Procedure

1. Pipette 1 mL standard or sample into a test tube
2. Add 4.0 mL ascorbic acid solution
3. Add 3.0 mL molybdate reagent and mix well
4. Leave for 1 hour for the colour to develop
5. Read the standards and the sample absorbance at 880 nm

Calculations

Plot a graph of absorbance against standard concentration. Determine solution concentrations for each sample and the blanks.

C (P µg/mL) = $P_{sample} - P_{mean\ blank}$

P in digest (%) = (C/W) * 0.1

Where W = weight of sample

(Adopted from Anderson & Ingram, 1993)

Appendix 2.1m Method used for determination of extractable phosphorus of soil used in the United Kingdom (NSRI/AL/SOP 15/Vesrion 1)

Phosphorus was extracted with sodium bicarbonate solution of pH 8.5. The concentration of the blue complex produced by the reduction with ascorbic acid of the phosphomolybdate which was formed when acid ammonium molybdate reacted with phosphate was measured spectrophotometrically at 880 nm.

Reagents for extraction

3. Polyacrylamide solution, 0.05% m/v (RSPUR 37)
4. Sodium hydroxide solution, 50% m/v (RSPUR 38)
5. Sodium bicarbonate reagent, 0.5 M (RSPUR 39)

Reagents for determination

1. Ammonium molybdate reagent, 1.2% m/v (RSPUR 40)
2. Ammonium molybdate reagent, 0.15% m/v (RSPUR 41)
3. Ascorbic acid solution, 1.5% m/v (RSPUR 42)
4. Phosphorus stock standard solution, 1000 mg/L P (RSPUR 3)
5. Phosphorus working standard solution, 0-7 mg/L P (RSPUR 43)
6. Sulphuric acid, 1.5 M (RSPUR 44)

Extraction

1. Transfer 2.5 ± 0.0004 g of air dried soil (< 2 mm) into a 100 mL wide mouthed plastic bottle with a screw top
2. Carry out a blank determination with each batch of samples
3. Add 50 mL of sodium bicarbonate reagent (RSPUR 39)
4. Cap bottle and shake for 30 minutes (NSRI/AL/SOP E15)
5. Immediately filter through a Whatman No. 2 filter paper and retain the filtrate for the determination of phosphate
6. Refrigerate samples if analysis is not to be carried out immediately

Preparation of standard graph

1. Pipette 5 mL of each phosphorus working standard into labelled 50 mL beakers
2. Add 1 mL of 1.5 M sulphuric acid (RSPUR 44) and swirl
3. Add 20 mL of 0.15% ammonium molybdate (RSPUR 41) reagent, 5 mL of ascorbic acid solution (RSPUR 42), swirl to mix and allow to stand for 30 minutes
4. Measure the absorbance at 880 nm (NSRI/AL/SOP E4 or NSRI/AL/SOP E6)

Determination

1. Pipette 5 mL of the blank and each extract into labelled 50 mL beakers
2. Add 1 mL of 1.5 M sulphuric acid and swirl
3. Add 20 mL of 0.15% ammonium molybdate reagent, 5 mL of ascorbic acid solution, swirl to mix and allow to stand for 30 minutes
4. Measure the absorbance at 880 nm (NSRI/AL/SOP E4 or NSRI/AL/SOP E6)

5. If the absorbance is higher than the top standard, repeat the determination using a diluted sample, calling the dilution factor D

Calculations

1. Call the sample value V_s and blank value V_b
2. mg/L of phosphorus = (V_s – V_b) = µg/mL phosphorus
3. 2.5 g sample extracted in 50 mL, but 5 mL used to produce Vs in µg/mL
4. Therefore, V * (50/2.5) = µg/g phosphorus = mg/kg phosphorus
5. From the standard graph calculate mathematically the amount of P corresponding to the absorbance
6. If the sample has been diluted ug/mL of phosphorus = (V_s – V_b) * D
7. Extractable P in mg/kg = (V_s –V_b) * 20 * D

(Adopted from MAFF, 1986)

Appendix 2.1n Method used for determination of extractable phosphate of compost used in Malawi

Reagents

Sodium bicarbonate, 0.5 M, pH 8.5: Dissolve 84 g sodium bicarbonate in 1000 mL water. Make up to nearly 2000 mL with water. Adjust the pH 8.5 with 10% NaOH, mix and make up to 2000 mL

Procedure

1. Weigh 2.5 ± 0.01 g compost (W) into a polyethylene bottle
2. Add 50.0 mL extracting solution
3. Shake the bottle for 30 minutes before filtering through a Whatman No. 42 filter paper
4. Determine the extracted phosphate in the filtrate as described in Appendix 2.2i, only that in this case the working standards be made in bicarbonate extracting solution, i.e. use extracting solution instead of water in step 3 and 4

Calculations

Extractable phosphate (ug/g) or mg/kg = (C * 20) / W

Where: C = corrected concentration after subtracting the mean blank value

W = weight of sample used

(Adopted from Anderson & Ingram, 1993)

Appendix 2.1p Method used for determination of Total Oxides of Nitrogen and Ammonium-N in moist soil used in the United Kingdom (NSRI/AL/SOP 13/Vesrion 1)

Ammonium and TON are extracted with 2 M potassium chloride. Ammonium-N is measured by an automated phenate method (NSRI/AL/SOP 8) while TON is measured by an automated hydrazine reduction method (NSRI/AL/SOP 7).

Reagents for extraction

- Potassium chloride, 2 M (RSPUR 45)

Extraction

1. Used 10.00 ± 0.05 g of wet soil into a 125 mL wide mouthed plastic bottle with a screw top
2. Take a small sample of the wet soil and determine the moisture content
3. Added 50 mL of 2 M potassium chloride to each bottle
4. Carry out a blank determination with each batch of samples
5. Cap the bottles and shake on the machine for 2 hours (NSRI/AL/SOP E15)
6. Filter through a Whatman No. 4 filter paper and retain the filtrate for the determination of ammonium-N and TON
7. Store all extracts in the refrigerator until analysed

Reagents for analysis

1. Sodium hydroxide, 0.4 M (RSPUR 81)
2. Sodium hydroxide, 0.5 M (RSPUR 82)

3. Stock copper sulphate solution (RSPUR 83)
4. Hydrazine-copper reagent (RSPUR 84)
5. Sulphanilamide (RSPUR 85)
6. Stock TON standard, 1000 mg N/L (RSPUR 86)
7. D.I.C. (RSPUR 90)
8. Citrate buffer (RSPUR 91)
9. Stock ammonium standard, 1000 mg N/L (RSPUR 92)
10. 2 M potassium chloride (RSPUR 100)
11. Standards in 2 M potassium chloride (RSPUR 101)

Analysis

- Used segmented flow analyser (NSRI/AL/SOP E10)

Calculations

1. Call sample V_s and blank V_b
2. $V = (V_s – V_b)$ mg/L
3. V/1000 converts to mg/mL
4. Total solution = (50 mL of potassium chloride + mass of water in 10 g of soil)
5. mg/kg TON or ammonium-N = (V/1000) * (total solution/dry mass of soil) * 1000

(Adopted from MAFF, 1986)

Appendix 2.1q Method used for determination of Nitrate-N of compost used in Malawi

Extraction for nitrate-N was done with 0.5 M K_2SO_4. 10.0 g of fresh sample was shaken in 20 mL of extractant for 30 minutes and centrifuged followed by analysis colorimetrically on a spectrophotometer at 410 nm.

Reagents

1. Sodium hydroxide, 4 M: Dissolve 160 g sodium hydroxide in 1000 mL water

2. Salicylic acid, 5%: Dissolve 5 g salicylic acid in 95 mL conc. Sulphuric acid (this is stable for 7 days if stored in the dark and cool place)

Standards

6. Dry 10 g potassium nitrate at 105^{o}C for 2 hours. Cool in a desiccator
7. Dissolve 7.223 g dry potassium nitrate in water and make up to 1000 mL in a volumetric flask. This represents a 1000 µg/mL NO_3-N stock solution
8. Pipette 25 mL of the 1000 µg/mL NO_3-N solution into a 500 mL volumetric flask and make up to the marl with water. This is a 50 µg/mL NO_3-N solution
9. Pipette 0, 2, 4, 6, 8 and 10 mL of the 50 µg/mL NO_3-N solution into labelled 50 mL volumetric flasks. Make up to the mark with extractant so that the standards and samples are in identical solutions, and mix well. These are the working standards and contain 0, 2, 4, 6, 8 and 10 µg/mL NO_3-N

Procedure

3. Pipette 0.5 mL of each standard and sample into suitably marked test tubes
4. Add 1.0 mL of salicylic acid solution to each test tube, mix well immediately the acid is added and leave for 30 minutes
5. Add 10.0 mL of sodium hydroxide solution to each test tube, mix well and leave for 1 hour for full colour development. The colour is stable for 12 hours
6. Read each standard and sample absorbance at 410 nm

Calculations

Plot a graph of absorbance against standard concentration. Determine the solution concentration of each sample and blanks. Subtract the mean blank value from the sample values to get a corrected concentration for each sample, designated C

NO_3-N (µg/g soil or mg/kg) = (C * V) / W

Where: C = corrected concentration (µg/mL)

V = extract volume (mL)

W = weight of sample (g)

(Adopted from Anderson & Ingram, 1993)

Appendix 2.1r Method used for determination of Cation Exchange Capacity (CEC) of soil in the United Kingdom

In this method the soil is quantitatively displaced of all exchangeable cations with barium, followed by replacement of barium by a known quantity of magnesium sulphate. The magnesium not exchanged is determined by EDTA titration from which the CEC of the soil can be determined.

Reagents

10. Triethanolamine solution (90 mL diluted to 1 L and pH adjusted to 8.1 by adding 140 mL 2 N HCl (162 mL of HCl 37% in 1 L distilled water). Dilute to 2 litres
11. $BaCl_2$, 2 N
12. Buffered $BaCl_2$ – mix equal amounts of 1 and 2
13. $MgSO_4$, 0.05 N
14. NH_4OH, 2 N
15. EDTA solution, 0.02 N
16. Erichrome black indicator

Method

1. Weigh 5 g of air dry soil (< 2 mm) into a polythene centrifuge bottle with tight stopper. Note the mass in grams of a bottle plus soil (M1)
2. If the soil is non-calcareous and non-saline proceed to 3
    a. Calcareous soil: Treat soil with 100 mL buffered BaCl2 reagent for 1 hour with occasional shaking. Centrifuge at 1500 r.p.m. for 15 minutes and discard supernatant liquid. Taking care not to lose any soil. If the suspension is turbid, centrifuge further until clear. Proceed as in 3
    b. Saline soil: Add 100 mL of 50% (V/V) ethanol and shake the suspension thoroughly for 10 minutes. Centrifuge as in 2a observing the same precautions. Repeat this procedure until the supernatant liquid is free of

soluble salts, e.g. no reaction of acidified silver nitrate solution to chloride ions. If the soil is calcareous, proceed as in 2a , if not proceed as in 3

c. If the soil is calcareous and saline, then both b and a must be followed in sequence with b first

3. Treat soil with 200 mL buffered $BaCl_2$ reagent and leave overnight
4. Centrifuge and discard supernatant liquid. Add 200 mL distilled water and shake to break up soil cake. Centrifuge and discard supernatant liquid. Weigh the bottle with content (M2)
5. Pipette into the bottle 100 mL $MgSO_4$, shake the stoppered bottle at intervals over a 2 hour period. Centrifuge and decant the supernatant liquid into a stoppered flask
6. Pipette 5 mL of that solution into a 250 mL conical flask, add 6 drops of 2 N NH_4OH and 2 drops of indicator
7. Titrate with EDTA solution until the end point is reached. Colour change from win red to inky blue. Note mL of EDTA used (A1)
8. Repeat step 6 and 7 using 5 mL of $MgSO_4$ (standardization of $MgSO_4$). Note mL of EDTA used B

Estimation of CEC

1. B mL of 0.02 N EDTA is equivalent to B/1000 * 0.02 equivalent or 0.02 B milliequivalent of Mg in the 5 mL aliquot
2. A1 mL of 0.02 N EDTA is equivalent to 0.02 A1 milliequivalent of Mg in the 5 mL aliquot of the soil solution after washing
3. Amount of Mg adsorbed by the soil from each 5 mL of $MgSO_4$ added is equal to 0.02 (B-A1) milliequivalent
4. 100 mL of $MgSO_4$ were added, hence the amount of Mg adsorbed by the 5 g of soil used in the test is equal to:

   0.02 * (B-A1) * 100/5 milliequivalent

5. CEC is assessed in terms of 100 g soil, thus:

   CEC = 0.02 (B-A1) * 100/5 * 100/5

CEC = 8 * (B-A1) meq/100 g

Calculations

1. The quantity A1 of 0.02 N EDTA used in the soil titration must be corrected for the effect of the volume of liquid retained by the centrifuged soil after the water wash.
2. Corrected quantity A2 = A1 (100 + M2 – M1) / 100 mL
3. CEC of air dry soil = 8 (B – A2) meq/100 g
4. The results are in oven dry basis. If the CEC obtained exceeds 50 meq/100 g the determination should be repeated using less soil.

(Adopted from Avery & Bascomb, 1982)

Appendix 2.1s pH of the soil and compost determination

The pH of the soil and compost was measured using a glass electrode. The measurement was done on a soil and compost suspension at soil/water ratio of 1:5 (m/m) and compost/water ratio volume of 1 + 5 in triplicates. The samples were weighed and put into a bottle with a screw cap. Water was added using measuring cylinder; shaken for 1 hour on a machine before taking the measurements.

The pH meter was calibrated before commencement of taking the pH readings. Calibration was done following manufacturer's instructions using two buffer solutions of pH 4.0 and pH 6.9 or pH 9 depending on the range of measurements. The electrodes were washed with distilled water and dried before immersing in the buffer solutions starting with buffer solution pH 4.0 alongside with the temperature probe. When the main pH and temperature settles, calibration was done accordingly. Once the calibration was complete, the measurement of the pH of the soil or compost was done. The soil was left to stand for 5 to 10 minutes before taking measurements. The compost suspension was stirred and the rinsed electrodes were immersed in order to measure the pH value.

Reagents

1. Distilled or demineralised water
2. Buffer solutions, pH 4.0 (at 20^{o}C): Dissolve 10.21 g dry potassium phthalate (105^{o}C for 1 hour), $KHC_8H_5O_4$ in water and dilute to 1 litre
3. Buffer solution, pH 6.9 (at 20^{o}C): Dissolve 3.39 g of dry potassium dihydrogen orthophosphate, KH_2PO_4 (dried at 105^{o}C for 1 hour and cooled in desiccator) in water, add 3.53 g of disodium hydrogen orthophosphate, Na_2HPO_4, dissolve and make up to 1 litre

(Adopted from BS EN 13037:2000)

Appendix 2.1t Method used for particle size analysis of the soil (clay, silt and sand)

Particle size analysis was done using pipette method. Hydrogen peroxide (H_2O_2) was used to destroy the organic material whereas calgon was used to disperse the soil particles. The analysis was done in three replications. Air-dried soil sample was used after passing through a 2 mm sieve. Part of the soil was used to determine soil moisture content of the soil in order to know the actual weight of the soil particles.

Reagents

- Hydrogen peroxide, H_2O_2, 27-30% (100 vol.)
- Dispersing agent: Dissolve 50 g sodium hexametaphosphate (calgon flake) and 7 g disodium carbonate, Na_2CO_3 (anhydrous) in water and dilute to litre

Procedure

1. Transfer 10.0000 g of air-dry soil (<2 mm) to a 1000 mL beaker for each replicate. Add 10 mL of H_2O_2 and repeated after 30 minutes observation time until all the organic matter has been destroyed. Leave to stand overnight covered with a wash glass.
2. Washed down the sides of beaker and dilute to 40 mL. Heat on hot plate at 90^{o}C for 1 hour, maintaining the volume at 25 mL above by washing down the sides. Allow to

cool, transfer quantitatively to 200 mL polypropylene bottle, add 120 mL of water, shake and centrifuged for 15 minutes at 2000rpm (making sure the centrifuge is balanced).

3. Decant off supernatant. Add by pipette to the residue 20 mL of dispersing reagent, releasing soil cake from the bottom of the bottle. Make up to approximately 150 mL with distilled water, put bottle in the aluminium canister and shake on end-over-end shaker for a minimum of 7 hours (shaker must be balanced).

   Note: 20 mL of dispersing reagent must be pipetted into a pre-weighed beaker and evaporated and dried at 105^{o}C, cooled and weighed to obtain mass of residue. This amount is R in calculation.
4. Wet sieve sample through a 63 μm sieve into a 500 mL cylinder, carefully washing bottle with distilled water, retaining the cylinder for later use.
5. Transfer the sieved contents to a drying tin and dry in an oven at 105^{o}C for 4 hours.
6. Allow to cool, weigh the sieves, then sieve the dry sample for 15 minutes on a sieve shaker using the following sieves in their order: 600 μm, 212 μm, 63 μm and receiver. Re-weigh the sieves with their retained sand. The residues on the receiver are to be added to the 500 mL cylinder. Weights from above represents the following: coarse sand (CS) > 600 μm g; sand (S) 600-212 μm g and fine sand (FS) 212-63 μm g and are entered on the result sheet.
7. The sample in the cylinder is now made up to 500 mL with distilled water.

   Note: The cylinder should be in a room where temperature changes are slow and not exceed 3^{o}C over 8 hours sedimentation period. Radiant heat, causing convection, should be particularly avoided. For the best results place cylinder in the water bath with constant temperature of 25^{o}C
8. When equilibrium temperature has been reached, use the hand stirrer for 30 seconds to thoroughly mix the contents. Avoid a vigorous action which might introduce air. The stirrer should not go above the surface of the liquid. Carefully withdraw the stirrer and take a 25 mL sampling pipette and sample immediately at 10 cm depth. Drain pipette into a pre-weighed beaker and add two 5 mL rinsing of the pipette. Contents represent the <63 μm fraction. Mix the contents of the cylinder again similarly. Allow to sediment, withdrawn 25 mL pipette sample from depth of 9 cm

after approximately 6 hours. Drain pipette into a pre-weighed beaker and add two 5 mL rinsings of the pipette

9. Oven dry the contents of the two beakers and denote their masses in g as A and C, representing fractions of <63 μm and <2 μm respectively
10. The textural triangle was used to determine the textural class of the soils.

Calculations

W	= C + D + CS + S + FS – R
Organic matter	= Z – W/Z * 100
Mineral matter	= W/Z * 100
Coarse sand	= CS/W * 100
Sand	= S/W * 100
Fine sand	= FS/W * 100
Silt < 63 μm	= D/W * 100
Clay < 2 μm	= (C – R)/W * 100

Where: R = weight of calgon in 20 mL solution

Z = Initial weight of soil

W = Total weight after destruction of organic matter

FS = Fine sand

S = Sand

CS = Coarse sand

C = Clay

D = Silt

(Adopted from BS 1377:1990; Avery & Bascomb, 1982)

Appendix 2.1u Method used for determination of CO_2 respiration of compost used in Malawi

Reagents

1. Sodium hydroxide solution (0.05 M)
2. Diluted hydrochloric acid (0.1 M)
3. Barium chloride solution (0.5 M): Dissolve 10.4 g of BaCl2 in distilled water and adjust the volume to 100 mL distilled water in a volumetric flask
4. Indicator solution: Dissolve 0.1 g of phenolphthalein in ethanol (60% v/v), and make up the volume to 100 mL with ethanol in a volumetric flask

Procedure

1. Weigh 10.0 ± 0.01 g moist compost into 50 mL beaker and place it in the 1 L incubation bottle containing 20 mL of sodium hydroxide solution
2. Seal the incubation bottles and incubate them at 22°C ± 3°C for 4 hours
3. Remove the beaker and add 2 mL of barium chloride solution to precipitate the absorbed CO_2 as barium carbonate. Add 3-4 drops of indicator solution
4. Titrate the remaining sodium hydroxide with diluted HCl
5. Prepare the controls following the same procedure excluding the compost.

Calculations

$$\text{mg } CO_2\ g^{-1}\ hr^{-1} = \frac{(C-S)\times 2.2\times 100}{SW\times \%dm} \Big/ 4h$$

Where: C = mean volume of HCl consumed by controls (mL)

S = mean volume of HCl consumed by samples (mL)

2.2 = conversion factor (1 mL of 0.1 M HCl corresponds to 2.2 mg CO_2)

SW = initial compost weight (g)

100 x $\%^{-1}$ dm = factor for compost dry weight

(Adopted from Schinner *et al.*, 1996)

Appendix 2.2a The principle for the determination of total carbon of crop residue, soil and compost

Carbon exists in different forms in soil. It can be elemental (*e.g.* graphite or diamond forms) or in inorganic or organic combinations (Cheng & Kimble, 2001). Carbon, a constituent of SOM, is vital in understanding the nitrogen transformation processes as it provides energy for microbial activities. The elementary analyser Vario EL II used in the UK is fully automated instrument for the quantitative determination of C, N and S. It works according to the principle of catalytic tube combustion in an oxygenated CO_2 atmosphere and high temperatures. During oxidised combustion the elements C and N produced, in addition to the molecular nitrogen (N_2), the oxidation products CO_2, NO_X. The combustion gases are freed from foreign gases (*i.e*. volatile halogens). The desired measuring components are separated from each other with the help of specific adsorption columns and determined in succession with a thermal conductivity detector (TCD). Helium (He) serves as flushing and carrier gas. The automatic control of the analysis procedure is accomplished through the software. For Malawi, organic carbon was oxidised by acidified dichromate and the amount of carbon was determined from the amount of chromic produced colorimetrically.

Appendix 2.2b The principle for the determination of total nitrogen of crop residue, soil and compost

Total N and total C of organic matter in the UK was determined from the same sample hence the extraction and analytical principle is similar to Appendix 2.3a. In Malawi, total N was extracted by wet oxidation based on Kjeldahl oxidation where organic N was converted to ammonium-N through digestion with concentrated sulphuric acid in presence of hydrogen peroxide, as an extra oxidising agent. Selenium was used as a catalyst while lithium was used to raise the boiling point when the mixture was heat at 360^{o}C. The total N analysis was based on the analysis of the extracted ammonium-N colorimetrically. The advantages of the wet oxidation used here include that only one

digestion is required to get all the nutrients in the solution and that no volatilization of nitrogen or metals takes place (Anderson and Ingram, 1993).

Appendix 2.2c The principle for the determination of total potassium of crop residues

The organic matter of the plant material constitutes the nutritional elements of the plant. Dry combustion of the organic matter releases the soluble mineral constituents into the ash. Dissolving the ash in hydrochloric acid solubilizes the nutrients and dehydrates any available silica such that it is insoluble so that it does not interfere with the analysis of potassium.

Appendix 2.2d The principle for the determination of extractable K of soil and compost

To estimate the amount of the available ion of the nutrient for the plant during its growing period, extractable nutrients were determined. Extraction of K was done by NH_4NO_3 for soil, $CaCl_2$/DTPA for compost (United Kingdom) and Mehlich 3 for compost (Malawi). The NH_4^+ displaced K from the colloidal complex into the solution when NH_4NO_3 and Mehlich 3 were used as extractants where as Ca^{2+} displaced K into the solution when $CaCl_2$/DTPA was used as an extractant. The displaced K was measured photometrically to determine its concentration.

Appendix 2.2e The principle for the determination of total phosphorus of crop residues

Following dry combustion of the organic matter to release the soluble mineral constituents form the organic matter into the ash (Appendix 2.3c), the sample solution remaining after the destruction of organic matter is dissolved in hydrochloric acid; and a coloured complex is formed by mixing the solution with hydrochloric acid and

ammonium molybdate-ammonium metavanadate reagent. Concentration of P is measured spectrophotometrically as a yellow phospho-vanado-molybdate complex.

Spectrophotometer consists of a spectrometer for producing light of any selected color (wavelength), and a photometer for measuring the intensity of light. The instruments are arranged so that liquid in a cuvette can be placed between the spectrometer beam and the photometer. The amount of light passing through the tube is measured by the photometer. The photometer delivers a voltage signal to a display device, normally a galvanometer. The signal changes as the amount of light absorbed by the liquid changes. Upon extraction of the phosphorus into the solution, other reagents are added to develop blue colour which is linked to the concentration of P in a solution. This concentration can be measured by determining the extent of absorption of light at the appropriate wavelength. When monochromatic light (light of a specific wavelength) passes through a solution there is usually a quantitative relationship (Beer's law) between the solute concentration and the intensity of the transmitted light. For Bunda, total phosphorus was extracted by wet oxidation based on Kjeldahl oxidation where phosphorus was digestion with concentrated sulphuric acid in presence of hydrogen peroxide, as an extra oxidising agent and Selenium as a catalyst and lithium helped to raise the boiling point when the mixture was heat at 360^{o}C (similar to total N, Appendix 2.3b). The total P analysis was based on the analysis of the extracted P colorimetrically (Anderson and Ingram, 1993).

Appendix 2.2f The principle for the determination of phosphate-P of the soil and compost

During extraction procedure with sodium bicarbonate solution a blue colour complex is produced by the reduction process with ascorbic acid of the phosphomolybdate produced when acid ammonium molybdate reacts with phosphate in the soil. The phosphate-P is determined spectrophotometrically

Appendix 2.2g The principle for the determination of available nitrogen (TON, NH_4-N and NO_3-N) of the soil and compost

TON and NH_4-N represent the inorganic fraction of the nitrogen in the soil or compost. These molecular forms are released during mineralization of the organic material. The concentration of these elements indicates the dominant bio-chemical processes taking place in the soil or compost system. It is crucially important to extract for these immediately after sampling or refrigerate the samples to arrest microbial activity so that the concentration of these molecular forms remains the same as at the time of sampling.

Under alkalinity, the nitrate in the sample is reduced to nitrite by hydrazine. The reduced nitrate together with original nitrite reacts with sulphanilamide forming diazonium compound which, in dilute phosphoric acid, couples with N-1 – naphthylene diamine dihydrochloride forming a reddish-purple azo dye. This is measured spectrophotometrically at 540 nm. On the other hand, ammonia reacts with hypochlorite ions from sodium dichloroisocyanurate and salicylate in the presence of sodium nitroprusside (at pH 12.6), to form a blue-green reaction product (related to indophenol blue). This is measured spectrophotometrically at 670 nm.

Appendix 2.2h The principle for the determination of cation exchange capacity (CEC) of the soil

Soil activity and fertility is closely related to its CEC which is a measure of the number of negative charges present. The process involves ion exchange processes in which the exchangeable cations are displaced and measured in a solution. The soil is first saturated with barium using barium chloride. Barium is then replaced from the exchangeable complex with magnesium by treating the soil with magnesium sulphate in which case barium precipitates as barium sulphate. The excess magnesium is determined by titration using EDTA and CEC is derived from this process. The following chemical formula gives the representation of the reaction which is undertaken.

$$Ba\text{-soil} + BaCl_2 + 2MgSO_4 \longrightarrow Mg\text{-soil} + MgCl_2 + 2BaSO_4 \downarrow$$

Appendix 2.2i The principle for the determination of pH of the soil and compost

The pH of a solution is a measure of its concentration of hydrogen ions. pH is defined as follows:

$$pH = \log_{10}(1/ [H^+]) = - \log_{10}[H^+]$$

A pH meter – potentiometer equipped with a glass electrode and a reference electrode determines the pH of the solution. A pH meter measures the electro-chemical potential between a known liquid inside the glass electrode (membrane) and an unknown liquid outside. Because the thin glass bulb allows mainly the agile and small hydrogen ions to interact with the glass, the glass electrode measures the electro-chemical potential of hydrogen ions or the potential of hydrogen. A reference electrode completes the electrical circuit. Measurement of soil pH is critical to understanding the soil's chemical and biological properties. Soil pH controls nutrient availability, the solubility of heavy metals (most are only freely available at low pH) and the activity and composition of the soil's microbial biomass. Soil pH can be determined using water, 1 M potassium chloride or 0.01 M calcium chloride as the extractant. pH in this experiment was measured to monitor the environment under which the composting and mineralization took place to establish presence of adverse conditions during the said processes

Appendix 2.2j The principle for the determination of Temperature of the compost

The temperature of the compost heap changes with time indicating the progression of the composting process, with three distinct temperature phases: mesophilic, thermophilic, and curing. Microbes release heat through metabolic activity. As the temperature increases, succession of microbial community is realized due to differences in tolerance to temperature ranges. The micro-organisms are denatured when the temperature exceed their tolerance range conforming to the three phases above (see Chapter 1, Section 1.3.2

& 1.3.3.4). The temperature of the composting heap was monitored by the use of thermistors and thermometers.

Appendix 2.2k The principle for the determination of particle size analysis of the soil

The method is based on Stokes' Law where the sedimentation velocity of a particle with a particular size through a liquid is related to its size and density as well as the viscosity of the liquid as follows:

$$v = \frac{2}{9} g r^2 \frac{(p_1 - p_2)}{\eta}$$

Where: v = velocity

g = acceleration due to gravity

r = effective radius of particle

P_1 = liquid density

P_2 = particle density

η = liquid viscosity

With constant liquid viscosity, particle and liquid density and acceleration due to gravity, the velocity of sedimentation for a given particle size can be determined.

Appendix 2.2m The principle for the determination of Carbon dioxide (CO_2) evolution from compost

Heterotrophic micro-organisms derive their energy supply from the mineralization of organic matter, in the process releasing carbon dioxide and water. The rate of microbial mineralization is related to the rate of CO_2 emission. Compost respiration may vary depending on the composition of available substrates, the current physiology of the microbial communities and microbial adjustments to the nutritional conditions. High nutrient cycling rates are characterised by high and sustained respiration rates.

CO_2 is determined by gas chromatography or by titration. In titration, the samples are incubated in a closed vessel at 25^{o}C and the CO_2 produced is absorbed in sodium hydroxide (NaOH) and quantified by titration.

Appendix 2.2n The principle for the determination of Cress (Lepidium sativum L.) seed germination

The initial phase of composting is associated with the production of phytotoxic materials (Zucconi *et al.* 1985 and Harada, 1992). These include ammonia (Ells *et al.* 1991), ethylene (Wong *et al.* 1983), and short-chain aliphatic acids (low-molecular fatty acids or volatile acids) such as acetic and phenolic compounds. Such compounds interfere with seed germination, root proliferation, plant growth and crop yields (Iannotti *et al.* 1993; Mathur *et al.* 1993b). Thus, absence of phytotoxic compounds in the compost is an indicator of maturity. Cress seed is one of the plants which are sensitive to toxicity and its failure to germinate indicates immaturity of the compost.