COMPOSTING PERFORMANCE OF VERMICULITE-CATTLE MANURE COMPOSTS AND THEIR EFFECTS ON SELECTED SOIL PROPERTIES AND MAIZE (*ZEA MAYS* L.) PRODUCTION ON SANDY LOAM SOILS IN ZIMBABWE

By

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PREFACE

The research contained in this thesis was completed by the candidate while based in the Discipline Soil Science, School of Agricultural, Earth and Environmental Sciences of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg Campus, South Africa.

The contents of this work have not been submitted in any form to another university and, except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.

[redacted]

Signed: Professor P Muchaonyerwa

Date: 15 March, 2021

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I, **Charity Pisa**, declare that:

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DECLARATION 2: PUBLICATIONS

My role in each paper and presentation is indicated. The * indicates corresponding author.

Pisa C.*, Wuta M. and Muchaonyerwa P. 2020. Effects of incorporation of vermiculite on carbon and nitrogen retention and concentration of other nutrients during composting of cattle manure. Bioresource Technology Reports, 9, 100383. https://doi.org/10.1016/j.biteb.2020.100383.

Pisa C, Gwara A, Dunjana N, Wuta M and Muchaonyerwa P. 2017. Effects of cattle manure – vermiculite co-compost on maize growth and yield. Serving the nation through research, innovation and strategic partnership. University of Zimbabwe 24-29 July 2017. Harare. *Abstract and Poster presentation*

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ABSTRACT

A study was carried out to determine the composting performance of vermiculite-cattle manure (VCM) composts and their effects on selected soil properties and maize (*zea mays* L.) production on sandy loam soils. The trial was carried out at Marondera University of Agricultural Sciences and Technology (MUAST) farm in Marondera, Zimbabwe.The effects of vermiculite inclusion in cattle manure on composting performance and nutrient retention were established by aerobically composting vermiculite and cattle manures mixtures with 0, 10, 20 and 30 % vermiculite on a w/w basis for 76 days. Composting performance was determined by measuring internal compost temperatures daily and analysing the compost for ammonium-N, nitrate-N, total N, total P, Ca, Mg, K, pH, electrical conductivity, total organic carbon and ash content on days 3, 12, 23, 38, 48, 60, 67 and 76. The final air-dried vermiculite cattle manure (VCM) composts were used to determine their effect of on soil K^+ and NH_4^+ fixation, early plant growth, nutrient uptake and soil nutrient retention. Incubation experiments were set up to determine effects of the composts on K^+ and NH_4^+ fixation. The VCM composts and soils amended with the respective composts were treated with 0, 90, 180, 360 kg K ha^{-1} and incubated for 6 weeks at room temperature. After incubation the composts and amended soils were analysed for exchangeable K and nitric acid extractable K from which fixed K, reserve K and Potassium Requirement Factor (KRF) were calculated. The effects of VCM compost on early plant growth, nutrient uptake and soil nutrient retention was also determined in pot trials using a sandy loam soil from MUAST farm. The trial was set up in a randomised complete block design. The soil was amended using 0 (manure compost only), 10, 20 and 30 % VCM co-composts at a rate of 5 t ha^{-1}. Positive (recommended fertiliser rate of 35 kg P_2O_5, 17.5 kg N and 14.5 kg K ha^{-1}) and a negative (no amendment) controls were included. Maize seed was sown in pots with a leachate collecting system and allowed to grow for 10 weeks. Leachate was periodically collected and analysed for N, P, Ca, Mg and K. Above- ground dry matter and soils collected after harvest were analysed for N, P, K, Ca and Mg. A second pot trial to determine moisture retention was set up in a completely randomised design, with the same treatments under greenhouse conditions. An irrigation schedule of 400ml per pot per week was adopted after successful establishment of the maize plants. Soil sampling was done every three days for gravimetric water content determination. The maize plants were left to grow up to 42 DAS after which dry matter yield was determined. To determine the effect of increasing the proportions of vermiculite in VCM co-compost on maize growth and yield and soil chemical properties under field dryland conditions, a field experiment was set up. The VCM co-composts of 0, 10, 20 and 30 % vermiculite were applied at 5 t ha^{-1} on plots measuring 5 x 5 m. Positive and negative controls similar to the pot trial treatments were included. Growth and yield parameters (leaf number, plant height, cob number, cob weight, shelling out and grain yield) were determined from the net plot (the 3 middle rows of each plot) of 9 m^2 and grain yield was expressed per hectare.

All compost mixtures passed through the major composting phases; mesophilic, thermophilic, cooling and maturing stages. The inclusion of vermiculite in the composting mixtures enhanced the retention of total nitrogen, with N losses decreasing with an increase in vermiculite content in composting mixtures. Vermiculite inclusion also reduced mineral N, NH_4^+:NO_3^- ratio and C:N ratio and increased the Ca and Mg concentrations of 10, 20 and 30 % VCM composts but lowered K concentration. The final VCM composts were mature. Inclusion of vermiculite in composts reduced exchangeable K and increased fixed K in both VCM composts and soils amended with these composts. Reserve K in soils was low, < 0.8 $cmole_c kg^{-1}$ and the KRF values for all soils were significantly higher than the threshold of 3 used in most laboratories. In the pot trials, the negative control recorded the least for all measured parameters while Ca, Mg, K and Na in leachate were negligible. Dry matter yield in the positive control, 0 % and 10% VCM treatments was significantly higher than the 20 and 30 % VCM treatments. Nitrogen, P and K uptake decreased with increasing vermiculite content in compost while Ca and Mg uptake increased. Soil retention of N, Ca and Mg increased with increasing vermiculite content. Soil moisture retention increased with an increase in vermiculite. In the field trial cob number, cob weight, shelling out were significantly different among treatments and were similar for the positive control, 20 and 30 % VCM treatments which were higher than the negative, 0 and 10 % VCM treatments. Maize grain yield significantly differed among treatments with the 30 % VCM treatment having yield similar to that of the recommended fertiliser treatment in both seasons.

In conclusion, vermiculite inclusion at 20 and 30 % in composting of cattle manure improved composting performance, nitrogen retention, and reduced mineral N content, NH_4^+:NO_3^- ratio and C:N ratio. Moderate fixation of K and low reserve K in soil amended with the 10, 20 and 30 % VCM composts suggests that application of these composts results in K^+ and NH_4^+ retention that may not be released during the growing season. However, the application of 10, 20 and 30 % vermiculite cattle manure compost on a sandy loam soil showed an improvement in early maize growth, plant nutrient uptake, and dry matter yield, and selected soil quality parameters after harvest when compared to the the negative control and 0 % VCM compost. Improved maize yields with the application of 20 and 30 % VCM composts can be realized under dryland conditions and therefore these composts can provide farmers with a cheaper alternative to basal fertilisers and improve soil organic matter content. However, with irrigation, the use 0 and 10 % VCM compost as basal fertilisers would be recommended, as these treatments were comparable to recommended fertiliser application . Further studies should focus on effects of applying these composts on physical soil parameters such as bulk density, porosity, water holding, root growth, which could contribute to improved growth of crops.

Key words: *Cattle Manure, Composting, Fixation, Maize, Nutrient Retention, Soil Fertility, Vermiculite*

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CHAPTER 1: INTRODUCTION

1.1 Rationale for the research

Smallholder crop production in sub-Saharan Africa (SSA) is constrained by many factors including low and erratic rainfall, recurrent droughts, soil surface crusting and poor inherent soil fertility (ten Berge et al., 2019; Assefa et al., 2019). The inadequate nutrient supply of most tropical and sub-tropical soils (Bationo et al., 2006) and inappropriate soil management strategies contribute to poor crop yields (Ncube et al., 2009). While use of inorganic fertilizers may increase yields, the high prices deter smallholder farmers from buying enough fertilisers, resulting in insufficient nutrient supply (Bationo et al., 2006), and in inappropriate proportions, causing nutrient imbalances and low soil organic matter (SOM).

Organic soil amendments improve soil physico-chemical properties, nutrient availability (Boldrin et al., 2009), water holding capacity (Diacono and Montemurro 2010; Tian et al., 2012), pH, microbial diversity and activity (Aleer et al., 2014; Fanish 2017) and SOM (Agbede et al., 2008; Tian et al., 2012). Decomposition of SOM results in mineralisation of N, P and S and therefore, the use of organic amendments such as crop residues and manure could be an appropriate solution for improving and maintaining soil fertility through recycling of nutrients and addition of SOM. In the smallholder farming sector of Zimbabwe cattle manure is the most popular organic soil amendment because it is easier to access than other organic materials (Zingore, 2006). The effectiveness of these, however, is largely dependent on the quality and accessibility of organic resources. The positive effects of organic amendments can be spread over a long period if large quantities are applied. Diacono and Montemurro (2010); Larney et al. (2011) observed that the application of organic amendments in very large quantities improved soil biological function for over 15 years and consequently crop production. Excessive amounts of organic fertilisers on sandy soil, however, could result in pollution of surface water and groundwater through leaching and subsurface flow (Kirchmann and Bergström, 2001; Vogeler et al., 2007; Ajdary et al., 2007).

However, such high application rates are not practical for smallholder farmers in Sub-Saharan Africa (SSA), who apply less than 5 t ha^{-1} as they cannot harness enough crop residues to return to the soil as their livestock depend on these for feed (Zingore 2007; 2011). The effects of limited available organic amendments are short term and therefore frequent applications are required. In smallholder farming systems, maintaining sufficient SOM is a challenge in because of low quantities and poor-quality organic manures. Low quality manure is a result of poor-quality feed in the veld and low-quality crop residues as a result of little or no fertiliser application resulting in stover of poor quality. The scarcity of the organic nutrient resources, necessitates integrated use of organic and inorganic fertilizers for sustainable soil fertility management on smallholder farms (Vanlauwe et al., 2015).

The function of mineral and organic nutrient resources on soil fertility and crop production differs and therefore their combined use can have synergistic effects, which lead to greater resource use efficiencies than when used separately (Zingore. 2006). Smallholder farmers, however, do not apply enough inorganic fertiliser due to high cost and the application of manures and/ or composts as basal fertiliser could free financial resources for the purchase of fertiliser for top/side dressing, so as to achieve the recommended rates of nutrient application. The little manure available to the farmer is often of poor quality, with large amounts of sand and high nutrient losses due to poor handling techniques, further reducing the fertiliser value (Mugwira and Murwiwa, 1997). Zimbabwean farmers pre-treat cattle manure before they apply it to their fields. During the dry season, cattle manure is removed from cattle kraals and stockpiled in the field where it undergoes decomposition or composting (Wuta and Nyamugafata, 2012).

The composting process transforms the manures into end-products of high agronomic value which can be used as fertiliser (Zhao et al., 2019; Gao et al., 2019), eliminates pathogens and weed seeds (Pisa and Wuta, 2013). Nutrient loss occurs during composting, and various studies have reported 10–76 % of nitrogen loss during composting (Luo et al., 2014; Wang et al., 2016; Chan et al., 2016). If smallholder farmers in SSA are to derive maximum benefits from their cattle manures proper handling is necessary. Co-composting with minerals has been seen to improve compost air circulation and moisture conditions that enable the transformation of agricultural waste, into stable organic material with little nutrient loss (Chan et al., 2016; Zhu et al, 2019; Li et al., 2012).

Mineral additives are chosen for their high cation exchange capacity (CEC), which aids soil nutrient retention. Turan (2009) reported that natural zeolite, expanded perlite and vermiculite reduced nitrogen losses during the composting of poultry manure because of their high cation exchange capacity. Vermiculite has a cation exchange capacity that ranges from 50 to 150 meq/100 g (van Straaten, 2002) and water holding capacity of up to 150% (Jayabalakrishnan, 2007). In Zimbabwe, this 2:1 phyllosilicate clay is mined in Buhera where it is graded as large, medium, fine and very fine vermiculite. The fine and very fine material, is regarded as waste. To assist with waste management at vermiculite mines, this fine material can be co-composting with cattle manure and consequently farmers can have a cattle manure compost with improved quality and enhanced nutrient status. However, there are limited studies on the effects of incorporating vermiculite on quality of cattle manure compost. In addition to improvement of the composting process and compost quality, vermiculite may fix K and N and therefore, reduce their availability.

In most agricultural soils, the available K and N are not enough for optimum crop yields and organic and inorganic fertilizers are often applied to address the deficiencies. Many soils with appreciable amounts vermiculite and hydrous mica have the ability to fix K^+ and NH_4^+, reducing their availability for plant uptake (Sparks and Haung, 1985; Fanning et al., 1989; Murashkina et al., 2007). For example, K deficiency has been reported in cotton grown in soils containing significant amounts of vermiculite, hydrous biotite and biotite micas, due to fixation. Soils of the sugarcane industry of South Africa have been found to vary in K^+ fixation capacity due to differences in mineralogical composition (Elephant et al., 2019). However, effects of co-composting cattle manure and vermiculite on K^+ and NH_4^+ fixation are not clearly understood. The potential saturation of fixation sites by the K^+ and NH_4^+ ions produced from the decomposition of cattle manure during composting, could limit this likely negative effect of vermiculite. There is a paucity of studies on K^+ and NH_4^+ fixation in composts of cattle manure-vermiculite mixtures and in soils amended with such composts. The overall effects of the improved nutrient availability in VCM composts, K^+/ NH_4^+ fixation and reserve K (the non-exchangeable potassium portion becomes available when exchangeable K has been depleted) on crop growth and nutrient uptake needs to be understood. The presence of vermiculite in the composts can also improve soil conditions which promote nutrient uptake by plants.

1.2 Aims

The aim of the study was to determine the fertiliser value of vermiculite-cattle manure composts for maize (*Zea mays* L.) production on sandy loam soils in Zimbabwe

1.3 Objectives

This study therefore sought to determine the effects of vermiculite addition to cattle manure on composting performance, compost quality and fertiliser value for crop production and selected quality parameters of low fertility sandy soils which are dorminant in smallholder farming systems of Zimbabwe. The objectives of the study were:

1. To determine the effects of vermiculite inclusion on composting performance and nutrient retention of cattle manure.
2. To determine the effects of vermiculite – cattle manure co-compost on potassium fixation and availability
3. To establish the effect of vermiculite – cattle manure co-compost co-composts on early maize growth, nutrient uptake and soil nutrient retention.
4. To establish the effect of vermiculite-cattle manure co-compost on maize growth and yield and selected soil chemical properties under dryland field conditions

1.4 Hypothesis

1. Vermiculite inclusion in cattle manure composting improves compost performance and nutrient retention in composts

2. Application of vermiculite to soils increases K/NH_4^+ fixation capacity in sandy loam soils.

3. The application of vermiculite-cattle manure (VCM) co-compost improves early maize growth, nutrient uptake and soil nutrient retention.

4. The application of vermiculite-cattle manure (VCM) co-compost improves maize growth and yield and soil chemical properties

1.5 Outline of dissertation/thesis structure

Each chapter stands on its own, containing an introduction, materials and methods, results and discussion (as one section or separated into two sections), and conclusions. The effects of vermiculite and/ or vermiculite-based composts on nutrient availability and retention are central to all chapters.

Chapter 1. The Chapter introduces the reader to soil fertility problems and the importance of organic resources in crop production in smallholder farming systems in Zimbabwe. It gives an insight on how mineral additives can be used to improve compost quality as a strategy to reducing nutrient loss during composting/ stockpiling. It introduces vermiculite waste as a potential mineral additive to cattle manure composting emphasising on the characteristics that can be exploited. The chapter then presents the specific objectives and the hypotheses that were made in the study.

Chapter 2 gives the literature review of the current state of knowledge and highlighting gaps this research seeks to fill, in relation to vermiculite-cattle manure composts and their fertiliser value.

Chapter 3 is an experimental chapter that focuses on the determination of composting performance of mixtures of cattle manure and vermiculite with varying proportions of vermiculite. The aim was to establish the best ratio of vermiculite and cattle manure that would retain plant nutrients giving a final compost of high agronomic value.

Chapter 4 is an experimental chapter devoted to the effects of vermiculite-cattle manure composts on the fixation of K^+/NH_4^+in soils and implication on the availability of these nutrients for plant uptake.

Chapter 5 looks at the influence of the different vermiculite-cattle manure composts on early maize growth, nutrient uptake and soil nutrient retention under controlled condition.

Chapter 6 seeks to establish the effects of using vermiculite-based composts, under field conditions, on yield of maize is the staple food in Zimbabwe's smallholder farming areas.

Chapter 7 integrates the work and provides conclusions and recommendations of this research. Included in this chapter also are future learning and research possibilities.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Increased evidence of widespread soil fertility decline, resulting in very low and declining food production and food insecurity in the smallholder farming systems has led increased research, development and dissemination of fertility technologies that promote of nutrient replenishment strategies (Waddington et al 2004, Nezomba et al., 2015, Vanluawe et al 2015., Katengeza et al 2019). Many parts of southern Africa have inherently infertile sandy soils that require good fertility management. Moderate and frequent application of nutrients, especially of nitrogen, from a range of sources is important to avoid losses from processes such as, leaching, volatilization and fixation. Major research topics by a number of agricultural researchers are now directed towards strategies that reduce soil fertility degradation in sub-Saharan Africa (Andriesse and Giller, 2015 Masso et al., 2017; Stewart et al., 2019). The increasing land and labour constraints and lack of adequate inputs faced by the low-income smallholder farmers make it difficult for them to maintain both soil fertility and crop productivity.

Smallholder farmers resort to continuous cropping with low inputs leading to soil degradation, including erosion. Mineral fertilizers are often costly and not available (Chianu et al., 2012, Chivenge et al., 2011), and combination of a range of on-farm soil fertility resources with external ones, could make a major contribution. These include modest mineral fertilizers in combination with organic soil amendments and N P K inputs from animal manures and legumes, and where possible inclusion of N-use efficient crops.

Farmers with very few resources are particularly interested in technologies that improve crop yields in the short term and therefore soil fertility technologies options need to provide some short-term soil-fertility and crop productivity benefits that are attractive to the farmers (Sommer et al., 2013). These technologies should be able to raise soil fertility in the long term, while raising crop yields and generating profit in the short term and should be compatible with other components of the farming system like little competition for arable land. Soil fertility management strategies to improve soil productivity have been developed by smallholder farmers using a variety of inputs ranging from use of inorganic fertilisers, compost to leaf litter, termitaria soil and livestock manure (Mavedzenge et al., 1999, Mapfumo and Giller 2001, Mapfumo et al., 2001).

2.2 Approaches to address soil fertility challenges in the smallholder sector

Smallholder farmers in sub-Saharan Africa produce crops on highly depleted old sandy soils and have poor access to external inputs and markets. Most smallholder farms receive little or no inorganic fertilizer thus rely on locally available small amounts of organic and mineral sources of nutrients. Improving crop productivity and yields result in increased nutrient demand and removal suggesting the need to enhance soil fertility management practices (Sosibo et al., 2017). In a bid to boost crop production, most farmers use mineral and organic fertilizers. Application of chemical fertilizers replenishes soil nutrients but the high cost of chemical fertilizers, which is out of reach for many small-holder farmers, and inaccessibility of inorganic fertilizers necessitates efficient use of organic in combination with inorganic fertilizers to sustain crop yields (Sathish et al., 2011). Intensive addition of ammonium-based N fertilizers has been seen to cause soil acidification. The negative impacts of chemical fertilizers, has also impelled the use of organic fertilizers as a source of nutrients. Organic amendments release plant nutrients much slower than mineral fertilizers but facilitate an increase in soil organic matter (SOM) content (Pinitpaitoon et al., 2011) which improves biological and physical soil properties and consequently productivity (Watson et al., 2002). Organic resources such as cattle manure, have been reported to improve crop growth by supplying plant nutrients and improving soil physical and biological properties providing an optimal environment for root development (Dejene et al., 2010). Research in agriculture is now emphasizing the development use of a number of strategies that support integrated soil fertility management for optimum management of smallholder agricultural resources. The combination of inorganic and organic fertilisers could be the best approach to soil fertility management. The application of inorganic fertilizer provides readily available nutrients while the organic fertilizer increases soil organic matter, improving soil structure and buffering capacity of the soil (Alemu et al., 2015).

2.3 The soil fertility challenge in southern Africa

Crop nutrient mining, with limited organic or inorganic nutrient addition to soils, has contributed to a lack of food security and poverty in sub-Saharan Africa (SSA) (FAO, 2017; Heger et al., 2018). Studies by Stewart et al., (2019) revealed that nitrogen and phosphorous deficiencies, acidity, and low soil organic C content were the most limiting factors regarding soil characteristics that contribute to poor crop yields in Africa. Nutrient balance studies in the smallholder farming system have shown that nutrient depletion rates far exceed replenishment (Zingore et al., 2007; 2011). Intensive continuous cropping results in high nutrient uptake and losses from other sources such as leaching can be large. Annual net nutrient depletion was estimated to exceeds 30 kg N and 20 kg K ha^{-1} of arable land in Malawi and Zimbabwe (Stoorvogel and Smalling, 1990; Stoorvogel et al., 1993) and these figures could be now higher with an increase in crop production. The sustainability of soil fertility on smallholder farms in the tropics is dependent on SOM (Zingore et al., 2011). Soil organic matter plays an important role in long-term soil conservation and restoration. It sustains soil fertility and agricultural production, by improving of soil physico-chemical and biological properties of soils (Reeves, 1997; Six et al., 2000; Weil and Magdoff, 2004). The application of organic resources (animal and plant residues) results in SOM build-up. The rate of decomposition through mineralization of both added and existing organic matter also affect SOM content. In most smallholder soils, organic inputs are insufficient to maintain SOM levels as these marginal areas receive low-rainfall making it less likely to produce enough biomass to maintain SOM (Mugwira and Murwira, 1997, Zingore et al., 2011). The 'Green Revolution' offered improved plant genetics and agronomic practises whose yield gains can only be attained if soil quality is optimum (Alumira and Rusike, 2005). Smallholder farmers cannot benefit from these technologies without addressing soil quality issues in their areas.

Crop residues are a major fertility input in smallholder farming areas. These are left above ground as stover at the end of the growing season, or remain in the soil as roots. The residues are also used as animal feed when animals are left to graze in the fields after harvest. Cattle in smallholder farming areas is kept in cattle kraals where manure accumulates and farmers collect this manure for use in their fields. Manure provides plant nutrients, improve soil structure, enhances nutrient and water holding capacity of the soil, and moderates soil temperature. Eighty seven percent of the total N content of locally available organic resources comes from cattle manure (Murwira et al., 1995) contributing significantly to the overall N budget. Constant applications of manure increase the fertility status of sandy soils by increasing their cation exchange capacity (CEC), pH and nutrient content (Grant, 1967). The rate at which carbon and nutrients are released into the soil via decomposition also determines the usefulness of manure on application. Manures generally mineralise C and N slowly as these are stabilised during aerobic composting, (Murwira and Kirchmann, 1993; Nyamangara, et al., 1999; 2005). The effectiveness of manure is determined by nitrogen content and nutrients losses through leaching and volatilisation during manure handling and storage. This therefore necessitates the importance of research to be focused on ways that improve the traditional methods of soil fertility management. The contribution of livestock manure to soil fertility management requires the improvement of the quantity and quality of manure by giving animals more, better quality feed; using more efficient composting techniques that is collection and processing, changing the methods and rates of application of manure and combining with mineral fertilisers.

2.4 Challenges of using livestock manure

The major challenge with the use of livestock manure is availability and access to good quality manure. The availability of manure differs significantly among farmers. In Zimbabwe the average application rate is less than 2 t manure ha^{-1} $year^{-1}$ (Zingore et al., 2007). Cattle manure, however, is used exclusively by cattle owners and in most smallholder farming areas it is a non-tradable commodity (Zingore et al., 2011). Farmers are neither willing to share nor sell the scarce cattle manure. The manure used is also variable in quality with nitrogen content ranging from 0.5

to 1.8 %, (Tanner and Mugwira, 1984; Murwira et al., 1995). This low N content is attributed to poor quality feed and nutrients losses during manure storage. During handling and storage, manure undergoes the composting process (Wuta and Nyamugafata, 2012) and substantial nutrient losses been reported (Lauer et al., 1976; Kirchmann, 1985). Kirchmann (1985) found that between 8 – 40 % of nitrogen is lost during storage while Lauer et al. (1976) measured losses of between 61 – 99 % of ammonium nitrogen. There is need to develop acceptable strategies for the management of crop residues and manures that make them more effective soil amendments for smallholder maize fields and vegetable gardens. One possibility would be to improve the composting process by including materials such as vermiculite. Vermiculite has the potential of reducing nutrient losses through fixing nutrients such as K^+ and NH_4^+ (Nommik and Vahtras, 1982; Nieder et al., 2011; Najafi-Ghiri and Abtahi, 2013; Pettygrove et al., 2011; Portela et al., 2019).

2.5 Composting

2.5.1 Definition and objectives of composting

Composting is a biological process that converts organic wastes into organic amendments of high agronomic value that improve soil fertility (Zhao et al., 2019; Gao et al., 2019) and reduce environmental risk (Awasthi et al., 2017; Wang et al., 2017). The final product should be sufficiently stable for storage and land application without adverse environmental effects (Pisa and Wuta, 2013). When this decomposition occurs in the presence of oxygen producing carbon dioxide, water and heat, it is termed aerobic composting and anaerobic composting occurs in the absence of oxygen. The metabolic end products of anaerobic composting include methane, carbon dioxide and numerous intermediates such as low molecular weight organic acids resulting in a higher odour potential (Haug and Haung, 1993).

The objectives of aerobic composting have traditionally been to convert putrescible organics to a stabilised form, destroy pathogenic organisms, plant diseases, weed seeds, insects and insect eggs that might be present in the raw waste (Haug and Haung, 1993; Kasmanian and Rynk, 1996). In addition, the volume and weight of the aerobically composted product is much less than that of the original raw waste as much of the carbonaceous material is converted to gaseous carbon dioxide (McGauhey and Gotass, 1980). Odour of this compost is reduced, as the organics remaining after composting are relatively stable with low rates of decomposition. Composting therefore increases the attractiveness of the waste for reuse and disposal. It also improves the handling of solid and semisolid organic waste such as night soil (a mixture of human faeces and urine), sewage sludge, animal manure (Kasmanian and Rynk, 1996), agricultural residues and municipal refuse and reduces the cost of subsequent handling.

2.5.2 The composting process

For decomposition to take place organic residues need to be broken in to small pieces to increase surface area for microbial activity. Under natural conditions, macrofauna like earthworms, nematodes and soil insects initially break down organic materials into smaller pieces. In controlled environments, composters break down large particles through grinding or chopping. When optimal physical conditions (moisture and aeration) are established colonization of organic material by soil bacteria, fungi, actinomycetes and protozoa occurs. These initiate the composting process. The initial colonisers grow rapidly and function well at mesophilic temperatures, which are less than 45^{o}C (Minnich and Hunt, 1979). The microorganisms use the readily available carbohydrates (sugars). Microbial activity results in an increase in temperatures. Mesophiles cannot tolerate high temperatures hence are self-limiting. As the compost internal temperatures increase, mesophiles die and thermophiles (microorganisms that function at temperatures above 45^{o}C) take over. These include thermophilic fungi and actinomycetes, which utilize cellulose and hemicelluloses.

The internal temperature of a compost pile will increase rapidly to thermophilic temperatures within 24-72 hours of pile formation. Thermophilic temperatures can be maintained for several days to several weeks (Cooperband, 2002). This is called the active phase of composting in which temperatures are high enough to kill pathogens (*Escherichia coli, Staphylococcus aureus, Bacillus subtillus*, and *Clostridium botulinum*) and weed seeds plus to break down phytotoxic compounds. Moisture needs to be adjusted as the high temperature drives off most of the moisture.

At temperatures, above 65^{o}C, bacterial spore formers become important and activity declines resulting in a decrease in temperatures. The mesophilic microorganisms recolonize the pile, and the compost enters the curing phase. The rate of oxygen consumption declines to the point where compost can be stockpiled without turning. During curing, organic materials continue to decompose and are converted to biologically stable humic substances, the mature compost. A long curing phase is needed if the compost is unfinished or immature (Cooperband, 2002). Immature compost is a result of poor aeration and moisture content. Immature composts contain high levels of organic acids, high C/N ratios, extreme pH values or high salt contents, all of which can have adverse effects on plants such as N immobilization, poor plant germination or plant diseases. In common composting the curing phase ranges from one to four months.

2.5.3 The fertilising value of compost

Compost quality refers to the capacity of a compost to function within natural or managed ecosystems boundaries for the sustaining plant and animal productivity, environmental quality maintenance and/or enhancement and support human health and habitation (Kozark, 2001). Agriculturalists are interested in compost that functions as a highly productive organic fertiliser sustaining or enhancing productivity, maximising profit or maintaining the soil resource for future generations. Studies have indicated compost use improves plant and soil parameters, making compost a stimulating option for soil fertility restoration and maintenance. Compost addition increases SOM content, which enhances soil structure via aggregate stability (Diacono and Montemurro, 2010). Good soil structure improves water infiltration and enhances water holding capacity reducing runoff generation and consequently soil erosion (Adugna, 2016). In sandy soils, compost helps in water retention thereby reducing drainage of water to below the root zone, whilst in clayey soils porosity is improved making it drain better, therefore, preventing waterlogging (Adugna, 2016). Improved microbial activity (Bastida et al., 2008; Hargreaves et al., 2008; Brown and Cotton, 2011), enhanced nutrient availability for plants (Boldrin et al., 2009; Soheil et al., 2012; Adugna 2016), and the suppression of soil borne diseases (Bonanomi et al., 2007) are benefits of mature compost soil application.

For many smallholder farmers that lack financial resources to purchase sufficient mineral fertilisers, composts are an essential plant nutrient source (Palm et al., 1997; 2001; Zingore et al., 2011; Wuta and Nyamugafata, 2012). The presence of alkaline cations such as Ca, Mg and K, which are released during organic matter (OM) mineralization results compost having a liming effect (Agegnehu et al., 2014 and Daniel and Bruno, 2012). Composts have a longer fertilization effect due to the gradual and slow release of plant nutrients (Seran et al., 2010). Composts, therefore, function as a slow-release store of nutrients, so that the nutrients are available, as the plants require them. This makes them less susceptible to loss by leaching compared to inorganic fertilizers.

The application of compost may, however, result in environmental and agronomic problems, such as gas emissions and leaching of nutrients, and increase in salt and heavy metal content (Hargreaves et al., 2008). This problem is not common in SSA as the manure produced is hardly enough. However, improper handling of the little manure can result in gaseous emissions especially if the manure is not well aerated reducing the agronomic value. Cattle manure derived composts can result in immobilisation of nutrients on soil application (Tayebeh et al., 2010; Kelley et al., 2020). The benefits and limitations of composts are directly associated to the quality of the final compost (Martínez-Blanco et al., 2013). The nutrient content of compost is related to the quality of the original organic substrate. The use of composts is however constrained by their heterogeneity and variability (Kirchmann and Widen, 1994). The nutrient status of composts is also variable as losses, especially of nitrogen, occur during the composting process and storage.

Nutrient loss during composting or stockpiling has been attributed to volatilisation, denitrification and leaching. All of which depend on prevailing conditions during manure handling, Volatilisation occurs when the manure is exposed to too much heat, while denitrification occurs in anaerobic conditions. Various studies have shown that about 10–65 % of initial total nitrogen is lost in the form of NH_3 emissions by the end of the composting process (Wang et al., 2016; Chan et al., 2016, He et al., 2018; Pisa et al., 2020). Turan (2009) observed a 72 % loss of initial N during composting of poultry manure while Barrington et al., (2002) reported that 16 – 76 % of nitrogen would be lost during composting of different materials like cereal straw cattle manure and food waste. To reduce these losses, proper handling of manure during composting is essential. The addition of stover with initial C/N ratio above 30 and adsorbents such as peat and zeolite have been found to reduce N losses during storage and decomposition respectively (Witter and Kirchman, 1989).

Co-composting manure with inorganic component has been done in a bid to improve nutrient content and quality of the final compost. Cattle manure, for example, has been co-composted with rock phosphate to increase P content in composts, (Soropa et.al, 2012; Nugroho et al., 2012). Minerals such as zeolite (Chan et al., 2016), biochar, montmorillonite (Zhu et al., 2019), and bentonite (Li et al., 2012) have been used added to composting organic wastes and they improved nutrient retention. The final composts have been reported enhance soil fertility and quality. These additives have high CEC, which aids in nutrient retention. Vermiculite has also been used in some instances and desirable results have been obtained (Liao, 1997; Turan, 2009; He et al., 2018). Reduced nutrient losses were reported by He et al., (2018) during the composting of mixtures of food waste and vermiculite due to a decline in volatilisation. Similar results were reported by Turan (2009) on the composting of poultry manure with vermiculite and other additives. The inclusion of vermiculite as an amendment in the composting mixtures was to assist in conditioning the mixtures as a way of improving the composting performance (Liao, 1997). An amendment in composts is defined as a material added to other substrates to condition the mixture and thereby facilitate the composting process.

Vermiculite has a layered structure making it a novel amendment in composting as it can bind both potassium and ammonium in its layers resulting in the conservation of these nutrients in the compost mixture resulting in an end product with high fertiliser value (Liao, 1997; He et al., 2018). The application of composts with vermiculite also increases the clay content and CEC of the amended soil and also the potential to store organic matter in sandy soils for longer. The use of vermiculite as an amendment for cattle manure composting has, however, not been adequately studied. Most vermiculite use studies are centred on using it as medium for seedling production to enhance seed germination (Bannister et al., 2013; Costa et al., 2015). A few studies have been reported where vermiculite has been co-composted with food waste (He et al., 2018) and poultry manure (Turan, 2009) but not cattle manure. The use of these mineral additives in agriculture is an example of agrogeology.

2.6 Agro-geology

Agro-geology, is a branch of science that uses rocks for crop production. It aims at studying geological processes and natural rock and mineral materials that contribute to the maintenance of agro ecosystems (van Straaten, 2002; 2006). It focuses on the role of parent material in soil development and enhancement of agricultural productivity by the applications of geological material contributing to improved management of agricultural land. A lot of research has been done in the past, though there has been poor uptake of the technology due to limited information dissemination of the technology. Gillman (1980) and Gillman et al. (2000; 2002) reported improved pH, cation exchange capacities and enhanced cation levels in soils of tropical Australia while Leonardos et al. (1987) reported increased yields of beans (*Phaseolus vulgaris*) and napier grass (*Pennisetum purpureum*) following the application of ground basaltic rocks. In Zimbabwe, Roschnik et al. (1967) reported exponential increase in yield of two slow growing legumes and sunflower when 5 - 40 t ha^{-1} of finely ground basaltic rocks were applied to strongly weathered Kalahari sands. This was attributed to nutrient release and liming effects (Roschnik et al., 1967; Leonardos et al., 1987, 2000; Gillman et al., 2000) of the silicate rocks. Fine grained silicate rocks contain high proportions of olivine, pyroxene, amphiboles and Ca-rich plagioclase feldspars (van Straaten, 2002).

In Zimbabwe, the application of the pelletized phosphate blends, composted in cattle manure, was seen to enhance the maize yields (Dhliwayo, 1999; Tagwira, 2003; Soropa et al., 2012) and this was attributed to increased phosphate rock solubility during the composting process (Akande et al., 1998; 2005) making P more available for plant uptake. Findings by Soropa et al. (2012) showed that yield increases were not realized if the enhanced pelletized phosphate blends manure were not composted first. Other rock-based soil amendments like vermiculite are gaining popularity. In Uganda, for example, a vermiculite-based rock fertilizer was seen to improve agronomic performance of many crops (Uganda Vermiculite Institute, 2005) through enhanced seed germination and emergence. Improved growth of maize, sunflower and cotton was noted and attributed to increasing root biomass and thus improving nutrient uptake. These positive effects were attributed to the presence of vermiculite in the fertiliser. This Ugandan example, illustrates the potential of vermiculite use in agriculture.

2.7 Vermiculite

Vermiculite is widely available, easily handled, odourless, and low-cost material found in various parts of the world, including South Africa, Brazil, Kenya, USA and Zimbabwe (Elliot, 2011). Vermiculite is a hydrated magnesium aluminium silicate mineral resembling mica at first glance. It is a 2.1 phyllosilicate mineral made of one octahedral sheet that lies between two tetrahedral sheets (Velde, 1992) and contains water molecules within its layered structure (Walker, 1951; Grim, 1968). Vermiculite minerals are formed through the hydration of the mica minerals (biotite and phlogopite) during weathering or hydrothermal alteration (Basset, 1963, Grim, 1968). The parent biotite or phlogopite is altered by the reaction of hydrothermal fluid (mostly hot water). During vermiculite formation, cationic exchange occurs within the crystal lattice in which interlayer potassium ions (K^+) are replaced Mg^{2+}, or combination of Mg^{2+} and Ca^{2+} ions occurs and water molecules are introduced into the interlayer space (Bergaya et al., 2006). The vermiculite has hydrated interlayer space and is bound together by a weak van der Waals bonds giving it the ability to swell and exfoliate. The general molecular formula for trioctahedral vermiculite is $(OH)_4(Mg.Ca)_X(Si_{8-X}\ Al_X)\ (Mg\ Fe)_6\ yH_2O$ (Deer et al., 1966; Grim, 1968; Bergaya et al., 2006,) and the structural structure is shown in Figure 2.1.

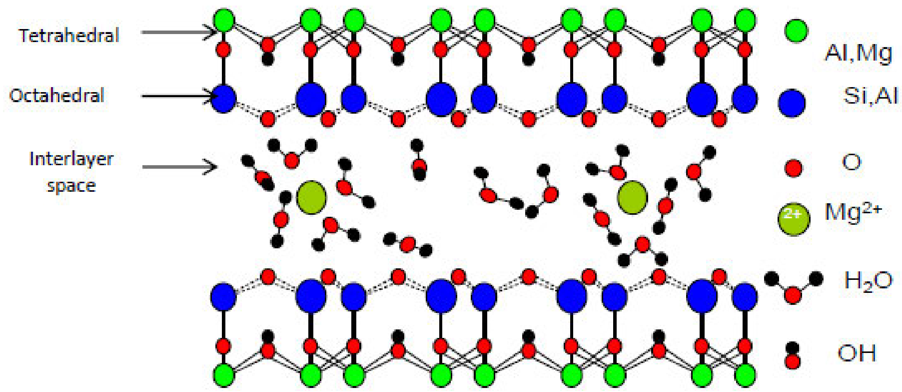

Figure 2.1: The vermiculite structural diagram. Adapted from (Reeves et al., 2006)

In Zimbabwe vermiculite is mined using open-cast mining techniques (Bergaya et al., 2006, The Vermiculite Association, 2011) in Buhera District (19º 31'S; 31º 43' E) in East–Central Zimbabwe at Shawa alkaline complex, by Samrec Vermiculite and Dinidza Vermiculite Mining Co. The vermiculite ore is formed as a weathering product underlying phlogopite and biotite rich pyroxenite (van Straaten 2002). The mined vermiculite from both companies is mainly for the international market with 14 841 tonnes exported in 1997 (van Straaten 2002). Barry (2020) reported that 21 625, 28 808, 29 500, 10 000 and 10 000 metric tonnes of vermiculite were produced in the year 2012, 2013, 2014, 2015 and 2016 respectively against a capacity of 49 000 metric tonnes. Very little is consumed locally for horticulture and spillage control (Chimbodza Stanely, Dinidza Vermiculite Mining Co. Zimbabwe; pers. Comm., 2014). In Zimbabwe vermiculite is sold at US$ 0.5 per kilogram translating to US$ 500 t^{-1}. A large amount of vermiculite waste is produced with open cast mining techniques. Vermiculite waste is in two categories, material discarded from the mining pit to access the ore and the material that comes from the processing of the ore. Fine vermiculite (< 250 micron) is also considered to be waste, although some of it is collected by consumers from Zimbabwe and South Africa for use in animal feed (van Straaten, 2002) where it is used as a carrier for nutrients such as fat concentrates, vitamin concentrates and molasses. It also releases active ingredients and provides extra roughage

2.7.1 Uses of vermiculite

Vermiculite has been used in construction, industrial, horticulture and agriculture industries (Muiambo et al., 2010, The Vermiculite Association, 2011, Bergaya et al., 2006). Raw vermiculite is used for circulation in drilling mud, manufacture of fire-resistant wallboard and in the hardening of steel. While lightweight exfoliated vermiculite with low density, is chemically inert, porous and with thermal, acoustic, adsorbent and fire-resistant properties (Obut and Girgin, 2002; Marcos et al., 2009; Muiambo et al., 2010; The Vermiculite Association, 2011). In agriculture, vermiculite is used as a growth medium, in animal feedstuffs, and as a carrier in fertilizer, herbicides and insecticides (Marwa et al., 2009; The Vermiculite Association, 2011).

2.7.2 Effects of vermiculite soil application

When applied to soil vermiculite has been seen to improve water holding capacity and aeration of the soil. Application of vermiculite to soil improves drainage, neutralises pH (Indrasumunar and Gresshoff, 2013) and reduces leaching of most nutrients due to its adsorption properties. Vermiculite has a CEC that ranges from 80 - 150 $cmol_c\ kg^{-1}$, and contains calcium and magnesium carbonates that neutralize soil acidity (Nelson, 1969; Brooking, 1976). Vermiculite also has the ability to adsorb ammonium ions (Shen et al., 1997; Shinzato et al., 2020). Unlike organic materials, which eventually breaks down into the soil, vermiculite does not break down resulting in long term residual benefits as a soil conditioner. The sterile nature of vermiculite makes it ideal for germinating seed and propagating cuttings. Vermiculite has a high-water absorption capacity and desirable water and fertiliser retention capacity. Using a large amount vermiculite can prevent bacterial and fungal problems such as damping off and root rot. The study by Okada et al., (2008) observed that to enhance the water retention capacity of planting concrete, allophane could be mixed with vermiculite as way of controlling various pore sizes. Li et al., (2017) observed that water absorption capacity increased with the increase of vermiculite dosage.

Soil containing appreciable amounts of vermiculite have been seen to fix potassium (K^+) and ammonium ($NH_4^{\ +}$). Ammonium and potassium are bound in such a way that they cannot be exchanged by other cations. Some researchers have reported this to be a good thing as it increases the nutrient retention capacity of the soil. Mineralogical studies have confirmed that the build-up of fixed K^+ reserve occurs slowly (Quémener, 1986) and is affected by the parent materials, degree of weathering, and nutrient balance (Bertsch and Thomas 1985; Simonsson et al., 2007; Simonsson et al., 2009; Schneider et al., 2013). Potassium fixation, though understood to reduce fertilizer efficiency, limits nutrient leaching. While early research by Allison et al. (1953), Axley and Legg (1960) and Lutz (1966) concluded that a very small amount of fixed NH_4^+ can become available to microorganisms and plants studies by Nommik and Vahtras (1982); Scherer (1993) and Lu et al. (2010,) in the last three decades suggest that fixed NH_4^+ may be released and used by crops. Ammonium fixation and release is important for the efficient use of N fertilizers as it influences the indigenous soil N supply towards crop N uptake. (Steffens and Sparks, 1999; Juang et al., 2001; Nieder et al., 2011. The phenomenon of temporary fixation and release of added fertilizer NH_4^+ may contribute to retarding nitrification and thus to reducing N losses from the soil–plant system via NO_3^- leaching and denitrification (N_2, N_2O). Soils with high fixation capacity bind part of the applied fertilizer K^+ and NH_4^+ making it less available for plant uptake, which can result in deficiencies, especially for smallholder farmers who usually apply less than the recommended fertilizer amounts.

It is necessary to understand the conditions under which non-exchangeable K^+ and NH_4^+ participate in replenishing soil solution K^+ and NH_4^+ respectively and consequently plant uptake. The diffusion process of both NH_4^+ and K^+ in the interlayer spaces of clay minerals affects fixation and release of theses ions, their concentration and the concentration of competing cations (Ca and Mg) in the soil solution (Hinsinger, 1998; Moritsuka et al., 2004). The K^+ and NH_4^+ ions have similar ionic properties (valence and size) having radius of 0.133 and 0. 143 nm, respectively, (Ajazi et al., 2013), and consequently competing for the same exchangeable and non-exchangeable sites of soil particles. When fixation occurs, the NH_4^+ or K^+ ions shed their hydration water shell and enter the lattice voids. This is because the electrostatic energy between NH_4^+ or K^+ and the negative charges in the crystal sheets is greater than the hydration energy of NH_4^+ or K^+ (Kittrick, 1966; Nieder et al., 2011).

2.8 Conclusion

The use of organic materials in agriculture has been seen to be beneficial to the farmer in improving soil fertility and increasing yields while reducing production cost. The quality of these is of utmost importance and thus proper handling of manures is essential. Nutrient loss during the composting process and storage can be reduced by introduction mineral additives that have high nutrient retention capacity to produce compost with high agronomic value. Vermiculite has been reported to reduce nutrient loss during food waste and poultry manure composting. The inclusion of vermiculite in cattle manure composting has not been done and therefore this study sought to determine vermiculite inclusion in cattle manure composting on agronomic value of the resultant compost focusing on the effects of the compost on composting performance, K and NH_4^+ fixation, early maize growth, nutrient uptake, dry matter and grain yield of maize.

CHAPTER 3: EFFECTS OF INCORPORATION OF VERMICULITE ON CARBON AND NITROGEN RETENTION AND CONCENTRATION OF OTHER NUTRIENTS DURING COMPOSTING OF CATTLE MANURE

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3.1 Abstract

An experiment was setup to evaluate the effects of mixing different proportions of vermiculite with cattle manure how compost performs and nutrient retention during composting. Cattle manure and vermiculite mixtures (0, 10, 20 and 30 % vermiculite) were aerobically composted in $1m^3$ composts bins over 76 days arranged in a RCBD with three replicates with blocking based on period of shading. Internal compost temperature was measured daily and composts samples collected on days 3, 12, 23, 38, 48, 60, 67 and 76 were analysed for pH, EC, mineral and total N, C, total P and cations (K, Ca, Mg). All compost mixtures passed through the mesophilic, thermophilic and curing stages. Nitrogen losses recorded were 27.8, 25.3, 21 and 14.5 % for the 0, 10, 20 and 30% vermiculite treatments respectively meaning vermiculite inclusion increased total N retention during composting. Increasing vermiculite content reduced mineral N and C:N ratio and increased the Ca and Mg concentrations of the final cattle manure composts. The determination of nutrient availability, particularly N, K, Ca and Mg on soil application of these co-composts as organic fertilisers is necessary and therefore recommended.

Key words: *cattle manure; composting; vermiculite; nutrient retention*

3.2 Introduction

Zimbabwean farmers continuously get low yields because of unpredictable rainfall, nutrient deficient sandy soils and unsuitable soil fertility management (Ncube et al., 2009). The scantiness of nutrient application on soils coupled with escalating prices of inorganic fertiliser has resulted in inadequate nutrient supply that fails to satisfy crop requirements (Bationo et al., 2006). The best option for smallholder farmers is to use organic amendments. Organic materials can supply plant nutrients, improve soil physical, chemical and biological properties and minimise the undesirable environmental effects of inorganic fertilisers.

The fairly high temperatures during the thermophilic phase of composting sanitises the cattle manure by killing both pathogens and weed seed (Pisa and Wuta, 2013). The agronomic value of composts can, however, be significantly reduced when nutrients are lost during composting, ammonia volatilisation and leaching (Latifah et al., 2015). A number studies have reported total nitrogen losses of 10–65 % of the initial total N as NH_3 gas (Wang et al., 2016; Chan et al., 2016, He et al., 2018). Nitrogen losses happen during handling of organic materials and therefore necessitates the need for proper management of manures and other organic materials during composting. Composting cattle manure mixed with mineral additives has been reported to improve internal air circulation and moisture conditions to enable the transformation of agricultural organic waste, into compost with relatively high nutrient content.

The application of organo-mineral co-composts has been seen to improve soil quality and health due in enhanced nutrient retention when organic materials were co-composting with mineral additives such as zeolite biochar, montmorillonite and bentonite. The improved nutrient retention is due to the high CEC in of these additives. Vermiculite has cation exchange capacity of between 50 and 150 meq/100 g (van Straaten 2002) and water holding capacity (WHC) of up to 150 % (Jayabalakrishnan, 2007).

In Zimbabwe communal farmers apply cattle manure to their fields and gardens as it is the most available organic amendment. The cattle manure is pre-treated before soil application by composting or stockpiling during the dry season. The end product is usually low in nutrients (Wuta and Nyamugafata, 2012) due to losses during the composting/ stockpiling process. To improve nutrient content of the final compost, vermiculite inclusion in the compost mixture can be an option. Fine vermiculite from mines in Zimbabwe can be co-composted with cattle manure to improve the nutrient content of the final compost. This fine vermiculite fraction is considered a waste and thus adding it to composting cattle manure can be a way of managing this waste. However, not many studies have been reported on the influence of vermiculite addition on quality of the final cattle manure compost. This study, sought to establish the effect of adding vermiculite to cattle manure on carbon and nitrogen losses and concentrations of Ca, Mg, K and P during composting of cattle manure. There is little research around the subject, and the findings of this research needs to be shared with farmers for them to possibly use the vermiculite waste and capitalize on its benefits in crop production

3.3 Materials and Methods

3.3.1. Characterisation of composting material

Fresh cattle manure and fine vermiculite (100 - 250 µm), were aerobically co-composted over a period of 76 days. Fresh cattle manure was obtained from the cattle kraal at Marondera University of Agricultural Sciences and Technology (MUAST) farm while the vermiculite of 100 -250 µm was obtained from Buhera (19^{o} 31'S; 31^{o} 43' E). Cattle at this farm are free ranging foraging in paddocks with the natural veld. MUAST farm is found in natural region IIb with annual rainfall ranging from 700 to 900 mm with about 80 % falling between November and March. The area is characterised by hot wet summers and dry cold winters. The cattle manure was air dried and analysed for carbon, total nitrogen, mineral nitrogen, calcium, magnesium, potassium, pH, EC and ash content using standard methods described in Okalebo et al. (2002) while vermiculite was subjected to X-ray florescence to determine its chemical properties

3.3.2. Composting procedure

Vermiculite and cattle manure were thoroughly mixed to give vermiculite-cattle manure mixtures with vermiculite proportions of 0, 10, 20 and 30 % on a w/w basis. The initial amount of manure for each treatment thus differed. As the amount of vermiculite increased the amount of manure decreased. The 0 % and 30 % treatments had approximately 500 and 350 kg of cattle manure respectively. The proportions used ensured that mixtures were not extensively diluted but were still high enough to reveal the effect of vermiculite on compost performance. Thorough mixing of composting material was done manually on polythene sheets by repeatedly mixing from one end of a spread polythene sheet to the other. The vermiculite cattle manure mixtures were placed into wooden compost bins measuring 1.2 m x 1.0 m x 1.0 m. The bins were made from wooden planks measuring 114 mm in width. The planks were separated from each other by 5-8 cm gaps to permit free air movement. Composting material was packed to a height on 1m to get the recommended volume of $1m^3$. One side of the bin was removable to allow for compost mixing. The composting trial was set up in a RCBD with three replications. Blocking was based on position of each set of compost boxes in relation to shading time and period.

Vermiculite-cattle manure mixtures were composted over a period of seventy-two days. and the composts were mixed at each sampling. Water was added during mixing to ensure compost moisture ranged between 50 and 60 % during the composting period. Application of excess water was avoided to limit oxygen deficient conditions and loss of nutrient in compost tea leachate. During composting, internal compost and ambient temperatures were measured daily at midday. Temperature profiles were used to categorize the composting stages and evaluate the success of the composting process.

3.3.3. Sample collection and analysis

Compost samples, 1000g, were collected by taking 5 sub samples randomly from each bin and mixing them and a composite sample was drawn. This was done on days 3, 12, 23, 38, 48, 60, 67 and 76. On the same days, the compost was turned after sampling. Compost samples were analysed for NH_4^+-N and NO_3-N. total N, total P, calcium, magnesium, potassium, pH, EC, total organic carbon and ash content using standard laboratory methods (Okalebo et al., 2002). Total nitrogen, phosphorus, potassium, calcium and magnesium were extracted by wet digestion using a mixture of concentrated H_2SO_4, selenium powder, lithium sulphate and H_2O_2. Nitrogen and phosphorus were determined colorimetrically while K was determined by flame photometry and Ca and Mg by atomic absorption spectrophotometry (Okalebo et al., 2002). Compost pH and EC were determined using a pH meter (Lasany 920, Haryana, India) and a digital conductivity meter (Lasany 9U1, Haryana, India), respectively.

3.3.4. Statistical analysis

Data was analysed in Genstat 14 by subjecting it to one-way analysis of variance (ANOVA). Least significance difference ($LSD_{0.05} = t_{0.05}$ x SE0.05) and Tukey's Honesty test at $\alpha = 0.05$ were used to separate means where necessary. Sigma Plot version 10 was used to draw graphs to show patterns of the measured parameters.

3.4 Results and Discussion

3.4.1. Chemical composition of raw materials and initial compost mixtures

Chemical properties of both cattle manure and vermiculite are shown on Table 3.1. The raw materials contained different amounts of Ca, Mg, K, Na and trace elements. The cattle manure and vermiculite mixtures had significantly different amounts of nitrogen and carbon initially

(Table 3.2). Total N was lowest in the 30 % vermiculite and highest in the 10 % vermiculite treatment while NH_4^+- N was lowest in the 30 % vermiculite treatment and highest in the 0 % vermiculite treatment. The high total N could be due to initial fixation of N by the added vermiculite. N fixation occurs within the first 4 hours of N addition (Neider et al., 2011). The more vermiculite in the mixture the more N fixed. Nitrate was highest in the 30 % treatment and lowest in the 0 % vermiculite treatment. The NH_4: NO_3, differed significantly among treatments ($p < 0.05$) and decreased with increasing vermiculite content in composting mixtures (Table 3.2). EC, pH, phosphorus and potassium were highest in 0 % vermiculite mixture, while calcium, magnesium, and ash were higher in the treatment with 30 % vermiculite (Table 3.2).

Table 3.1: Chemical composition of fresh cattle manure and vermiculite used in the trial.

	Concentration (%)	
Element	**Cattle manure**	**Vermiculite**
N	1.29	-
O C	28.9	-
P	0.42	0.31
Ca	0.08	0.38
K	1.3	0.96
Mg	0.35	8.5
Cur	0.0009	0.001
Fe	2.65	3.19
Mn	0.03	0.03
Zn	0.005	0.002
Na	-	0.104

The – in the table indicated undetectable concentrations

Table 3.2: Selected chemical parameters of the initial vermiculite cattle manure mixtures.

Chemical parameter	0 % VCM	10 % VCM	20 % VCM	30 % VCM	l.s.d
Total C %	23.36^{b}	22.8^{b}	20.27^{a}	19.31^{a}	1.31
Total N %	1.07^{b}	1.03^{b}	0.95^{a}	0.92^{a}	0.04
Carbon:Nitrogen	35.3b	31.6b	24.3a	19.6a	5.81
Min. N of TN^0 %	21.3^{b}	25.1^{b}	18.8^{ab}	16.4^{a}	4.68
NH_4-N of TN^0 %	19.1^{c}	19.07^{c}	14.5^{bc}	9.80^{a}	4.55
NO_3-N of TN^0 %	2.15^{a}	6.07^{c}	4.36^{b}	6.56^{c}	1.28
NH_4-N:NO_3-N	8.89^{b}	3.17^{a}	3.38^{a}	3.50^{a}	2.22
Phosphorus %	0.39^{b}	0.28^{a}	0.31^{a}	0.31^{a}	0.08
Calcium %	0.57^{ab}	0.53^{a}	0.56^{ab}	0.63^{b}	0.08
Magnesium %	0.44^{a}	0.46^{a}	$0. 70^{b}$	0.76^{b}	0.09
Potassium %	1.01^{d}	0.64^{b}	0.56^{a}	0.82^{c}	0.07
pH	8.31^{b}	7.93^{ab}	8.26^{b}	7.74^{a}	0.43
Electrical Conductivity	0.63^{b}	0.313^{a}	0.35^{a}	0.32^{a}	0.18
Ash (%)	53.1^{a}	52.6^{a}	55.0^{a}	64.8^{b}	8.26

Values in the same row followed by the same lowercase alphabetical letters are not significantly different at $p<0.05$ according to Tukey's HSD**.** *TN^0 - initial N added; TC^0 – initial C added; TN - total nitrogen; TC - total carbon; Min – mineral. The 0 % VCM, 10 % VCM, 20 % VCM and 30 % VCM represent composts mixtures of cattle manure with 0, 10, 20 and 30% vermiculite.

3.4.2. Compost Temperature Profiles

The temperature profiles of the composts (Figure 3.1) revealed that they all passed through the mesophilic, thermophilic, cooling and maturing composting phases. Composts remained in the mesophilic stage (40 and 45^{o} C) (Latifah et al., 2015), for 9 and 16 days for the 0 % vermiculite treatment and all vermiculite containing treatments respectively. In this composting stage, a mesophilic microbial population made use of available C for energy and released carbon dioxide, water and heat (Chang et al., 2006). Internal compost temperature rose to above 45^{o}C, thermophilic stage, (Westerholm et al., 2018), as a result of heat generated during catabolism of microbes. The thermophilic stage lasted for 38, 12, 13 and 15 days for the 0, 10, 20 and 30 % vermiculite treatments, respectively.

The highest temperatures attained by the 0, 10, 20 and 30 % vermiculite treatments were 59.7, 59.9, 56.9 and 55.2 ^{o}C respectively suggesting variations rate of decomposition and the microbial populations present in the composts (Wang et al., 2015). All composts managed to self-sanitise as they attained and maintained internal temperatures between 50 and 60 ^{o}C for more than 3 days. Research has shown that compost sanitation standards are reached when internal temperatures are maintained at 50^{o}C to 60^{o}C for 3–4 days. Within this temperature range and time period pathogenic microorganisms are inhibited (Wang et al., 2015, Zhang and Sun, 2014). High compost temperatures also transformed unstable N into stable forms.

The thermophilic phase was longest in the 0 % vermiculite treatment because the treatment had most organic substrate initially. The mixtures with vermiculite stayed in the thermophilic phase for a shorter period than the 0 % vermiculite treatment, possibly as a result of lower organic substrate, due to dilution with vermiculite. Vermiculite could have also caused more air circulation, allowing for more heat and water losses and therefore slowing down composting (Zeng et al., 2016). The decline in organic material and microbial activity (Ogunwande et al., 2008) got the composts into the cooling and curing phases.

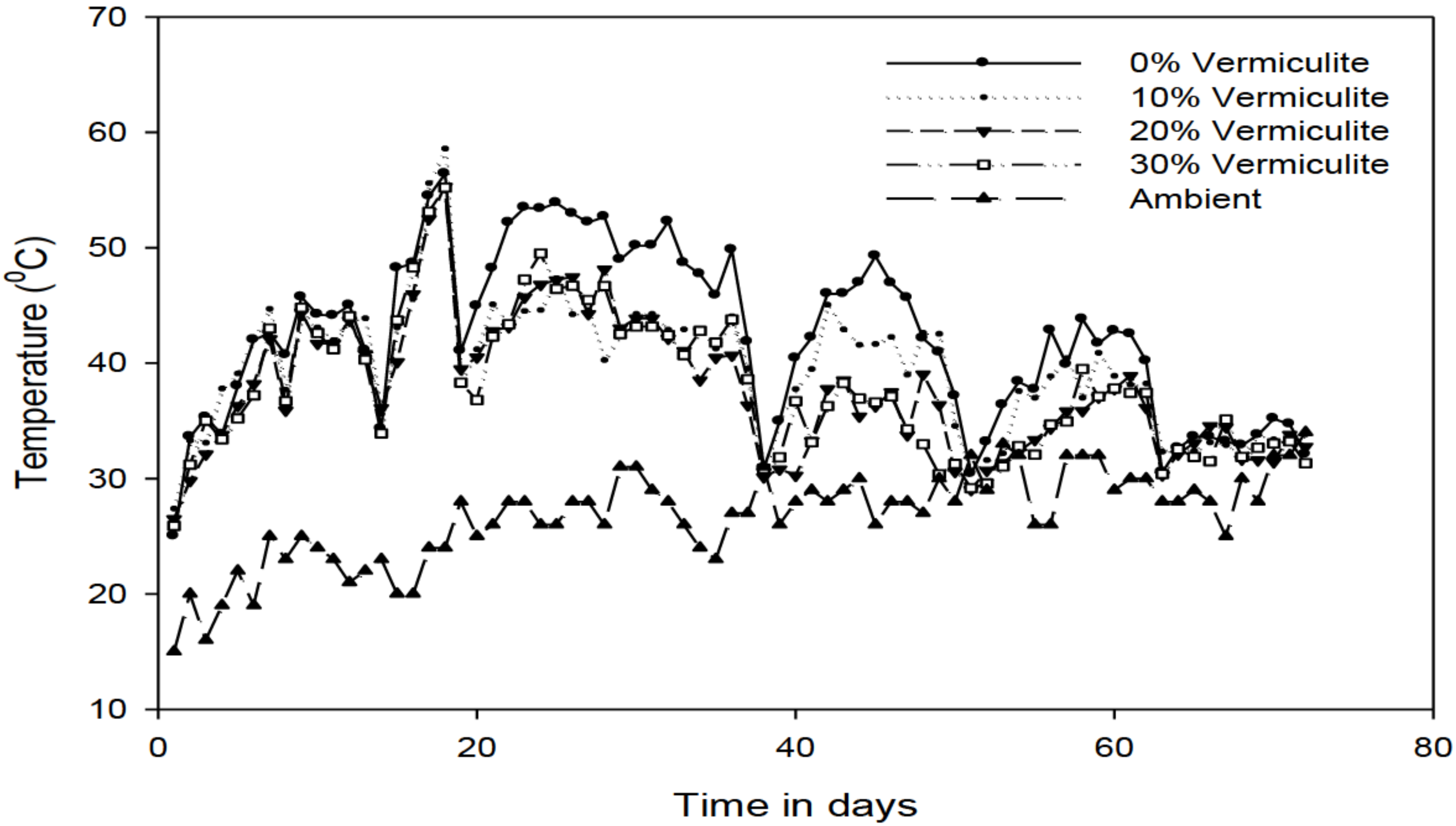

Figure 3.1: Temperature profiles of mixtures of cattle manure and vermiculite in differing proportions over a period of 76 days. (Data points are the mean of the three replicates).

3.4.3. Total Carbon and Nitrogen, and C: N ratio of the composting mixtures

A decline in C, as a percentage of initial C, was seen for all treaments (Figure 3.2a). Carbon percent differed significantly among treatments with the 0 and 10 % vermiculite having significantly more carbon than the 20 and 30 % vermiculite treatments, throughout the composting period (Figure 3.2a). Carbon loss increased with increasing vermiculite in the compost mixtures (Figure 3.2a). The 0, 10, 20 and 30 % vermiculite treatments recorded C losses of 34.4, 30, 36.9 and 43.8 % respectively on day 48. Decrease in carbon (Figure 3.2a), indicated a decline in organic matter with composting for all composts. During composting, C losses occur through the transformation of C by bacteria and fungi to carbon dioxide (Tittonell et al., 2010). The C content was in the order 10 > 0 > 20 > 30 % at the end of composting Vermiculite content at 20 and 30 % could have increased compost aeration resulting in greater C oxidation to carbon dioxide, which was lost to the atmosphere.

Total nitrogen (as % of initial N) declined with composting for all the treatments and it differed significantlty among treaments ($p < 0.05$) for the greater part of the composting period. The 20 and 30 % vermiculite treatments recorded significantly more nitrogen than the 0 and 10 % vermiculite treatments (Figure 3.2b). Reduction in total nitrogen with composting, could have been attributed to the immobilisation by microbes and mineralisation of organic nitrogen to inorganic forms which can be lost via the processes of volatilization, denitrification and leaching. Nitrogen content differed significantly ($p < 0.05$) amongst treatments on the first day of sampling with the 30 % vermiculite treatment recording 100 %. The 0, 10 and 20 % treatments had less than 100 % of initial N added after three days possibly due to losses during preparation of compost mixtures. Total N was highest in the 30 % vermiculite treatment at the end of seventy-six days and this could be attributed to fixation of ammonium N in vermiculite interlayer spaces of during composting (Rees et al., 2013) consequently preventing further nitrification and volatilisation. He et al. (2018) also observed nitrogen retention in 10 % vermiculite-food waste co-compost and attributed this to reduced volatilisation. The fixation notion can be supported by lower ammonium-N measured in composts as vermiculite content increased.

The C:N ratio decreased with composting for all the treatments (Figure 3.2c) which differed significantly ($p < 0.05$) throughout composting. The 30 % vermiculite treatment recorded the least C:N ratio and the 0 % vermiculite treatment recorded highest. C:N ratio decreased with increasing vermiculite content as increase in vermiculite content reduced nitrogen losses. These findings agree well with Pisa and Wuta (2013) who observed a decrease in C:N ratio during the composting of chicken blood and maize stover. Latifah et al., (2015) also reported a decrease in C:N ratio in the composting of paddy husk, chicken manure and clinoptilolite zeolite. The 0, 10, 20 and 30 % vermiculite treatment all attained a C:N ratio lower than the maturity threshold of 20 (Brady and Weil, 2010) and therefore the final composts were considered mature.

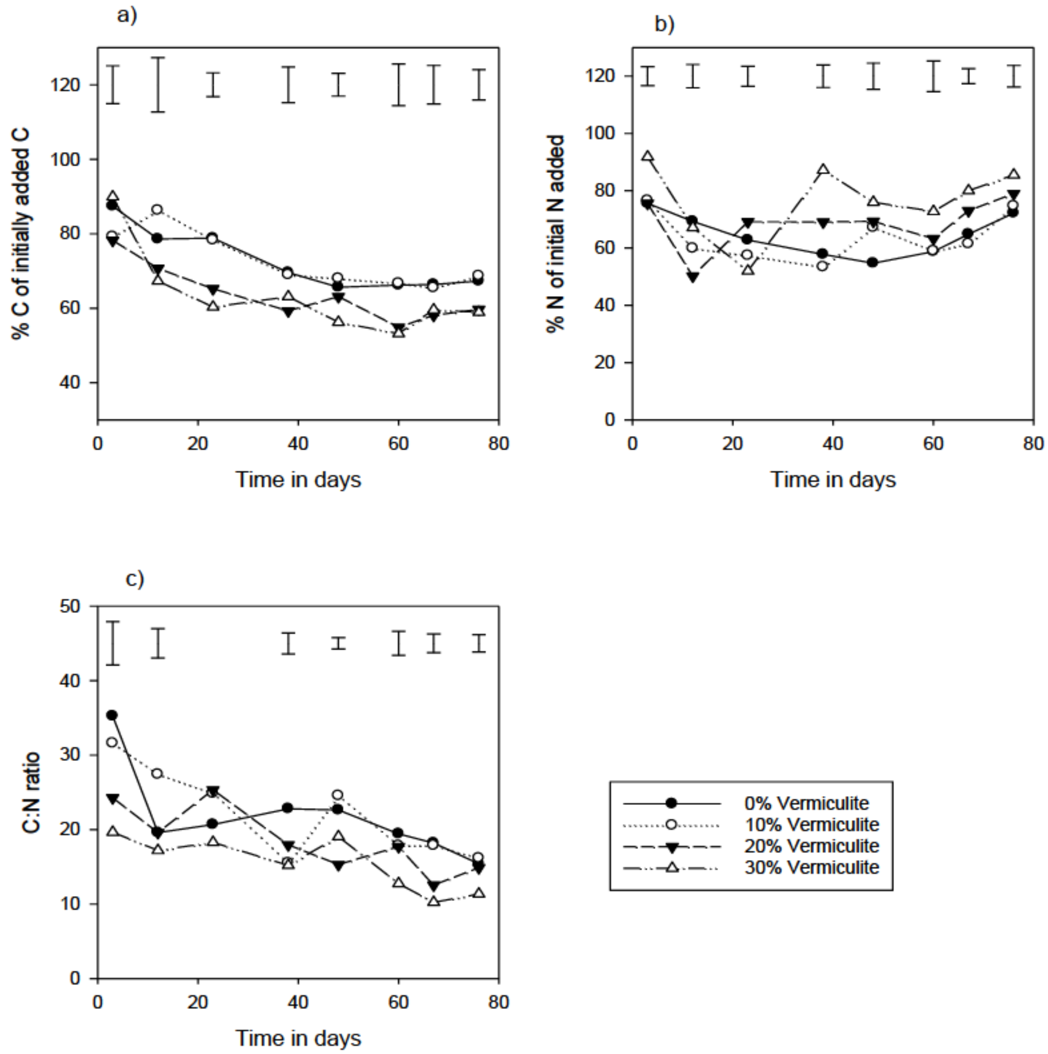

Figure 3.2: Changes in proportion of a) total C to TC_0 and b) total N to TN_0 and c) C: N ratio with composting of the mixtures of vermiculite and cattle manure. (Data points are the mean of the three replicates). **TC_0 – Initial C added; TN_0 – initial N

3.4.4. Mineral N content

Ammonium-N, as proportion to initial N added, declined with composting during the first 48 days, for all the treatments (Figure 3.3a). Ammonium-N content differed significantly ($p < 0.05$) amongst all the treatments over a 67 day period. Ttreatments with 0 and 10 % vermiculite had significantly more NH_4^+ - N than the 20 and 30 % vermiculite treatments. The decline in NH_4^+ -

N content (Figure 3.3a), could be attributed the ammonium transformations such as nitrification of NH_4^+- N, NH_3 volatilization of ammonia due to the high internal compost temperatures and pH (Hao and Benke, 2008) and immobilization through formation of nitrogenous compounds by micro-organisms in the compost (Sánchez-Mondero et al., 2001). Nitrate N was seen to increase as composting progressed while ammonium N was decreasing supporting the fact the NH_4^+ underwent nitrification. Ten to forty six percent of initial N is lost as ammonia gas as composting progressed (Jiang et al., 2011, Wang et al., 2016; Luo et al., 2014). In this study reduction in NH_4^+-N in the first 3 weeks coincided with high pH, (Figure 3.4a) and high internal temperatures (Figure 3.1). He et al., (2018), observed the same pattern with NH_4^+ - N content which declined with an increasing temperature and pH during the composting of food waste and vermiculite mixtures. Leaching losses in the present study were reduced by ensuring that not too much water was added to the compost during turning. Appreciable amounts of water soluble NH_4^+ can be lost through leaching though they usually account for small proportions (Eghball et al., 1997; Hao and Benke 2008), when application of excessive amounts of water is avoided during composting.

The decline in ammonium N with increasing vermiculite content throughout composting suggests significant NH_4^+ fixation by vermiculite. The NH_4^+ ion is liable to fixation by both the organic matter and clay minerals (Nommik and Vahtas, 1982) thereby reducing ammonium in solution. The possibility of NH_4^+ fixation is supported by the high total N recorded in the 30 % vermiculite treatment, which also had the lowest mineral N (as a percentage of initial N) in composting mixture (Figure 3.3c). All compost were stable as indicated by the ammonium concentrations below 0.4g kg^{-1} at the end of composting. Basing on ammonium concentration these composts were suitable for soil application. Ammonium N content above 0.4 g kg^{-1}, is an indication that compost is unstable and therefore inapt for use as a soil amendment in crop production (Sanchez – Mondero et al., 2001).

Nitrate-N (as proportion to initial N added) increased for all treatments as composting progressed (Figure 3.3b) and treatments significantly differed from each other ($p < 0.05$). More NO_3^- - N was recorded in the treatments with 0 and 10 % vermiculite and was significantly higher than in the 20 and 30 % vermiculite treatments from day 48 onwards. At the end of the composting the 0 % and 30 % treatments recorded the highest and least nitrate-N respectively (Figure 3.3b). Nitrate-N decreased with an increase in vermiculite content. Low nitrate concentrations during the first 38 days in all treatments (Figure 3.3b), were due to the inhibition of growth and activity of nitrifying bacteria because of the high internal compost temperatures (Bustamante et al., 2008). As internal composts temperatures declined, from day 38, nitrate-N increased as temperatures where now favourable to nitrifying bacteria. Limitations in ammonium N for nitrification, due to fixation, can be the reason why the 20 and 30 % vermiculite treatments had lower NO_3^-concentrations as compared to the 0 and 10 % vermiculite treatments throughout the composting period.

Mineral N significantly declined with composting for all the treatments (Figure 3.3c). Treatments also significantly differd from each other ($p < 0.05$) The 30 % and 0 % vermiculite treatments recorded the least and highest mineral N respectively throughout composting. Mineral N in the final composts of the 0, 10 and 20 % vermiculite treatments was significantly higher than the 30 % vermiculite treatment (Figure 3.3c).

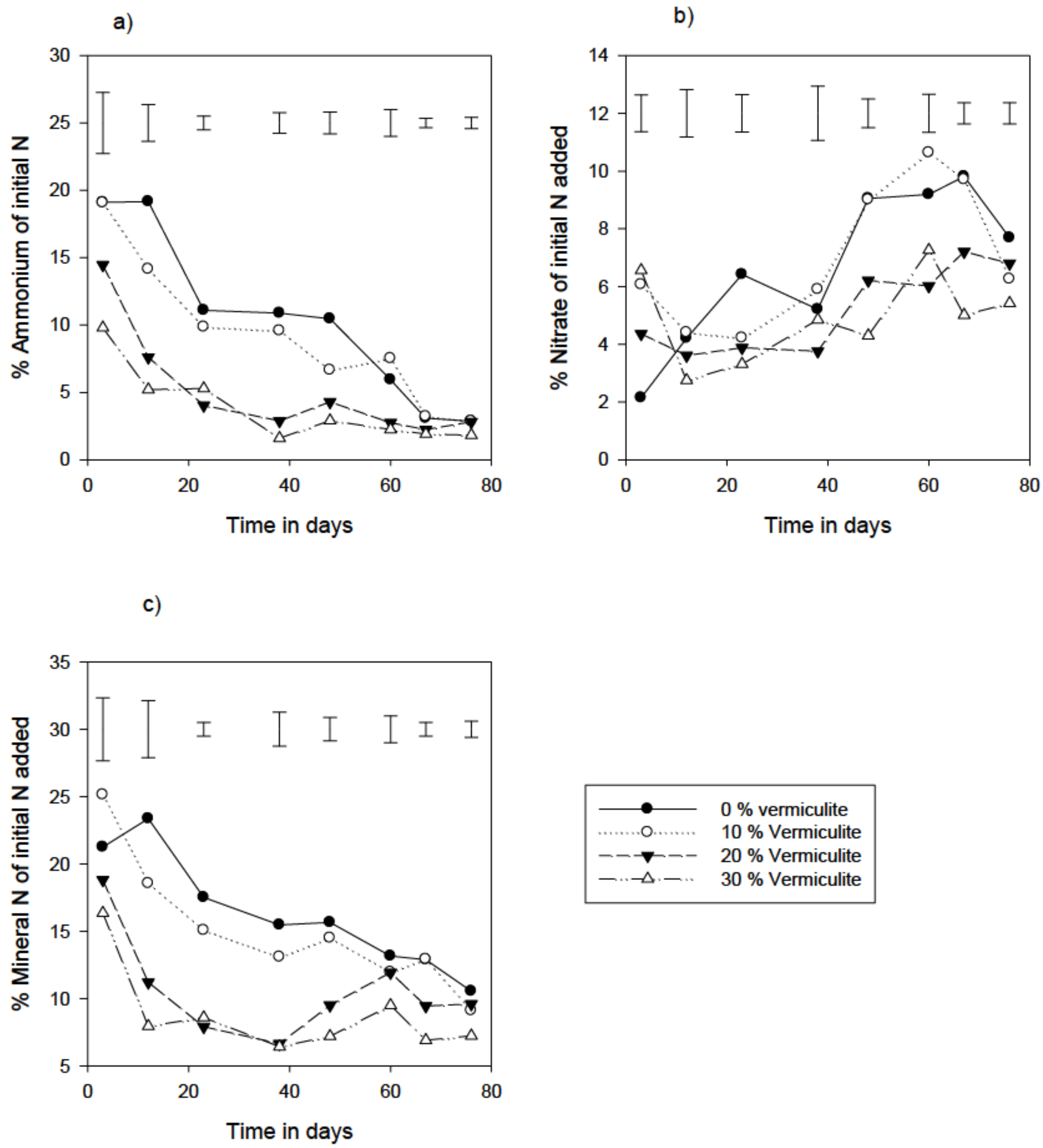

Figure 3.3: Changes in proportion of a) ammonium N to TN_0 and b) nitrate N to TN_0 and c) available N to TN_0 with composting of the mixtures of vermiculite and cattle manure. (Data points are the mean of the three replicates) **TC_0 – Initial C added; TN_0

3.4.5. pH and Electrical Conductivity

Compost pH decreased with composting for all the treatments (Figure 3.4a) but did not differ significantly ($p > 0.05$) among the treatments. The decomposition of organic materials results in the production of organic acids which could have contributed to pH reduction as composting progressed (Ogunwande et al., 2008, Pisa and Wuta 2013). These results are comparable to results by Ogunwande et al. (2008), who reported pH reduction when they composting chicken litter in turned windrow pipes. The compost pH ranged between 7 and 8.5 falling within the 6.7-9 pH range which is optimum for microbial growth (Lili et al., 2013). This is evidenced by the prolonged mesophilic phase, which suggests optimum compost conditions for microbes to thrive. During the first 48 days the EC of the composts was constant for all treatments (Figure 3.4b). From day 60, electrical conductivity increased for all treatments as complex OM were broken down into more soluble components such as ammonium, phosphates and cations (Kebibeche et al., 2018, Chan et al., 2016, Wang et al., 2017, Gómez-Brandón et al., 2008). A rise in electrical conductivity could also have been due to high concentration of the basic cations, Ca and Mg which increased with a reduction in compost volume (Figure 3.5a,b). The higher EC observed for the 0 % vermiculite treatment can be attributed to cations released from decomposition remaining in solution while in treatments containing vermiculite the cation could have been excluded from compost solution due to adsorbed on the clay surfaces or were entrapped within the vermiculite interlayer space. Electrical conductivity is an important parameter which affects the suitability of the compost for application in soil (Gómez-Brandón et al., 2008). All the composts achieved EC levels within the prescribed range of 1.0 to 10.0 dS/ m making them apt for use in crop production.

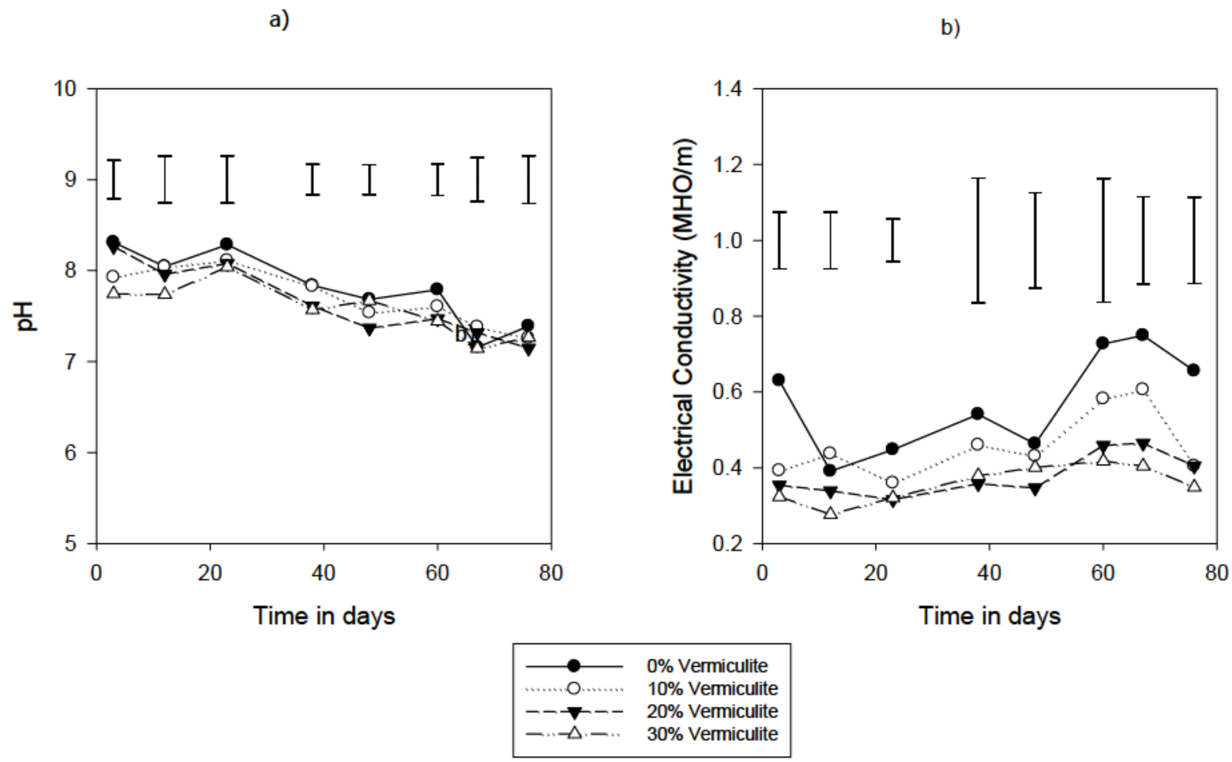

Figure 3.4: Changes in a) pH and b) Electrical conductivity with composting of the mixtures of vermiculite and cattle manure. (Data points are the mean of the three replicates)

3.4.6. Changes in P, ash Ca, Mg and K during composting of cattle manure and vermiculite mixtures

Noteworthy, total P concentration differences were observed among treatments ($p < 0.05$). Phosphorus content in the 0 and 10 % vermiculite treatments was significantly lower than the 20 and 30 % vermiculite treatments. Phosphorus concentration for all the treatments declined during the five weeks then increased (Table 3.3). Decrease in P concentration could have been due to immobilisation by microbes and possible precipitation into monocalcium and tricalcium phosphates at the elevated pH levels experienced during this period. As compost volume decreased P concentration increased from 6 weeks onwards. The decrease in organic matter content in the compost material caused an increase in P concentration in relation to the total proportion of the composting material (Galvez-Sola et al., 2010) Ash content significantly differed among treatments during the first 38 days ($p < 0.05$) (Table 3.3) with 30 % vermiculite treatment compost recording the highest ash content for the first 3 weeks. From the seventh week, ash content did not differ significantly ($p > 0.05$) among treatments.

Total calcium and magnesium content (Figure 3.5a, b) increased significantly with composting and differed significantly among treatments ($p < 0.05$). At the end of composting, the 20 % and 0 % treatments had the highest and lowest Ca concentration respectively. Magnesium content was lowest in the 0 % treatment throughout composting. The K concentration for all treatments varied within first 38 days after which it nearly stabilised for all the treatments (Figure 3.5c). The 0 and 10 % vermiculite treatments recorded higher K percentages than the 20 and 30 % vermiculite treatments.

Table 3.3: Changes in ash content and phosphorus with composting of the mixtures of vermiculite and cattle manure. (Data points are the mean of the three replicates)

	Ash content (%)				Phosphorus content (%)			
Sampling day	0 % VCM	10 % VCM	20 % VCM	30 % VCM	0 % VCM	10 % VCM	20 % VCM	30 % VCM
3	53.1[a]	52.6[a]	55.0[a]	64.8[b]	0.40[b]	0.28[a]	0.31[a]	0.31[a]
12	52.2[a]	50.9[a]	57.2[a]	64.2[b]	0.30	0.25	0.30	0.29
23	48.8[a]	53.4[ab]	56.7[ab]	62.3[b]	0.16[a]	0.21[b]	0.19[ab]	0.20[b]
38	65.6[b]	59.3[a]	55.9[a]	58.6[a]	0.17[a]	0.19[ab]	0.23[b]	0.23[ab]
48	63.8	59.8	61.8	59.1	0.32[ab]	0.29[a]	0.31[ab]	0.35[b]
60	64.7	63.0	59.7	58.0	0.29[a]	0.28[a]	0.42[c]	0.33[b]
67	59.7	63.2	66.1	59.6	0.28[a]	0.26[a]	0.38[b]	0.38[b]
76	66.3	65.6	63.8	57.9	0.36	0.39	0.43	0.35

Values in the same row followed by the same lowercase alphabetical letters are not significantly different at $p<0.05$ according to Tukey's HSD**.** The 0 % VCM, 10 % VCM, 20 % VCM and 30 % VCM represent composts from mixtures of cattle manure with 0, 10, 20 and 30 % vermiculite.

The Ca, Mg and K (Figure 3.5a, b, c) concentration of composts increased with composting as compost volume decreased. Increased cation concentration can be attributed to the reduction of compost volume. Compost volume decreases as the organic material decomposes leaving behind the inorganic components. The 10, 20 and 30 % vermiculite composts had more Ca than the 0 % treatments as a result of Ca impurities in the vermiculite used. The impurities found in the interlayer spaces include Ca, K and Na (Bergaya et al., 2006; Jayabalakrishnan 2007). The structural formula of vermiculites is often reported on the basis of the structure unit with a general formula X_4 $(Y_{2\text{-}3})$ O_{10} $(OH)_2$ M. n H_2O, where M represents the cations in the interlayer space that neutralise negative layer charge. The significant difference in Mg concentration between the vermiculite-based composts (Figure 3.5b) and the 0 % vermiculite treatment is attributed to the vermiculite in the composts which was a Mg-Al-Fe silicate clay (Jayabalakrishnan 2007).

The higher potassium content in the 0 and 10 % vermiculite treatments was due to the initially high organic material content from which K was released during decomposition. The lower K observed as vermiculite content increased could also have been due to K fixation. The increase in calcium, magnesium and potassium with composting corresponds well with an increase in electrical conductivity of the composts.

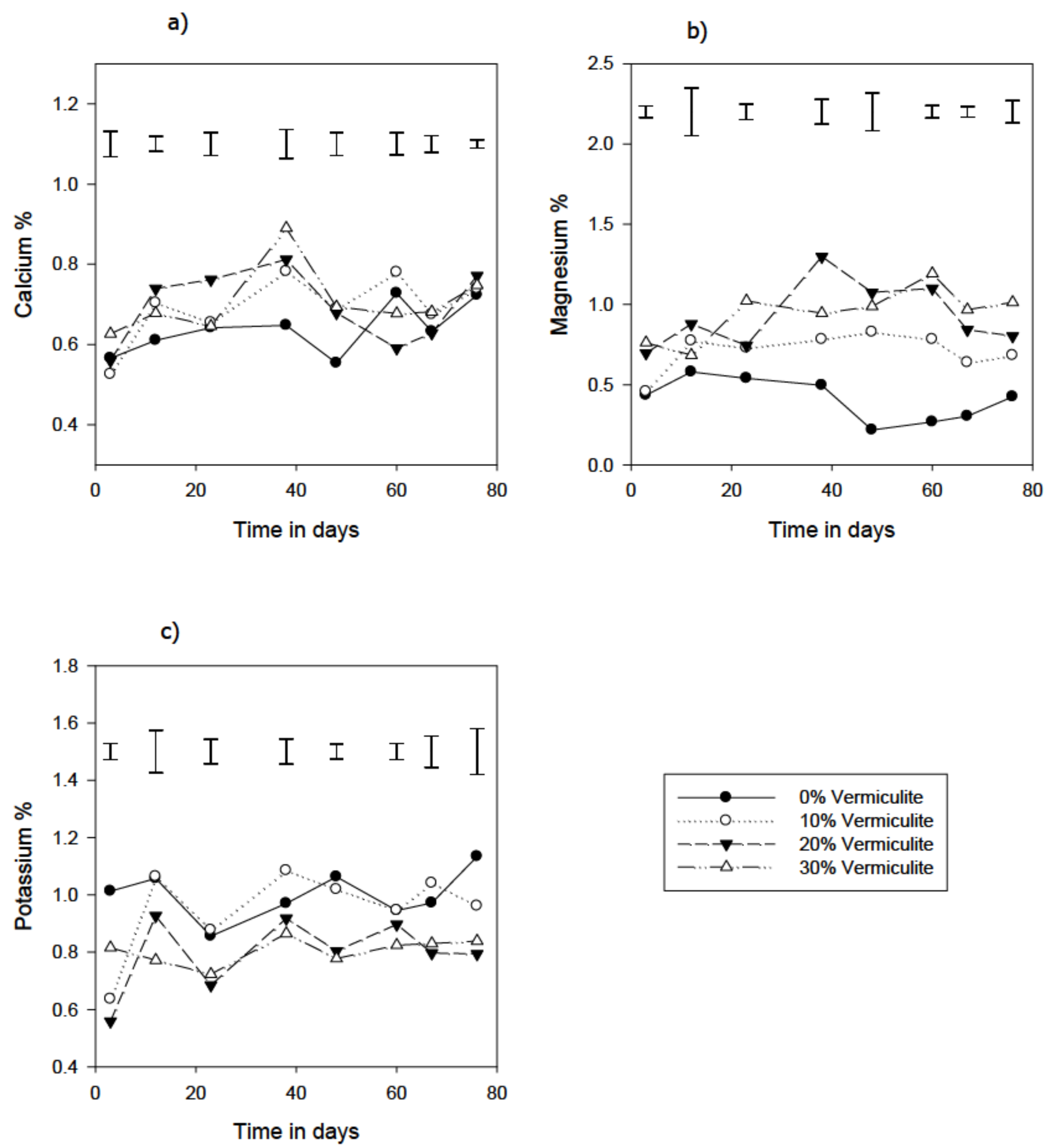

Figure 3.5: Changes in a) calcium, b) magnesium and c) potassium content with composting of the mixtures of vermiculite and cattle manure. (Data points are the mean of the three replicates).

3.4.7. Characteristics of final composts

Total C and N differed significantly ($p < 0.05$) amongst the final composts (Table 3.4). The 30 % vermiculite treatment recorded the highest total N and the least total carbon giving the lowest

C:N ratio whilst the 10 % vermiculite treatment recorded the highest C:N ratio. At the end of composting the 0, 10, 20 and 30 % vermiculite treatments had 72.2 , 74.7 , 79 and 85.5 % nitrogen as a percentage of initial N respectively, whilst the C:N was in the order 10 > 0 > 20 > 30 %. Mineral N, NH_4^+-N, and NO_3-N were highest in the 0 % vermiculite treatment and lowest in the 30 % vermiculite treatment. Although composts with vermiculite may have retained more N, as seen by the highest total N at the end of composting, its availability to crops may not be guaranteed as the available forms were lowered with an increase in vermiculite content.

While the pH and ash content of final composts did not differ significantly (Table 3.4) electrical conductivity, potassium, phophorus, magnesium and calcium differed significantlty amongst treatments ($p < 0.05$). Electrical conductivity, K and P and lower Mg content was highest in the teatment that did not have vermiculite, 0 %. At the end of composting all compost had C:N ratio less than 20, a NH_4^+: NO_3 below 1 and pH within the 6 – 7.5 range, indicating that the composts were stable and mature and suitable for crop production. Mature composts do not have negative effects of N immobilisation, oxygen depletion or phytotoxicity (Pisa and Wuta, 2013). The Ca: Mg ratios of 1.67, 1.2, 1.2 and 0.9 for the 0, 10, 20 and 30 % vermiculite composts, respectively suggest that vermiculite containing composts with Ca:Mg ratio below 1 could upset the Ca:Mg ratio of soil which should be above 2. However, this effect would depend on the amount of compost added and native Ca in the soil.

Table 3.4: Selected chemical parameters of the final vermiculite cattle manure co-composts

Chemical parameter	0 % VCM	10 % VCM	20 % VCM	30 % VCM	LSD
TC of TC^0 %	67.3^b	68.7^c	59.7^a	58.9^a	8.15
T N of TN^0 %	72.0^a	74.7^a	70.0^a	85^b	7.49
C:N	15.4^a	16.2^{ab}	14.9^b	11.4^b	2.31
Min. N of TN^0 %	10.6^c	9.12^b	9.61^{bc}	7.25^a	1.22
NH_4-N of TN^0 %	2.87^b	2.87^b	2.82^b	1.83^a	0.85
NO_3-N of TN^0 %	7.69^b	6.26^a	6.80^a	5.42^a	0.74
$NH_4:NO_3$	0.38^a	0.46^a	0.41^a	0.34^a	0.13
pH	7.39	7.26	7.15	7.26	0.52
EC (uS cm^{-1})	0.66^b	0.41^a	0.41^a	0.35^a	0.23
Ash (%)	66.3	65.6	63.8	57.9	8.50
Calcium %	0.72^a	0.82^b	0.96^d	0.92^c	0.03
Magnesium %	0.43^a	0.68^b	0.80^b	1.01^c	0.17
Ca:Mg ratio	1.67	1.2	1.2	0.9	-
Potassium %	1.13^b	0.96^{ab}	0.79^a	0.84^a	0.20
Phosphorus %	0.36^b	0.35^b	0.34^b	0.24^a	0.07

Values in the same row followed by the same lowercase alphabetical letters are not significantly different at $p<0.05$ according to Tukey's HSD. *TN^0 - initial N added; TC^0 – initial C added; TN - total nitrogen; TC - total carbon; Min – mineral. Ca – calcium, Mg – magnesium, K- potassium, P- phosphorus. The 0 % VCM, 10 % VCM, 20 % VCM and 30 % VCM represent composts from mixtures of cattle manure with 0, 10, 20 and 30% vermiculite.

3.5 Conclusion

The inclusion of 20 and 30% vermiculite in cattle manure enhanced nitrogen retention and Ca and Mg concentration. Reductions of mineral N content, K concentration, $NH_4^+:NO_3^-$ ratio and C:N ratio result from the inclusion of 20-30 % vermiculite. Inclusion of vermiculite reduced N losses and increased the concentration of basic cations. Compost with vermiculite had more K and P than the sole cattle manure compost. Further work is, however, recommended to determine the availability of nutrients, particularly nitrogen, potassium, calcium and magnesium when vermiculite cattle manure co-composts are applied to soil.

CHAPTER 4: EFFECT OF VERMICULITE-CATTLE MANURE (VCM) CO-COMPOST ON POTASSIUM FIXATION AND AVAILABILITY IN A SANDY LOAM SOIL

4.1 Abstract

The extent of potassium and ammonium fixation in soils is of agronomic importance as it allows for better understanding of what proportion of applied fertiliser K^+ and NH_4^+ will be available to crops. Vermiculite-cattle manure composts (VCM) containing 0, 10, 20 and 30 % vermiculite and soils amended with these composts were treated with nutrient K^+ equivalent to 0, 90, 180, 360 kg K ha^{-1} and incubated moist for 6 weeks at room temperature. The incubated composts and soils were analysed for exchangeable K^+ and nitric acid extractable K^+ from which fixed K^+, reserve K^+ and potassium requirement factor (KRF) were calculated. Exchangeable, fixed and reserve K^+ were seen to increase with an increase in added K^+ levels. Inclusion of vermiculite reduced exchangeable K^+ and increased fixed K^+ in the VCM composts and soils amended with these composts resulting in reduced K^+ availability for crop uptake and reduced leaching losses. Reserve K^+ in soils increased with increasing vermiculite in VCM. The KRF values for both composts and soils were significantly higher than the threshold used in most South African laboratories, which range from 2.5 to 3. Moderate fixation capacity and low reserve K^+ in soil amended with the 10, 20 and 30 % VCM composts suggests that application of these composts results in K^+ and NH_4^+ retention that may not be released during the growing season for plant use increasing fertiliser needed compared with composts without vermiculite.

Key words: *Potassium fixation, Potassium requirement factor (KRF), Reserve K, Vermiculite*

4.2 Introduction

Potassium (K) and nitrogen (N) are major fertilizer nutrients in crop production. In most soils the available K and N are not enough for optimum crop yields and organic and inorganic fertilizer materials are often applied to address the deficiencies. Potassium is taken up as K^+, while N can be absorbed either as the cation, NH_4^+ or the anion, NO_3^- (Marschner, 2002). Many soils have the ability to bind K^+ and NH_4^+ in such a manner that they cannot be readily available for plant uptake or replacement by other cations (Nommik and Vahtras, 1982). The K^+ and NH_4^+ ions have similar ionic properties viz they are monovalent with 0.133 and 0. 143 nm radii, respectively (Ajazi et al., 2013). Consequently they compete for the same exchangeable and non-exchangeable sites on soil particles. When K^+ and NH_4^+ are trapped between the silicate sheets they cannot participate in soil exchange reactions (Nommik, 1965) and are unavailable for plant uptake. Research has emphasized the importance of 2:1 phyllosilicate vermiculite and hydrous mica in controlling K^+ and NH_4^+ fixation (Sparks and Haung, 1985; Sparks, 1987; Fanning et al., 1989; Murashkina et al., 2007).

Potassium deficiency, reported in cotton grown in soils containing significant amounts of vermiculite, hydrous biotite and biotite micas (Pettygrove et al., 2011), has been attributed to fixation. Nieder et al. (2011) also reported fixation of applied NH_4^+ in soils with high vermiculite contents. Soils of the sugarcane industry in South Africa have been found to vary in K fixation capacity and reserve K due to differences in mineralogical composition (Elephant et al., 2019). Soils with high fixation capacity bind part of the applied fertilizer K^+ and NH_4^+ making it less available for plant uptake, which can result in deficiencies, especially for smallholder farmers who usually apply less than the recommended fertilizer amounts. The results of Chapter 3 showed that incorporation of vermiculite during composting of cattle manure improves the composting process and the quality of the product (Pisa et al., 2020). The total K in the composts with vermiculite (especially 30 %), based on digestion with sulphuric acid, was lower than that without vermiculite mainly because of lower manure in the mixture. The digestion method is usually used for analysing organic materials (plant materials and manures and composts). The digestion method used for total K and the extraction of ammonium-N do not account for the ions held in the interlayer spaces of minerals like vermiculite. The proportion of

K^+ and NH_4^+ tightly held in the interlayer spaces needs therefore to be determined in order to clearly understand the effects of co-composting cattle manure and vermiculite on K^+ and NH_4^+ fixation.

The application of the VCM composts in soils has the potential to improve the soils physico-chemical conditions such as aeration, nutrient retention and water holding capacity but appreciable amounts of vermiculite can induce immediate K^+ and NH_4^+ unavailability due to fixation. It has, however, been shown that some of the fixed K (non-exchangeable K) can be released through mineral weathering (reserve K) during the growing season, improving K availability (Martin and Sparks, 1983; Srinivasarao et al., 1999; Öborn et al., 2005), which could also happen in VCM composts. Reserve K refers to the fixed K portion that becomes available to plants when all solution and exchangeable K has been exhausted. While the presence of vermiculite in the VCM composts could increase the K^+ and NH_4^+ fixation of the soils, the fixation sites could be saturated by the ions produced from the decomposition of cattle manure during composting. The presence of organic material in the composts can also promote the release of fixed K^+/ NH_4^+. Compost decomposition promotes the activity of the soil microflora and microbial K and N uptake which indirectly affect the K/ NH_4^+ fixed pool. Plants can take up soluble or exchangeable NH_4^+ in the vicinity of NH_4^+ fixing clays, vermiculite in this case, and thus promote diffusion of ions out of the interlayers. There is a paucity of studies on K^+ and NH_4^+ fixation and reserve K in the composts of cattle manure-vermiculite mixtures and in soils amended with such composts. The study of K^+ and NH_4^+ fixation in soils is of particular agronomic importance as it allows for a better understanding of the soil behaviour to the application of NH_4^+ and K^+ fertilizers and contributes to a more effective evaluation of crop fertiliser needs. It is therefore important to determine the effect of vermiculite-cattle manure (VCM) composts on NH_4^+/K^+ fixation capacity of soils before recommendation for use.

Several methods have been proposed for the determination of NH_4^+ fixation in soil. Comparison of some of the methods has shown widely different results for a given amount of applied NH_4^+ (Nieder et al., 2011). The variability in results can be explained by the fact that it is difficult to distinguish between native fixed and recently fixed NH_4^+. These are affected by soil type, mineralogical composition, agro-climatic conditions and methodology (Nieder et al., 2011). Different methods have shown variable results. Moyano and Gallardo (1988) obtained significantly lower values with the method of Mogilevkina (1964) than the Silva and Bremner (1966) method. which gave higher values than the Dhariwal and Stevenson (1958) and Mogilevkina (1964) methods. This was attributed to the varying effectiveness of the methods used to remove organic matter interference. Organic matter will decompose during incubation and nitrogen released undergoes many transformations resulting in less accurate values. A number of pre-treatment methods (dry combustion at 400°C and oxidation with hot H_2O_2 or KOH or alkaline KOBr solution) to remove organic matter have been used by a number of researchers and again variable results were obtained. Nitrogen in soil also tend to undergo a number of transformations depending on soil conditions like moisture, microbial populations and soil additions. The NH_4^+ can also be oxidized to nitrite and NO_3^- through microbial activity. Addition of NH_4^+ fertilizers also affect the microbial activity of soil and thus N transformations, which would lead to inaccurate results. It is because of this complication that this study focused on effect of VCM composts on K fixation, with the assumption that the amount of K fixed will directly translate to the amount of NH_4^+ that could also be fixed as the mechanism of NH_4^+ fixation is closely related to that of K^+. The K^+ in soil does not undergo many transformations as available potassium is only found in the K^+ form in soils. The results would give an indication on whether ammonium will be fixed if VCM composts were applied to soils. The aim of this study was to determine the effects of vermiculite content in VCM composts on K fixation capacity and reserve K in the composts and compost amended soils.

4.3 Materials and Methods

Two experiments were set up to determine the K/NH_4^+ fixation capacity of (i) VCM composts and (ii) soils amended with the VCM composts in March 2019. The study with K^+ was also used as a proxy for the behaviour of NH_4^+ as the two ions have similar fixation and release mechanisms (Ajazi et al., 2013).

4.3.1 K fixation in co-composts of vermiculite and cattle manure

Four co-composts of vermiculite - cattle manure (VCM) were used in this experiment. The trial set up in a completely randomised design with each treatment replicated three times. The different co-composts had 0, 10, 20 and 30 % vermiculite and were produced via the composting procedure described in Chapter 3 (Pisa et al., 2020). Table 4.1 shows the chemical properties of the co-composts used in the study.

Table 4.1: Selected chemical properties of the vermiculite cattle manure co-composts used

Chemical parameter	0 % VCM compost	10 % VCM compost	20 % VCM compost	30 % VCM compost	LSD
pH	7.39	7.26	7.15	7.26	0.52
EC (µS cm^{-1})	0.66^{b}	0.41^{a}	0.41^{a}	0.35^{a}	0.23
Total P %	0.36^{b}	0.35^{b}	0.34^{b}	0.24^{a}	0.07
Mineral N %	0.076^{b}	0.067^{a}	0.09^{c}	0.096^{c}	0.01
Total N %	1.26^{a}	1.23^{a}	1.17^{a}	1.50^{b}	0.1
Total C%	19.4^{b}	19.9^{b}	17.3^{ab}	17.0^{a}	2.34
C:N ratio	15.4^{a}	16.2^{ab}	14.9^{b}	11.4^{b}	2.31
Total K %	1.13^{b}	0.96^{ab}	0.79^{a}	0.84^{a}	0.20
Total Ca %	0.72^{a}	0.82^{b}	0.96^{d}	0.92^{c}	0.03
Total Mg %	0.43^{a}	0.68^{b}	0.80^{b}	1.01^{c}	0.17

Values in the same row followed by the same lowercase alphabetical letters are not significantly different at $p<0.05$ according to Tukey's HSD. 0 % VCM compost = cattle manure compost without vermiculite; 10 % VCM, 20 % VCM and 30 % VCM = cattle manure composts with 10, 20 and 30 % vermiculite, respectively in the original mixture.

Ammonium acetate extractable K (Kextr) was determined before treating the composts with KCl (Okalebo et al., 2002). The composts (10 g) were treated using 0 (control), 50, 100, 200 mg kg^{-1}, as KCl, and the treatments were replicated three times. All composts were adjusted to near field capacity and incubated, at room temperature (20 - 25^{o}C) for 42 days. The composts were kept moist throughout the incubation period. After incubation, the compost samples were allowed to air-dry and extractable K was determined with 1 M ammonium acetate as described in Okalebo et al. (2002). The amount of K fixed was calculated using the formula in Goli -Kalanpa et al., (2008) and Najafi- Ghiri and Abtahi, (2013)

$$\text{Fixed K} = \text{K added} + \text{K extractable before treatment} - \text{K extractable after treatment} \quad (4.1)$$

Where K added refers to the K added as KCl; K extractable before treatment is the exchangeable K determined before the addition of KCl; K extractable after treatment is the exchangeable K determined at the end of the incubation period

Fixed K is conventionally determined with an ammonium salt, which is also the most widely used method of estimating plant available K (Novozamsky and Houba, 1987, Portela et al., 2019). Its quantification relies on the principle that applied K that cannot be replaced by the ammonium cation corresponds to the fixed K.

4.3.2 Fixation capacity of soils amended with VCM co-composts

The soil used in the study was a sandy loam soil, derived from granite, from Marondera University of Agricultural Science and Technology (MUAST) farm in Marondera. The soils are classified as Marondera 6G according to the Zimbabwean soil classification (Thompson 1965; Nyamapfene, 1991) and a Lixisols according to FAO (1998). The soils are essentially para-ferrallitic but tend to integrate towards the orthoferrallitic group as they dry out quickly at the end of the rainy season limiting the time for weathering (Thompson, 1965). This accounts for the presence of ferrallitic clay fractions (biotite and muscovite) which can fix potassium and ammonium. The soil used in the study has a sandy loam texture with a pH of 5.3 and mineral N and P are 8 and 54 mg kg^{-1} respectively. The soil also had 0.2, 0.84 and 0.41 me % of K, Ca, Mg respectively.

The co-composts of cattle manure with 0, 10, 20 and 30 % vermiculite were applied to the soil at a rate equivalent to 5 t ha^{-1}. Soils were amended by adding 2.5 g of the respective co-compost to 1000 g of soil and mixing them thoroughly. Before treating with KCl, the CEC, organic C and extractable cations (K, Ca, and Mg) of the amended soils were determined. The amended and control soil samples were then treated with KCl by placing 10 g of amended soil in 50 ml plastic bottles and adding 10 ml of KCl solutions of concentrations of 0, 50, 100, 200 mg K L^{-1} (equivalent to 0, 90, 180 and 360 kg K ha^{-1}, respectively) replicated three times. The application rates were chosen to accommodate scenarios where some farmers do not apply fertilisers and some where farmers apply too much. The soils were arranged in a completely randomised design then incubated at room temperature 20-25^{o}C for 42 days and air dried before analysing for exchangeable K (ammonium acetate), which was used for calculation of the amount of fixed K. Potassium requirement factor (KRF) for each amended soil was determined from the inverse of the slope of the graph of exchangeable K vs K added. Reserve K was also determined for each sample (Pratt, 1965).

4.3.3 Laboratory analysis

Ammonium acetate extractable K (Exchangeable K)

The method described in Okalebo et al., (2002) was used to determine ammonium extractable K. Air dried compost/soil (5g) were weighed into clean plastic containers and 100ml of 1M ammonium acetate (NH_4OAc) added. The contents were shaken for 30 minutes on a reciprocal shaker at 200 rpm and filtered through Whatman No 42-filter paper. Potassium concentration was determined by flame photometry (Okalebo et al., 2002). The measured K was used to plot extractable K vs added K and the potassium requirement factor (KRF) determined for each soil. Fixed K was calculated by subtracting extractable K from incubated soil from the sum of added K and initial K in untreated soil.

Reserve K

The compost/soil mixtures (2.0 g) were suspended in 20 ml 1M HNO_3 and boiled in a water bath at 113°C for 25 minutes (Pratt, 1965). After cooling, contents were filtered and K was determined from the extract by flame photometry. Reserve K calculated as the difference between nitric extractable K and exchangeable K.

4.3.4 Statistical analysis

Data was analysed in Genstat 14 by subjecting it a two-way analysis of variance (ANOVA) with added K level and compost treatment as the factors. Least significance difference level ($LSD_{0.05} = t_{0.05}$ x SE0.05) was used to separate means and graphs were drawn in Sigma Plot version 10 to show the relationship between added K and exchangeable K.

4.4 Results

Selected properties of soils amended with different VCM composts differed significantly ($p<0.05$). Organic matter, potassium and CEC were highest on the soil amended with 0 % VCM composts. OM and exchangeable K decreased with an increase in vermiculite in VCM composts used while Ca and Mg increased. Soils with 20 and 30 % VCM had similar soil properties, Table 4.2.

Table 4.2: Selected properties of soil amended with different composts before adding K.

	Unamended soil	**0 % VCM**	**10 % VCM**	**20% VCM**	**30 % VCM**
$pH_{(CaCl)}$	5.67^{a}	5.80^{b}	5.83^{b}	5.80^{b}	5.79^{b}
% OM	0.16^{a}	0.40^{c}	0.38^{c}	0.26^{b}	0.24^{b}
K_{exch}, mg kg^{-1}	41.9^{a}	108.3^{c}	105.3^{c}	76.7^{b}	79.1^{b}
Ca_{exch}, mg kg^{-1}	30.4^{a}	44.1^{b}	44.9^{bc}	52.0^{c}	50.0^{c}
Mg_{exch}, mg kg^{-1}	11.0^{a}	10.3^{a}	14.0^{b}	15.3^{bc}	16.3^{c}
CEC me%	11.1	15.1	12.9	14.6	14.8

Values in the same row followed by the same lowercase alphabetical letters are not significantly different at $p<0.05$ according to Tukey's HSD. OM refers to organic matter. The 0 % VCM, 10 % VCM, 20 % VCM and 30 % VCM represent composts from mixtures of cattle manure with 0, 10, 20 and 30 % vermiculite.

4.4.1 Exchangeable and fixed K in VCM co-composts incubated with increasing K levels

Exchangeable K differed significantly among treatments and was in the order 0 >10 >20 > 30 % VCM at all levels of K added (Figure 4.1). The exchangeable K values ranged from 321 -359 mg kg^{-1} for 0 % VCM, 227 to 332 mg kg^{-1} for 10 % VCM, 150 to 195 mg kg^{-1} for 20 % VCM, and 110 to 142 mg kg^{-1} for 30 % VCM. Exchangeable K generally increased with an increase in added K levels.

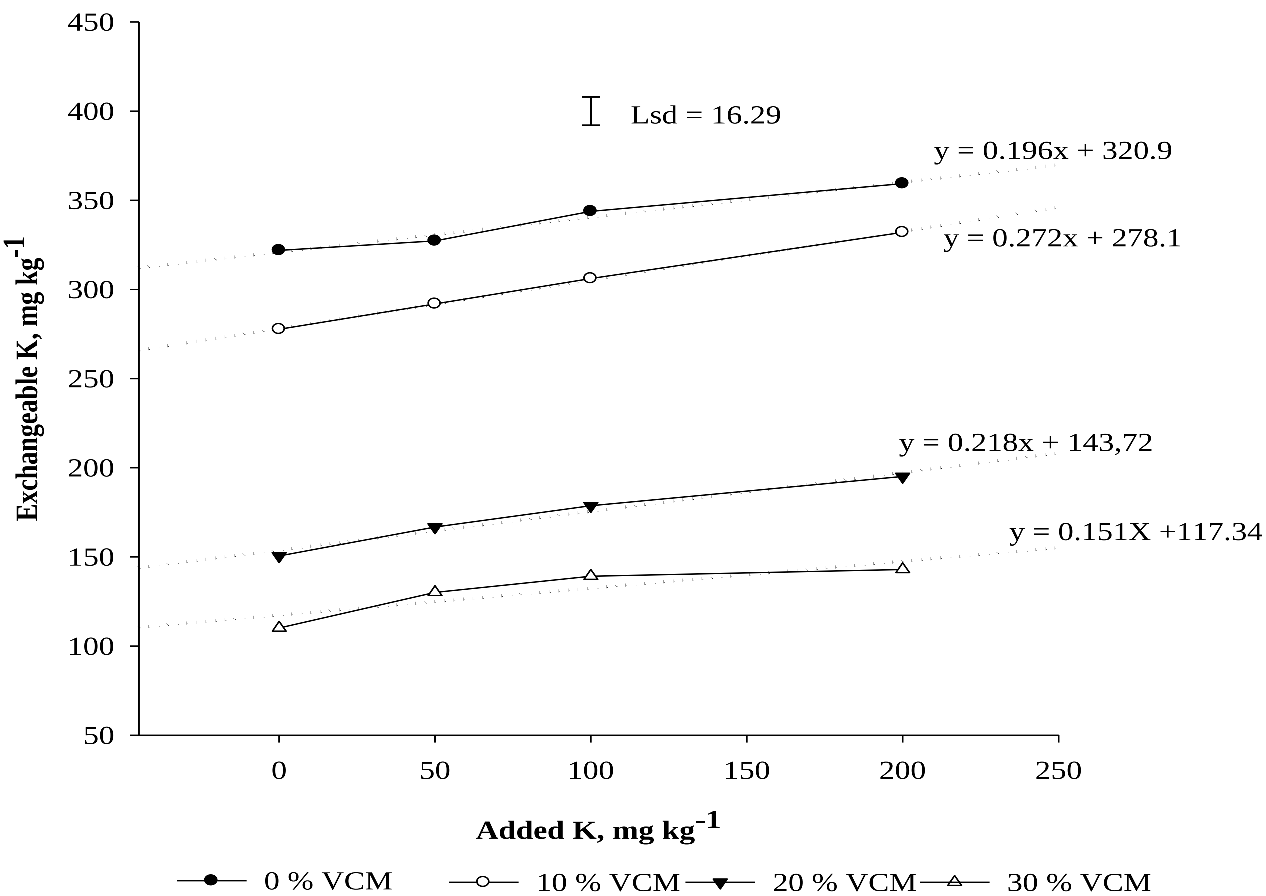

Figure 4.1: Relationship between added K and exchangeable K in vermiculite cattle manure co-composts. The 0 % VCM, 10 % VCM, 20 % VCM and 30 % VCM represent composts from mixtures of cattle manure with 0, 10, 20 and 30% vermiculite. Dotted line represent regression between added K and exchangeable K.

The amount of K fixed differed among treatments, $p < 0.05$, and it increased with an increase in added K and the 0 % VCM compost fixed the least K, which increased with an increasing vermiculite in the compost, at all added K levels (Table 4.3).

Table 4.3: Fixed K (mg kg^{-1}) in vermiculite cattle manure co-composts incubated with increasing rate of fertilizer K.

Added K levels kg ha^{-1}	Fixed K in mg kg^{-1}				
	0 % VCM	10 % VCM	20 % VCM	30 % VCM	LSD (p<0.05)
0	-1.0^{a}	49.9^{c}	72.9^{d}	77.7^{de}	
90	20.5^{b}	94.6^{e}	107^{f}	116^{f}	
180	84.8^{e}	128^{g}	155^{h}	198^{i}	
360	155^{h}	233^{j}	268^{k}	268^{k}	10.91

Values followed by the same lowercase alphabetical letters are not significantly different at p<0.05 according to Tukey's HSD. The 0 % VCM, 10 % VCM, 20 % VCM and 30 % VCM represent composts from mixtures of cattle manure with 0, 10, 20 and 30 % vermiculite.

4.4.2 Reserve K in co-composts incubated with increasing fertilizer K levels

Reserve K in the composts differed significantly among all the treatments at all levels of added K (Table 4.4). The reserve K decreased with an increase in vermiculite in the co-compost. The 0 and 10 % VCM composts had significantly ($p<0.05$) more reserve K than the 20 and 30 % VCM co-composts at all added K levels. Overall, the reserve K values for all the treatment combinations ranged from 413 to 769 mg K kg^{-1} (1.05 to 2 cmolc K kg^{-1}).

Table 4.4: Reserve K in vermiculite cattle manure co-composts incubated with increasing rate of fertilizer K (kg ha^{-1}).

Added K kg ha^{-1}	**Reserve K mg kg^{-1}**				
	0 % VCM	10 % VCM	20 % VCM	30 % VCM	LSD (p<0.05)
0	696^{b}	671^{b}	426^{a}	433^{a}	
97.5	668^{b}	599^{ab}	413^{a}	423^{a}	
195	685^{b}	650^{b}	456^{a}	465^{ab}	
390	769^{b}	708^{b}	519^{ab}	471^{ab}	188.5

Values followed by the same lowercase alphabetical letters are not significantly different at p<0.05 according to Tukey's HSD. The 0 % VCM, 10 % VCM, 20 % VCM and 30 % VCM represent composts from mixtures of cattle manure with 0, 10, 20 and 30 % vermiculite.

4.4.3 Exchangeable and fixed K in soils amended with co-composts and incubated with increasing K levels

Exchangeable K significantly differed ($p < 0.05$) among treatments at all levels of K added. The unamended soil recorded the least exchangeable K at all added K levels while the 0 % VCM treatments recorded the highest (Figure 4.2). Exchangeable K, however, decreased with increasing vermiculite content in co-compost at all added K levels.

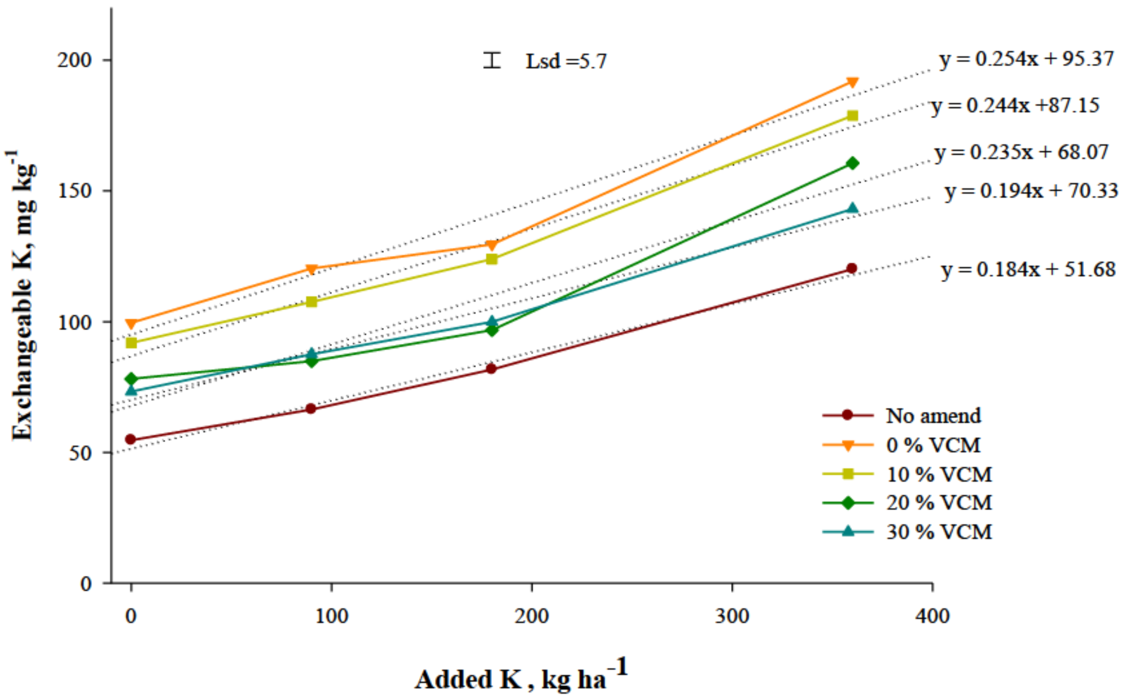

Figure 4.2: Relationship between K applied and exchangeable K in soils amended with vermiculite cattle manure composts. The 0 % VCM, 10 % VCM, 20 % VCM and 30 % VCM represent composts from mixtures of cattle manure with 0, 10, 20 and 30 % vermiculite while the no amend represents the treatment that did not receive any composts. Dotted line represent regression between added K and exchangeable K

The amount of K fixed after 6 weeks of incubation was significantly different among the treatments, ($p < 0.05$) at all levels of added K, with the lowest observed in the unamended soil (Table 4.5). Fixed K increased with both an increase in added K and amount of vermiculite. The KRF values were 5.55, 3.95, 4.10, 4.35 and 4.55 for the no amendment, 0, 10, 20 and 30 % VCM treatments, respectively. The no amendment had the highest KRF while the 0 % VCM had the least.

Table 4.5: Fixed K and Potassium Requirement Factor of soils amended with vermiculite cattle manure co-composts and incubated with increasing rates of fertilizer K.

	Fixed K in mg kg^{-1}					
Added K kg ha^{-1}	Control	0 % VCM	10 % VCM	20 % VCM	30 % VCM	LSD (p<0.05)
0	0	0	0	0	0	
90	19.1^{a}	28.9^{b}	37.5^{c}	39.3^{c}	49.2^{d}	
180	65.5^{e}	71.5^{e}	81.8^{f}	80.9^{f}	91.6^{g}	
360	115^{h}	117^{h}	122^{h}	136^{i}	142^{i}	6.9
KRF	5.55	3.95	4.1	4.35	4.55	

Values followed by the same lowercase alphabetical letters are not significantly different at p<0.05 according to Tukey's HSD. The 0 % VCM, 10 % VCM, 20 % VCM and 30 % VCM represent composts from mixtures of cattle manure with 0, 10, 20 and 30 % vermiculite. NB: where treatments were not treated with K (0 mg kg^{-1}) the assumption was that there was no K to fix as K was not added K to the samples.

4.4.4 Reserve K in soils amended with co-composts incubated with increasing K levels.

Reserve K increased with increasing amounts of added K for all the compost treatments and was significantly different among the treatments ($p < 0.05$; Table 4.6). The unamended soil recorded the least while 30 % VCM had the highest amount of reserve K at all added K levels. An increase in vermiculite content in composts resulted in an increase in reserve K.

Table 4.6: Reserve K of soils amended with vermiculite cattle manure co-composts and incubated with increasing rates of fertilizer K.

Added K kg ha-1	Reserve K in mg k^{-1}					LSD (p <0.05)
	Control	0 % VCM	10 % VCM	20 % VCM	30 % VCM	
0	86.2^{a}	110^{b}	122^{bc}	128^{c}	147^{de}	
90	89.5^{a}	131^{c}	154^{de}	151^{de}	158^{e}	
180	98.2^{ab}	169^{ef}	174^{f}	182^{f}	201^{g}	
360	145^{d}	183^{f}	182^{f}	230^{h}	237^{h}	12.23

Values followed by the same lowercase alphabetical letters are not significantly different at p<0.05 according to Tukey's HSD. The 0 % VCM, 10 % VCM, 20 % VCM and 30 % VCM represent composts from mixtures of cattle manure with 0, 10, 20 and 30 % vermiculite.

4.5 Discussion

The general increase of exchangeable K in VCM compost and amended soil with increasing K added, was a result of higher K added, and is consistent with results by Khan et al., (2014), who observed that exchangeable K increased as more K was applied. The increase in the capacity to fix K by both composts and amended soil also resulted in a decrease in exchangeable K. The increased K fixation and reduction in exchangeable K with increase in vermiculite (Figure 4.1 and Table 4.5), indicates that a significant proportion of the added K is fixed. Vermiculite is known to have a high K (and ammonium-N) fixation capacity and the more there is in the compost applied the higher the amount of K fixed. High vermiculite content explained the difference in fixation capacities of different soil (Portela et al., 2019) and thus the same can be used to explain high fixation with increasing vermiculite content. The added K goes into the non-exchangeable K pool of the soil thus lowering exchangeable K. The optimum (target) soil exchangeable K for optimum maize production, irrespective of yield target of maize, is 120 mg kg^{-1} (Saïdou et al., 2018). The initial concentrations of exchangeable K in the soil (78 mg K kg^{-1} (0.2 me %), indicated that fertiliser K would be required to reach the optimum required for maize production. The target was achieved when 180 kg K ha^{-1} was added to the soils amended with 0 and 10 % VCM treatment, but not 20 and 30 % VCM and the unamended control, which needed 360 kg K ha^{-1}. This observation was explained by the higher K added in the 0 and 10 % VCM composts (Table 4.1) and the compost amended soils (Table 4.2). The finding suggests that up to 360 kg K ha^{-1} is required when using VCM composts with 20 % vermiculite or higher, and the control, when compared with compost with 10 % or less vermiculite which can achieve the optimum amount when 180 kg ha^{-1} is applied. The findings are, however, based on a laboratory incubation experiment where temperature and moisture were kept optimum and as such the availability of the K in the presence of plants and under field conditions needs to be established. In order to properly account for K fixation, the actual fertilizer recommendation has to be based on the potassium requirement factor (KRF), fertilizer K that would be required to raise exchangeable K by one unit (Johnston et al., 1999; Elephant et al., 2019).

The increase in fixed K with increasing amounts of K input and vermiculite content in the co-composts used, shows the contribution of vermiculite in fixation of K. Goli-Kalanpa et al. (2008) and Portela et al. (2019) reported increased K fixation rates when soils had appreciable amounts of vermiculite content present. The importance of vermiculite in K fixation has been reported in a number of studies (Barshad 1954 and Murashkina et al., 2007; Portela et al., 2019). Vermiculite is a phyllosilicate clay with a high capacity to fix K in its interlayer space (Douglas 1989; Fanning et al., 1989; Sawhney 1972) especially on drying, making it unavailable for plant uptake. The composts used in this trial had an appreciable amount of vermiculite. The application of these vermiculite-based composts in sandy loam soils can result in fixation of added ammonium as the mechanism of ammonium fixation is similar to that of K fixation and can result in initial N deficiency as N is made unavailable for plant uptake. Kowalenko and Cameron, (1976), Kowalenko (1978), Chantigny et al., (2004) and Rider et al., (2006) observed that 32-59 % of the added NH_4^+ is fixed within a short period of time in soils with high phyllosilicate clays. The soil used in this trial generally had high amounts of fine sand and silt which play a very important role in cation fixation if they contain fixing minerals like illite and vermiculite. The soils are derived from alkali feldspar granite with appreciable amount of muscovite and biotite which are phyllosilicate minerals capable of fixing K (Thompson 1965) explaining why fixation was also observed in the unamended soil. Fixation occur in particle size fractions from clays through to coarse sand (Fanning et al., 1989, Murashkina et al., 2007) as long as fixing minerals are present. Rider et al., (2006) observed the high NH_4^+ fixation potential (NH_4^+ fixation is analogous to K^+ fixation) when they studied ammonium fixation in decomposed granite substrates of Northern California. The K fixation was generally high for all treatments with soils fixing almost 50 % of the added K. Similar results were observed when 100 and 200 mg kg^{-1} of K were added to unamended soil (Table 4.5). The observation can be explained by the presence of the phyllosilicate minerals, muscovite and biotite which fix K. The fixation of both K^+ and NH_4^+ is influenced by clay content, clay mineralogy, pH and CEC. Fixation reduces the availability of K and NH_4^+ for uptake by crops even at high K/ NH_4^+ applications (Zhang and Sun., 2014).

The KRF values for all the treatments (composts and soils) were higher than the average 2.5 to 3 used by South African laboratories when formulating K requirements (Elephant et al., 2019). The KRF is an important factor for K fertilizer formulations asincluding it avoids over- and under-application of K fertilisers. Values of KRF greater than 3 would mean fertilizer recommendations based on a KRF of 3 would underestimate K required, in soils amended with these vermiculite-based compost and thus the need to account for fixation. Brady and Weil (2007) reported that a KRF values less than 2 indicated a soil could release K with wetting and drying. Higher reserve K observed in the amended soils, however, can result in a significant reduction in soil K requirements as it affects K supplies for crop use.

The amount of reserve K in all treatments was low according to the classification in Elephant et al., (2019) which classified reserve K below 0.8 $cmol_c\ kg^{-1}$ (312 $mg\ kg^{-1}$) as low. This is the amount of non-exchangeable K that becomes available when exchangeable K has been depleted and is part of fixed K trapped in silicate inter layer spaces. Reserve K for all the treatments was below 312 $mg\ kg^{-1}$ range. Application of the VCM composts improves K retention due to fixation. However, the low reserve K and high K fixation observed meant that the non-exchangeable K may not be released for plant use and the application of VCM co-composts means that more fertiliser K is required to meet plant requirements. Where soil was not treated with fertiliser K, reserve K increased from 0.220 to 0.376 $cmol_c\ kg^{-1}$ with increase in vermiculite. This was also true for the treated soil. Based on the decision tree in Elephant et al. (2019), the fertiliser K recommendation need to be calculated to account for the high K fixation and low reserve K by multiplying the original K requirement by KRF/3.0. For example, the recommended K for the unamended soil; Fertiliser K = (120-78) x 3 x 5.55/3 = 233 kg K ha^{-1}).

In cases where reserve K is high the non-exchangeable pool can actually become the main source for potassium for plants (Raheb and Heidari 2012) when the K is released into soluble and exchangeable forms. This notion of reserve K being a source of K for plants is shared by Nieder et al., (2011) with NH_4^+, as they suggested that NH_4^+ fixation is a way of building up soil N to enhance crop recovery and lessen N losses to the environment. In this trial, however, the application of VCM composts resulted in the fixation of more than 50 % of the applied K and low reserve K (Elephant et al., 2019). This means that of the fixed K only a small portion would be available when exchangeable and solution K depleted. The application of vermiculite cattle manure composts to sandy loam soils can result in N and K retention however the low reserve K means the fixed nutrients cannot be used in the same growing season. A review by Nieder et al., (2011) give variable time length for the release of fixed N which is dependent on environmental conditions. Dou and Steffens (1995) found reported that 90 - 95 % of fixed N is released over a 14-week period in the soil planted with perennial ryegrass under greenhouse conditions while Kowalenko (1978) reported 66 % release under field conditions, in the first 86 days after fixation.

With the composts however reserve K decreased with an increase in vermiculite content which would not have been expected. This can be explained by the fact that the decomposition of the organic material contributed more to the K recorded. This is supported by the fact that exchangeable K was much higher that the added K and the additional K originated from the organic fraction of the compost. Where no K was added, reserve K decreased with increase in vermiculite, possibly because of decline in organic matter contribution as the proportion of vermiculite increased.

4.6 Conclusion

Inclusion of vermiculite at 20 and 30 % rate increases fixed K and KRF and reduces exchangeable and reserve K in the VCM composts and soils amended with these composts. The composts increased soil K retention. Low exchangeable K and reserve K, however, meant low K availability for crop uptake resulting in an increased fertiliser K requirement. Moderate fixation capacity and low reserve K in soil amended with the 10, 20 and 30 % VCM composts suggests that application of these composts results in K^+ and NH_4^+ retention and may not be released during the growing season. It can be concluded that inclusion of vermiculite in cattle manure composts results in the need for higher fertiliser requirement than where vermiculite was not included, but less than the requirements for the control soil. Higher fertiliser requirements make it difficult to recommend VCM to smallholder farmers who are already resource constrained. It should also be noted that K saturation was not reached even at high K^+ application rate. It is also possible to that vermiculite application results in K^+ fixation without the farmers realising, however if the soils are able to release the K^+ as reserve K^+ then K^+ fixation can be viewed as a way of building a soil K pool which can be used when K^+ becomes deficient in the soil. The findings in this study, however, were based on laboratory incubation experiments and the availability of K and N, as affected by VCM composts needs to be tested with growing plants.

CHAPTER 5: EARLY GROWTH, NUTRIENT UPTAKE AND NUTRIENT RETENTION IN A SANDY LOAM SOIL AMENDED WITH CO-COMPOST OF CATTLE MANURE WITH INCREASING VERMICULITE COMPOSITION

5.1 Abstract

Two pot experiments were set up to determine the effects of vermiculite-cattle manure (VCM) compost application (i) on early maize growth, nutrient uptake and selected properties (ii) moisture retention of sandy loam soil from Marondera University of Agricultural Sciences and Technology farm. The soil was amended using 0, 10, 20 and 30 % VCM co-composts at a rate of 5 t ha^{-1}. Positive (recommended fertiliser) and negative control (no amendment) treatments were included. Maize seed was sown in pots with a leachate collecting system and allowed to grow for 70 days. Leachate was collected and analysed for N, P, Ca, Mg, Na and K while number of leaves and plant height were recorded biweekly from 2 to 6 weeks after emergence. Above-ground dry matter yield was determined and analysed for N, P, K, Ca and Mg. Soils were collected at the end of the trial and analysed for pH, total N, extractable P, and exchangeable K, Ca and Mg. In the moisture retention trial, pots were irrigated with 400 ml of water once a week and soil samples were collected every 3 days and gravimetric water content determined. In the first pot experiment, the negative control recorded the least maize growth, nutrient uptake while Ca, Mg, K and Na in leachate were negligible. Leachate P was observed in all treatments on day 3 and thereafter only the positive control had measurable concentrations. Dry matter yield, N and P uptake did not significantly differ between the positive control 0 % and 10 % VCM treatments and were higher than the 20 and 30 % VCM treatments for both trials. The N, P and K uptake decreased with increasing vermiculite content in compost while Ca and Mg uptake increased. The P, K and Ca in soils did not significantly differ between the positive control and the 10, 20 and 30 % treatments. Total N and exchangeable Ca and Mg in soil increased with increasing vermiculite content in the compost. Moisture retention increased with increasing vermiculite content in the composts. The application of VCM compost to a sandy loam soil improved early maize growth, plant nutrient uptake, and dry matter yield, selected soil quality parameters after harvest and moisture retention.

Key words: *Dry matter yield, early growth, nutrient uptake, vermiculite cattle manure composts*

5.2 Introduction

Escalating costs of inorganic fertilizers have encouraged many smallholder farmers to make use of organic resources, including manures and composts. Organic fertilizers not only improve soil fertility and yields, they reducing the input cost of mineral fertilizers while promoting sustainable environments (Ahmad et al. 2006; Garrat et al., 2018). In developing countries, nutrient imbalances in soil and environmental pollution are common as smallholder farmers continuously apply inorganic fertilizers with very little prowess. Organic resources are known to improve soil physico-chemical properties, including nutrient adsorption and availability, water holding capacity (Tian et al., 2012), electrical conductivity (Scotti et al., 2013), pH, microbial diversity and activity (Aleer et al., 2014; Fanish 2017) and soil organic matter (Agbede et al., 2008; Tian et al., 2012). These attributes of soil fertility are fundamental for long-term sustainable crop production. The organic wastes are a valuable plant nutrient source, and can be converted into high quality soil amendments via composting (Khatun et al. 2016). However, nutrient loss during composting, through processes such as ammonification and leaching can be substantial leading to reduced nutrient and agronomic value of the compost (Latifah et al., 2015).

The agronomic value of composts can, however, be improved by co-composting with mineral additives like vermiculite. The inclusion of vermiculite in the composting of cattle manure has been reported to improve compost quality, producing a high potential organic fertiliser, with improved nitrogen retention, enhanced Ca and Mg concentrations and C:N ratio (Chapter 3; Pisa et al., 2020). Preliminary incubation experiments have shown that amending soils with vermiculite-based cattle manure composts results in K fixation (and possibly ammonium-N) and higher reserve K, than composts without vermiculite (Chapter 4). The moderate fixation capacity and low reserve K (Elephant et al., 2019) in soils amended with VCM composts suggests that application of these composts results in K^+ and by proxy NH_4^+ retention that may be released to a limited extent during the growing season. The results showed that between 180 and 360 kg K ha^{-1} would be required to reach the optimum soil test K of 120 mg kg^{-1}. However, some smallholder farmers apply composts at less than 5 t ha^{-1} and compound fertiliser 7N: 14 P_2O_5: $7K_2O$, as basal fertiliser, to supply 35 kg P_2O_5 ha^{-1}. The overall effects of the improved nutrient availability in VCM composts, K/NH_4^+ fixation and reserve K, on crop growth and nutrient uptake needs to be understood. It is also reported that vermiculite positively influences soil moisture retention (Li 2001). Vermiculite has spaces between its layer which are easily penetrated by water and thus it retains water. The application of VCM composts introduces vermiculite to soil. This study therefore sought to determine the effects of increasing vermiculite content in co-composts with cattle manure, as basal fertiliser, on early maize growth, nutrient uptake, soil moisture retention and selected soil quality parameters.

5.3 Materials and methods

5.3.1 Determination of effects of VCM composts on plant growth, nutrient uptake and selected soil quality parameters

A pot experiment was set up to determine the effects of vermiculite-cattle manure (VCM) compost application, as basal fertiliser, on early plant growth, plant nutrient uptake, soil nutrient retention, and CEC using a sandy loam soil from Marondera University of Agricultural Sciences and Technology (MUAST) farm in October 2017. The soils are derived from granite (Nyamapfene 1991), classified as Lixisols (FAO 1998). The soil was colleceted from the 0 - 15 cm depth, and passed through a 10-mm sieve to remove gravel, before characterisation. The characteristics of the soil are detailed in Section 4.3.2. Chapter 4. Briefly, the soils had $pH_{(water)}$ 5.3, 0.65 % organic C, 0.21 % total N, 8 mg kg^{-1} mineral N, 54 mg available P kg^{-1}. The soil also had 0.20, 0.84, and 0.41 me/100 g of K, Ca and Mg, respectively, and 14 % clay, 9 % silt and 77 % sand.

The VCM co-composts used in the study were produced by aerobic composting of cattle manure and vermiculite as described in Chapter 3 and Pisa et al. (2020). Selected chemical composition of the co-composts is given in Table 4.1 and 5.1. The potassium requirement factor (KRF) of the composts was determined as detailed on Section 4.3.3 (Chapter 4). Reserve K was determined in the incubated composts by boiling the composts in 1 M HNO_3 acid at 113°C for 25 minutes then determining K the extract (Pratt, 1965), as detailed on Section 4.3.3 (Chapter 4).

Table 5.1: Reserve K and potassium requirement factor of the vermiculite cattle manure co-composts used

Parameter	**0 % VCM**	**10 % VCM**	**20 % VCM**	**30 % VCM**	**LSD**
Reserve K mg kg^{-1}	695.9[b]	671.1[b]	425.9[a]	432.8[a]	63.87
KRF	5.2	3.7	4.6	6.6	-

Values in the same row followed by the same lowercase alphabetical letters are not significantly different at $p<0.05$ according to Tukey's HSD. 0 % V-CM compost = cattle manure compost without vermiculite; 10 % V-CM, 20 % V-CM and 30% V-CM = cattle manure composts with 10, 20 and 30 % vermiculite, respectively. KRF – potassium requirement factor

The soil was amended using 0, 10, 20 and 30 % vemiculite-cattle manure (VCM) composts at a rate of 5 t ha^{-1} which supplied equivalents of 63, 61.5, 58.5 and 75 kg N ha^{-1}; 18, 17.5, 17 and 12 kg P ha^{-1} and 56.7, 53.4, 49.7 and 59.9 kg K ha^{-1} respectively. The soil and compost mixture were thoroughly mixed on a plastic sheeting before packing. Basal fertiliser (7 N: 14 P_2O_5: 7 K_2O) was applied at planting to supply FAO (2006) recommended rates of 35 kg P_2O_5, 17.5 kg N and 14.5 kg K ha^{-1} to the positive control, while an unamended soil was included as a negative control. Twenty litre pots with height of 33 cm, and top and bottom internal diameters of 35 and 25 cm, respectively, were used. The pots had a V-shaped base with a central outflow point attached to a flexible plastic tubing connected to a detachable bottle to facilitate leachate collection. A cotton wool plug was placed at the outlet point to prevent soil particles from getting into plastic tubing. The bottom of the pot was filled with acid washed gravel to a height of 3 cm and a 10-cm layer of unameded soil was placed on top of the gravel layer. This was done to imitate the method used by small holder farmers when applying manure/compost which is usually broadcast and incoporated in the top soil layer (0 -15 cm) during ploughing with animal drawn plough. Subsequently, a 15-cm layer of the amended soil, as per treatment requirement, was added to each pot representing the plough layer. To ensure uniform packing, for each soil layer added, the pot was swirled manually in a circular motion until no volume change occurred then more soil was added. A head space of approximately 5 cm was left on top of the amended soil to facilitate irrigation. The pots were arranged on brick stands at 50 cm above the ground in a randomized complete block design, with blocking based on shading during the day.

The circular soil surface in the pots was subdivided into 3 equal segments, and one maize seed of SeedCo SC503 variety was planted in each segment, giving a total of 3 seeds per pot. After emergence, seedlings were thinned to one plant per pot with the seedling showing the greatest vigour selected. Additional N equivalent to120 kg N ha^{-1} was split applied at 3 and 6 weeks (60 kg N ha^{-1} each time) after emegence (FAO, 2006) to all pots except the negative control. The pots were subjected to uniform irrigation to ensure 60 - 80 % field capacity. twice a week. At the selected sampling dates plants were irrigated above field capacity to allow for leaching to imitate what would happen after heavy rains. Leachate collection started at point of irrigation before. Each leachate system was emptied 24 hours after irrigation on days 3, 10, 24, 35, 45 and 63.The leachate collection dates were chosen to ensure leachate collection was done a week after fertiliser application.

The leachate collected was analysed for N, P, Ca, Mg and K. Nitrogen and P were measured colorimetrically at a wavelength of 650 nm and 400 nm respectively using a UV/Vis spectrophotometer (LasanyL1 296; Haryana, India). The amount of solution K, Mg and Ca in the leachate was determined by flame photometry (K) and by atomic absorption spectrophotometry (Ca and Mg) (Okalebo *et al.,* 2002). Number of leaves and height of the maize plants were recorded biweekly from 2 weeks after emergence (WAE) to early flowering stage (10 WAE,), at which the plants were harvested. Positive increments of dry matter are generally observed from the beginning of growth and development up to the beginning of the reproductive phase, approximately 70 days after emergence (Martins et al., 2017). The plants were cut at the base, 1.0 cm aboveground, chopped into short pieces and placed in a khaki paper. Total above-ground dry matter was determined by oven drying at 65^{o} C until there was no change in the weight of samples. Samples of above-ground-biomass were ground (<0.25mm, 60 mesh) then analysed for N, P, K, Ca, Mg after wet digestion with sulphuric acid, and analysed for N and P (colorimetric determination), K (flame spectrometry) and Mg and Ca (atomic absorption spectophotometry). Cation exchange capacity (CEC) was determined using the ammonium acetate method as described in Okalebo et al. (2002).

The soil samples from in each pot were collected from the 0-15 cm depth after harvest, dried, crushed and thoroughly mixed and analysed for available N (ammoniun- and nitrate- N), resin P (Anderson and Ingram, 1993), exchangeable K, Mg and Ca (Okalebo et al., 2002).

5.3.2 Determination of the effects of VCM composts on soil moisture retention

A second pot experiment was set up to determine the effect of VCM composts on soil moisture retention in a sandy loam soil from Marondera University of Agricultural Sciences and

Technology (MUAST) farm. Soil collection, preparation and analysis were similar to the descriptions in detailed in Section 5.3.1. Soil (6 kg) was placed in each pot and 13 g pot^{-1} of compost, as per treatment requirement, was spread on the surface and incorporated to a depth of 5cm in each pot. The treatments used were similar to those in Section 5.3.1. Four maize seeds were sown in each pot and the pots were kept moist to facilitate seed emergence. At 10 days after sowing (DAS) plants were thinned to one plant per pot and an irrigation schedule of 400ml per pot per week was adopted. Soil sampling was done every three days by taking two soil scoops per pot using a 20g scoop. The soil was weighed and oven dried at 105°C for 48 hours. Oven dry weight was determined and gravimetric water content was calculated by dividing the mass of water by mass of oven dry soil. The maize plants were left to grow up to 42 DAS after which dry matter yield was determined.

5.3.3 Statistical analysis

The data collected was subjected to a one-way analysis of variance in Genstat 14. Least significance difference ($LSD_{0.05} = t_{0.05}$ x SE0.05) and Tukey's Honesty test at $\alpha = 0.05$ were used to separate means where necessary. Sigma Plot version 10 was used to draw graphs to the effects of vermiculite cattle manure composts on leaf number and plant height

5.4 Results

5.4.1 Effects of VCM composts on plant growth, nutrient uptake and retention

Leachate analysis

The amount of nitrogen in leachate increased with sampling time for the treatments that received composts, except after 35 days (Table 5.2). The 0 % VCM treatment recorded the highest amount of N in leachate at each sampling time in comparison to the other composts treated soils. Phosphorus was observed in leachate from all the treatments on day 3, where the concentrations differed significantly ($p < 0.05$) among the treatments. The recommended fertiliser treatment recorded the highest P whilst the 30 % VCM treatment had the least P (Table 5.2). Thereafter (beyond 3 days) negligible P was observed in the leachate from pots amended with VCM composts and the negative control. The concentration of cations in the leachate was also undetectable.

Table 5.2: Total N and P content (mg L^{-1}) in leachate collected at different sampling times

	Sampling time	No Fert	Rec Fert	0 % VCM	10 % VCM	20 % VCM	30 % VCM	LSD
				TREATMENT				
	Day 3	0.031^{b}	0.020^{a}	0.084^{f}	0.076^{e}	0.035^{c}	0.067^{d}	0.004
N %	Day 10	0.008^{a}	0.007^{a}	0.010^{a}	0.1341^{c}	0.111^{b}	0.116^{b}	0.009
	Day 24	0.005^{a}	0.131^{c}	0.154^{d}	0.135^{c}	0.111^{b}	0.116^{b}	0.015
	Day 35	0.002^{a}	0.029^{b}	0.006^{a}	0.002^{a}	0.005^{a}	0.003^{a}	0.004
	Day 45	0.019^{a}	0.158^{b}	0.579^{f}	0.555^{d}	0.320^{c}	0.309^{c}	0.024
	Day 63	0.001^{a}	0.169^{b}	1.314^{e}	1.219^{d}	1.163^{d}	0.955^{d}	0.072
	Day 3	1.40^{a}	15.90^{f}	6.96^{e}	6.72^{d}	5.67^{c}	4.42^{b}	0.70
P %	Day 10	-	7.00	-	-	-	-	-
	Day 24	-	4.23	-	-	-	-	-
	Day 35	-	1.93	-	-	-	-	-
	Day 45	-	1.76	-	-	-	-	-
	Day 63	-	0.06	-	-	-	-	-

Values in the same row followed by the same superscript alphabetical letters in the same row are not significantly different at $p<0.05$ according to Tukey's HSD. - means there was undetectable concentrations. (Data points are the mean of the three replicates). The 0 % VCM, 10 % VCM, 20 % VCM and 30 % VCM represent composts from mixtures of cattle manure with 0, 10, 20 and 30 % vermiculite while No Fert and Rec Fert means no fertiliser was applied and recommended fertiliser was applied respectively.

Growth, dry matter yield and nutrient uptake

Number of leaves and Plant height

The number of leaves per plant and plant height differed significantly (P<0.05) among the treatments (Figure 5.1a). All the treatments with soil amendments did not differ from each other throughout the vegetative stage. Significant differences in leaf number were first observed at 4 WAE with all treatments receiving fertility amendment having significantly more leaves than the negative control. At 6 WAE the positive control, 20 and 30 % VCM treatments had significantly more leaves than the negative control (Figure 5.1a). Plant height did not differ among all the amended treatments, which were higher than the negative control at 4 and 6 WAE (Figure 5.1b).

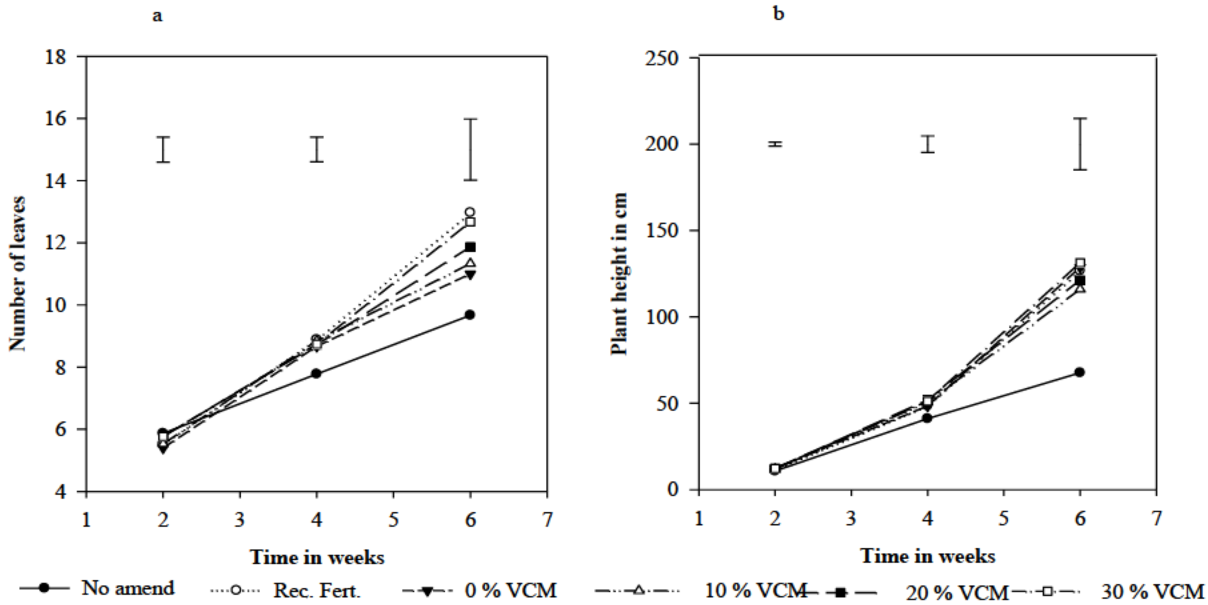

Figure 5.1: Effects of the application of VCM co-composts on a) leaf number b) plant height growth of maize (*Zea mays* L) to end of vegetative growth. No Amend – no fertility amendment applied (-ve control). Rec Fert – recommended fertiliser application. (Data points are the mean of the three replicates).

Dry matter yield at 10 WAE differed significantly among the treatments ($p < 0.05$) with the no amendment treatment recording the least (518.7 g/pot). The pots that received composts with higher rate of vermiculite (20 and 30 % VCM) had lower maize dry matter yield than the positive control, and 0 and 10 % VCM treatments (Table 5.3).

Nutrient uptake differed significantly amongst treatments ($p < 0.05$) (Table 5.3). Nitrogen uptake was least in the no amendment treatment (5.4 g pot^{-1}) and highest in the positive control and the 0 % VCM. N uptake decreased with increasing vermiculite content in the compost (Table 5.3). The uptake of P significantly differed among the treatments ($p < 0.05$) and was in the order positive control =10 % VCM = 0 % VCM > 20 % VCM > 30 % VCM > negative control. K uptake differed significantly among treatments, ($p < 0.05$), and was in the order of positive control > 0 % VCM > 30 % VCM > 20 % VCM > 10 % VCM > negative control. The K uptake in pots amended with composts with vermiculite increased with increasing vermiculite (Table 5.3). Magnesium and calcium uptake differed significantly among the treatments ($p < 0.05$). The 30 % VCM treatment recorded the highest concentrations for both elements whilst the no amendment recorded the least. The uptake of Mg for the recommended fertilizer, 0 and 10 % VCM treatments was significantly lower than the 20 and 30 % treatments, which did not differ from each other. Magnesium and Ca uptake increased with increasing vermiculite in composts (Table 5.3). The uptake of Ca in the recommended fertilizer was significantly lower than the other treatments receiving fertility amendment.

Table 5.3: Dry matter and nutrient uptake of Maize (*Zea Mays*) 10 WAE after emergence

Parameter	No Fert	Rec Fert	0 % VCM	10 % VCM	20 % VCM	30 % VCM	LSD
DM (g/pot)	519^{a}	1479^{c}	1489^{c}	1497^{c}	1414^{b}	1423^{b}	50.8
N (g/pot)	5.4^{a}	23.6^{d}	22.9^{cd}	22.1^{c}	21.7^{bc}	21^{b}	0.88
P g/pot	0.85^{a}	3.26^{d}	3.14^{cd}	3.16^{cd}	3.11^{c}	2.96^{b}	0.15
K g/pot	6.3^{a}	23.74^{d}	17.37^{c}	14.1^{b}	14.9^{b}	15.18^{b}	1.22
Ca g/pot	1.33^{a}	7.1^{b}	7.11^{bc}	7.54^{c}	8.49^{d}	9.17^{e}	0.35
Mg g/pot	0.83^{a}	3.16^{b}	2.97^{b}	3.05^{b}	3.59^{c}	3.63^{c}	0.37

Values in the same row followed by the same superscript alphabetical letters are not significantly different at $p<0.05$ according to Tukey's HSD. (Data points are the mean of the three replicates). The 0 % VCM, 10 % VCM, 20 % VCM and 30 % VCM represent composts from mixtures of cattle manure with 0, 10, 20 and 30 % vermiculite while No Fert and Rec Fert means no fertiliser was applied and recommended fertiliser was applied respectively. DM – dry matter biomass.

Soils

The nutrient content of soils after maize harvest was significantly different among the treatments. Mineral N was highest in the positive control soils while the negative control recorded the least (Table 5.4). The VCM treatments had significantly lower N than the positive control but significantly more available N than the negative control. The 20 and 30 % VCM treatments had lower mineral N than the 0 and 10 % VCM treatments. Available P significantly differed among treatments, ($p < 0.05$), with the treatments receiving composts having lower P than the recommended P after harvest. The negative control recorded the least soil P while the positive control recorded the highest. The soil P content did not significantly differ among the pots that received VCM compost.

All treatments receiving soil fertility amendment had significantly higher exchangeable Ca than the negative control. The 0 % VCM treatment had the highest Ca content differing significantly from the other treatments that received amendment. Exchangeable Mg differed significantly among treatments with the 20 % VCM and 30 % VCM treatments having the highest concentration. The negative control had the least Mg content. The 0 % and recommended fertiliser treatments had significantly less magnesium compared to the other treatments that received fertility amendment. Exchangeable Mg increased with increasing proportion of vermiculite in the VCM co-compost (Table 5.4).

5.4.2 Effects of VCM composts on soil moisture retention

Soil moisture retention differed significantly amongst treatments ($p < 0.05$) from 21 DAS to termination of experiment. The 30 % VCM compost treatment recorded the highest gravimetric water content at each sampling whilst treatments without composts recorded the least. The controls did not differ from each other on 14, 21, 28, 31 and 35 DAS whilst gravimetric water content increased with an increase in vermiculite content (Table 5.5) at each sampling. Dry matter yield differed significantly ($p < 0.05$) among treatments at 42 DAS. The controls significantly differed from each other and all the other treatments ($p <0.05$) with the positive and negative control recording the highest and least dry matter respectively. Dry matter yields generally decreased with increasing vermiculite content.

Table 5.4: Nutrient content of soils after harvesting of maize (*Zea mays* L.) biomass at 10 weeks after emergence.

Measured parameter	**Treatment**						
	No Fert	Rec Fert	0% VCM	10% VCM	20% VCM	30% VCM	LSD
pH	4.87^{a}	5.03^{a}	5.1^{a}	5.067^{a}	5.1^{a}	5.4^{b}	0.24
Min N (mg kg^{-1})	21.0^{a}	131^{d}	96.3^{c}	95.3^{c}	87.3^{b}	85.3^{b}	7.69
Avail. P_2O_5 (mg kg^{-1})	118^{a}	141^{c}	129^{b}	125.7^{b}	127.7^{b}	128^{b}	3.51
Exch. K (me/100g)	0.39^{ab}	0.48^{c}	0.34^{a}	0.37^{ab}	0.40^{b}	0.40^{b}	0.05
Exch. Ca (me/100g)	2.04^{a}	2.19^{b}	2.44^{c}	2.3^{b}	2.27^{b}	2.19^{b}	0.11
Exch. Mg (me/100g)	0.40^{a}	0.47^{b}	0.49^{b}	0.54^{c}	0.59^{d}	0.56^{cd}	0.03

Results are for measurements done on 0-15cm soil depth of the respective pots. Values in the same row followed by the same superscript alphabetical letters are not significantly different at $p<0.05$ according to Tukey's HSD. (Data points are the mean of the three replicates). The 0 % VCM, 10 % VCM, 20 % VCM and 30 % VCM represent composts from mixtures of cattle manure with 0, 10, 20 and 30 % vermiculite while No Fert and Rec Fert means no fertiliser was applied and recommended fertiliser was applied respectively. Min N -mineral N, Avail P_2O_5 – available P_2O_5.

Table 5.5: Gravimetric water content at different sampling times

	Gravimetric water content g g^{-1}							
	14 DAS	**21 DAS**	**24 DAS**	**28 DAS**	**31 DAS**	**35 DAS**	**42 DAS**	**DM g pot^{-1}**
No Fert	0.027	0.028^{a}	0.114^{a}	0.004^{a}	0.008^{a}	0.015^{a}	0.027^{a}	6.71^{a}
Rec Fert	0.026	0.027^{a}	0.127^{b}	0.004^{a}	0.011^{ab}	0.022^{b}	0.03^{b}	14.62^{d}
0 % VCM	0.029	0.037^{b}	$0.134b^{c}$	0.006^{a}	0.014^{b}	0.027^{bc}	0.032^{b}	9.09^{c}
10 % VCM	0.024	0.037^{b}	0.140^{c}	0.011^{b}	0.016^{bc}	0.032^{c}	0.034^{c}	8.55^{bc}
20 % VCM	0.029	0.037^{b}	0.154^{d}	0.014^{b}	0.019^{c}	0.036^{cd}	0.039^{d}	8.45^{bc}
30 % VCM	0.03	0.045^{c}	0.159^{d}	0.023^{c}	0.02^{d}	0.038^{d}	0.040^{d}	8.04^{b}
LSD	0.007	0.006	0.009	0.003	0.003	0.005	0.002	0.664

Results are for measurements done on 0-5cm soil depth of the respective pots. Values in the same column followed by the same superscript alphabetical letters are not significantly different at $p<0.05$ according to Tukey's HSD. (Data points are the mean of the three replicates). The 0 % VCM, 10 % VCM, 20 % VCM and 30 % VCM represent composts from mixtures of cattle manure with 0, 10, 20 and 30 % vermiculite while No Fert and Rec Fert means no fertiliser was applied and recommended basal fertiliser was applied respectively. DAS is days after sowing

5.5 Discussion

5.5.1 Leachate analysis

The higher leachate N observed in the 0 % VCM compost treatment was due to the higher initial total N than the 10, 20 and 30 % VCM composts. The mineralisation of the N resulted in higher mineral N, which was leached when excess water was added. Nitrogen leaching losses were lower with increasing vermiculite content in composts and this can be attributed to lower N added and adsorption and fixation of portions of released ammonium from the 10, 20 and 30 % VCM composts, thus reducing leaching losses. This is very important as it assist in the retention of nutrients which can be used by the plants as the season progresses.The treatments with VCM composts had more mineral N in their leachate compared to the recommended fertiliser treatment because of the higher N added as the composts, which mineralised increasing mineral N than added in the positive control. The VCM composts added 63 to 75 kg N ha^{-1} compared with 17.5 kg N ha^{-1} (as inorganic N) in the positive control. The application of similar levels of inorganic N fertiliser, as topdressing, to these treatments may have enhanced organic matter decomposition thus the release of a high amount of N in the treatments with composts, resulting in excess mineral N which was prone to leaching. There are reports indicating that inorganic N fertilizer enhances soil organic matter (SOM) mineralization (2002; Mulvaney et al., 2009; Russell et al., 2009; Chen et al., 2014) by altering microbial activity and biomass explaining why the VCM treatments had more N in their leachate.

The concentration of cations recorded in the leachate was very negligible. The absence of these elements in leachate could have been due to crop uptake and/ or adsorption on exchange sites on organic matter and vermiculite. The addition of composts with vermiculite, increased the clay and organic matter content, which reduced the potential for leaching in these soils compared to the sandy soil treated with inorganic fertiliser. The recommended fertiliser treatment continued to lose P via leaching because P was in a more soluble anionic form and therefore could not be retained in the soil, while that in the VCM was largely in organic form. The orthophosphates, $H_2PO_4^-$ and HPO_4^{2-} anions remain in soil solution and are therefore prone to leaching in a sandy soil used in the study (Kang et al., 2011). Unlike in inorganic basal fertilisers, P in VCM composts is released following organic matter decomposition, therefore, providing a slow P release fertiliser. The absence of P in leachate in addition to the low soil P levels at the end of the experiment indicates that mineralised P was taken up by plants.

5.5.2 Maize Growth, dry matter yield and nutrient uptake

Maize growth was lower in the pots without any soil amendment when compared to composts enriched and NPK fertilizer treatments as a result of lower uptake of N, P and K. This is because the plants only depended on what the soil supplied while in the other treatments, additional nutrients were added. Similar results were reported by Koutroubas et al., (2016) when they observed higher growth, productivity and nutrient dynamics of winter wheat (*Triticum aestivum* L.) the effect in treatments that received organic manure. The higher plant growth in the pots treated with fertility amendments is a result of N, P and K availability, the major nutrients required by crop for vegetative growth, seed and root development as observed by the high dry matter biomass. In addition to the 120 kg N ha^{-1} applied as top dressing the 0, 10, 20 and 30 % VCM compost treatments each supplied an additional 63, 61.5, 58.5 and 75 kg N ha^{-1}, meaning the maize plants received enough nitrogen as maize requires 120 -160 kg N ha^{-1} depending on target yield (FAO 2006; Manson et al 2017). All the composts except the 30 % VCM also supplied the recommended amounts of P (15.4 kg ha^{-1}) (FAO 2006; Manson et al 2017) as the 0, 10, 20 and 30 % VCM compost treatments each supplied 18, 17.5, 17 and 12 kg P ha^{-1}. This is supported by the higher dry matter yield in the pots that received fertility amendment and nutrient uptake observed

The plants that received fertility amendment had higher dry matter yield than the negative control, which was similar to results by Zhang et al., (2020) who observed that the application of organic fertilizer significantly increased both underground and aboveground biomass of cotton. The high dry matter in pots receiving fertility amendment was synonymous with more growth (the higher leaf number and plant heights) in the respective pots. The application of a fertility amendment, increased nutrient availability, promoting vigorous vegetative growth and increased chlorophyll content, which together accelerate the photosynthetic rate (Bairwa et al. 2009; Velmurugan & Swarnam 2017) and thereby increased the dry matter yield of treatments that received VCM amendment over the negative control. The higher dry matter biomass observed with the recommended fertilizer, 0 and 10 % treatments for both pot experiments were due to more N and P uptake compared to the 20 and 30 % VCM compost treatments. This is supported by the nutrient uptake data. The 20 and 30 % VCM composts supplied less nutrients as compared to the 0, 10 % VCM and the positive control and therefore both nutrient uptake and dry matter were lower. Lower N uptake observed with the 20 and 30 % VCM treatments could be explained by the fact that portions of the ammonium-N released during mineralisation could also have been fixed by the vermiculite in the co-compost, making it less available for uptake. An increase in vermiculite content increased K fixation and thus it is possible that NH_4^+ from the decomposition of composts was fixed resulting in similar or lower N uptake between the positive control and the VCM treatments. Similarly, K uptake reduced with presence of vermiculite in the composts. The similarity in N uptake between the positive control and the 0 and 10 % VCM treatments regardless of the fact that the compost treatments had much higher total N can be explained by the fact that organic N in the composts had to undergo mineralisation to become available. Nitrogen in composts is less readily available for crop uptake due to slow decomposition (Helgason et al., 2007; Koutroubas et al., 2016). In this study greater N uptake could have been expected in treatments that received both inorganic fertilizer and composts than the positive control but the presence of vermiculite in the compost could have reduced N uptake due to fixation. The higher dry matter yield in soils receiving VCM than the negative control can also be attributed to improved soil conditions with the application vermiculite in the co-composts. Vermiculite enhances germination and development of roots and shoot due to its high-water holding capacity (203 %), good aeration and excellent thermal properties (Uganda Vermiculite Institution, 2005). Good root development ensures adequate nutrient and water uptake. Calcium and magnesium uptake were seen to increase as vermiculite proportion in the co-composts increased. The availability of sufficient Mg is important for increased uptake and utilisation of P (Mengel et al., 2001; Marschner 2002).

5.5.3 Soils

Despite receiving more nitrogen, soil amended with VCM composts treatments had lower mineral N than the recommended fertilizer, as they experienced more leaching and possibly fixation. The 0 and 10 % VCM compost treatments had less mineral N than the 20 and 30 % VCM treatments due to higher nutrient uptake. All the VCM compost treatments however resulted in significantly more build-up of soil available nitrogen than the negative control. These results are consistent with those by Velmurugan & Swarnam, (2017), who reported higher residual N in soil after application of vermicompost and poultry manure in a vegetable-rice system for 3 years. The higher N in the soil amended with composts than the negative control could also be due to N retention as a result of adsorption of NH_4^+ ion on the exchange sites of both the vermiculite and organic matter in these treatments which were absent in the negative control. The application of these vermiculite-based composts could allow for the adsorption and fixation of NH_4^+ building up on the available N pool and therefore increasing agricultural productivity of the soil for subsequent crops.

Despite having leached more P, the positive control, recorded the highest available soil P at the end of the trial. Phosphorus release from treatments receiving composts depended on OM decomposition which releases (Arancon, et al., 2006) little P which was immediately taken up by the crop. The amount of Ca in the treatments that received compost with vermiculite was lower than that which received 0 % VCM composts, even if it received lower Ca (lower concentration than the others) was because of higher Ca uptake for the vermiculite-based composts, resulting in much less Ca in the soil at harvest. Exchangeable Mg increased with increasing vermiculite proportions in the VCM co-compost, because the vermiculite used in the trial was a magnesium-alumunium-iron silicate clay with a structural formula of $(Mg,Fe^{2+},Fe^{3+})_3[(Al,Si)_4O_{10}](OH)_2 \cdot 4H_2O)$ (Fleisher and Madarion 1991, Jayabalakrishnan, 2007). Application of this clay mineral in the co-composts added significant amounts of Mg.

The CEC was affected by the amount and type of clay and SOM content as CEC is a factor of amount and type of clay and also amount of SOM (Peinemann et al., 2000). Application of vermiculite-based co-compost could have increased clay content in the soil. Tahir and Marschner (2016) reported that addition of clay to sandy soil increased the amount of clay in the soil significantly affecting soil properties. Research has been done in Australia has shown that claying enhances soil properties (Harper and Gilkes 2004; Hall et al., 2010; Schapel et al., 2016). Even though none of the claying research were specific to vermiculite, application of vermiculite to soils can have similar effects. Vermiculite is a 2:1 silicate clay which has high CEC ranging from 50 to 150 meq/100 g (van Straaten, 2002) and thus its application could significantly increase the CEC (Tahir and Marschner, 2016) of the soil together with addition of organic matter. The high CEC recorded with the 0 % VCM treatments can be explained by the significant influence OM has on CEC. Organic matter generally increases CEC (Parfitt et al., 1995; Peinemann et al., 2000) due to the high amount of carboxylic, phenolic and enolic groups making up organic matter increasing CEC especially as pH approaches neutral to alkaline

5.5.4 Moisture retention and dry matter yield

The VCM composts retained soil moisture due to increased organic matter content and vermiculite. The application of organic materials has been reported to improve soil quality (nutrient retention, aggregation and soil structure), enhancing soil biotic activity (Lal, 2004; Minasny and Mcbratney 2018) increase the water holding capacity of soils and consequently yields (Yang et al., 2014; Williams et al., 2016). In this experiment the addition of VCM composts improved water holding capacity as shown by the higher gravimetric water content in the treatments that received composts. In addition to organic matter the composts also supplied vermiculite which improved water retention and therefore improved water availability for plant uptake. As the proportion of vermiculite was increased, the water content also increased, showing that adding vermiculite increases water content. Vermiculite is porous and allows water entry in the interlayer spaces thus enhancing water retention. The dry matter yield results did not follow the same trend as the water content, suggesting that at the watering regime used in this study, water availability was less important than nutrient availability, because the results followed a similar trend as those in the first pot trial.

5.6 Conclusion

The application of vermiculite-cattle manure composts to a sandy loam soil improved early maize growth, plant nutrient uptake, and dry matter yield, soil moisture retention and selected soil quality parameters after harvest. Plant growth and biomass were greatly improved on application of 0 and 10 % VCM co-composts as they were comparable to the recommended fertilisers. There were no negative effects of fixation of K and ammonium N by vermiculite in the 10 % VCM compost on growth and dry matter yield but where 20 and 30 % vermiculite was included K and N were lower. The application of composts resulted in increased Ca and Mg uptake, from the organic matter and the vermiculite. Leaching losses are greatly reduced with application of composts as seen by the lower mineral N in treatments with higher vermiculite and negligible amounts of cations and P in the leachate from VCM treaments reducing environemntal hazards of fertilisers. The application of N, as top-dressing, may need to be reduced when using composts to reduce on fertiliser costs and underground water pollution through leaching. The fact that K uptake decreased with increased vermiculite proportion in composts necessitate care when using vermiculite so as not to induce fixation of K^+. It can be concluded that the 10 % VCM is the best compost containing vermiculite with similar drymatter yield, N, P and K uptake and soil nutrient composition after harvest than those with higher vermiculite proportions. The results of this trial were based on controlled water application and the crop did not reach physiological maturity for grain harvest. There was need to test the effects of vermiculite cattle manure composts on maize growth and yield under dryland field conditions.

CHAPTER 6: CO-COMPOSTS OF CATTLE MANURE AND VERMICULITE - IMPROVE MAIZE GROWTH AND YIELD, AND FERTILITY OF ACIDIC SANDY LOAM SOIL IN ZIMBABWE.

6.1 Abstract

A study was carried out to determine the effect of increasing the proportions of vermiculite in VCM co-compost on maize growth and yield and soil chemical properties under field conditions. The field experiments were conducted during the 2016/17 and 2017/18 seasons on a sandy loam soil at the Marondera University of Sciences and Technology (MUAST) farm (Natural Region IIb). The vermiculite cattle manure (VCM) co-composts of 0 (manure only), 10, 20 and 30 % vermiculite were applied at 5 t ha^{-1} on plots measuring 5 x 5 m. Positive (recommended fertilizer) and negative (no amendment) control treatments were included. Crop establishment (%) was determined 2 weeks after emergence (WAE) while leaf numbers and plant heights were measured at 2, 4, 6, 8, 10, and 14 WAE. Yield parameters (cob number, cob weight, shelling out and grain yield) were determined from the net plot (the 3 middle rows of each plot) of 9 m^2 and grain yield was expressed per hectare at 10 % moisture content. Maize establishment percent was significantly lower ($p < 0.05$) in the negative control (< 80 %) than all other treatments which had 92-98% in the 2016/17 and 87-89 % in the 2017/18 season. Yield parameters were significantly different among treatments and were similar for the positive control, 20 and 30 % VCM treatments which were higher than the negative, 0 and 10 % VCM treatments. Maize grain yield significantly differed among treatments and was in the order of positive control = 30 =20 = 10 > 0 % > negative control and positive control = 30 > 20 > 10 > 0 % > negative control in the 2016/17 and 2017/18 seasons respectively. The VCM composts can be used as alternatives to basal fertilisers as they provide the necessary nutrients in the right quantities to improve maize growth and yield. Smallholder farmers can therefore co-compost cattle manure with 20 and 30 % vermiculite and get good yields for improved household food security and for improved soil fertility.

Key words: *maize, vermiculite cattle manure composts, yield*

6.2 Introduction

Sustainable smallholder crop production in sub-Saharan Africa (SSA) is constrained by both biotic and abiotic factors. Poor native soil fertility, low and erratic rainfall, recurrent droughts, low water-holding capacities, and surface crusting are the main abiotic constraints (De Meyer et al., 2011; Gerola et al., 2014; Muyayabantu et al., 2012; Roba, 2018), that have resulted in low maize yields in small holder farming systems in SSA (ten Berge et al., 2019, Assefa et al., 2019). Application of mineral fertilisers is essential to maintain food production for a rapidly growing population. While inorganic fertilizers are known to increase soil productivity, the high cost is a major challenge for smallholder farmers, and result in limited organic matter addition, which induces degradation of soil and pollution of water and air and cause some risks for human health. The use of organic amendments (organic fertilisers), such as crop residues and manure could be an appropriate solution for improving and preserving soil fertility through recycling of nutrients and addition of organic matter.

Smallholder farmers in Zimbabwe, often use organic materials such as leaf litter, cattle manure and composts as plant nutrient sources. A number of studies have shown the beneficial effects of these amendments on crop yields and various soil properties, with the degree of benefit being influenced by the types of amendment, soil management and environmental conditions (Yanagi and Shindo, 2016). However, cases of delayed seedling emergence, reduced crop growth after the incorporation of some compost products, have been reported (Tiquia, 2010). These negative impacts have been attributed to unstable or immature compost, which may cause N immobilisation, oxygen depletion or presence of phytotoxic compounds, such as the organic acids; propionic, acetic and butyric acid. Mineral additives have been reported to improve compost performance and result in a mature compost.

Cattle manure co-composted with varying amounts of vermiculite, from Zimbabwe, has produced mature and stable vermiculite- cattle manure (VCM) co-composts with C:N ratio < 20, a NH_4^+: NO_3 below 1 and pH within the 6 – 7.5 range within 72 days (Pisa et al., 2020). The co-composts can result in improvement of soil physical properties like aeration, aggregation, water holding capacity and root penetration, which influence nutrient uptake. The application of vermiculite cattle manure compost on a sandy loam soil were seen to improve in early maize growth, plant nutrient uptake, and dry matter yield, and selected soil quality parameters after harvest, compared to the negative control, under controlled environment. However, the 20 % VCM and 30 % VCM resulted in lower dry matter and uptake of N, P and K, than the positive control, and 0 % VCM and 10 % VCM (Chapter 5).

Results in Chapter 5 were based on controlled water application and the crop did not reach physiological maturity for grain harvest. The effects of vermiculite cattle manure composts therefore needed to be tested for a full maize cycle under dryland field conditions, which is often practiced by the target smallholder farmers that will benefit from this technology. Wetting and drying under dryland conditions could affect mineralisation of nutrients in the composts when compared to continuously moist soil, possibly affecting crop nutrient uptake, growth and yield. Ullah et al., (2020) reported that the relationship between gross N mineralisation and soil moisture was less clear when soil moisture was above 9 % suggesting that other factors were at play. Re-wetting of soil after a dry spell may results in a sudden increase in available carbon (C) substrates and microbial activity (Xiang et al., 2008), the Birch effect (Birch 1958), which could then revitalize microbes to increase N mineralization. This increased mineralisation together with improved physical soil conditions can result in different crop responses to addition of composts and fertilisers.

The aim of this study therefore was to determine the effect of increasing the proportions of vermiculite in VCM co-compost on maize growth and yield and soil chemical properties under dryland field conditions. Results from this study can give an insight on whether VCM co-composts can improve maize yields by providing essential nutrients and improving soil fertility thus providing farmers with a cheaper alternative that is less detrimental to the environment than inorganic fertilizer, and also improves soil organic matter.

6.3 Materials and Methods

6.3.1 Site description

The field experiments were conducted during the 2016/17 and 2017/18 seasons, at the Marondera University of Science and Technology (MUAST) farm (Natural Region IIb) in Zimbabwe (18°23′S 31°48′E). This sub-region receives an average of 16-18 rainy pentads per season and is subject either to rather more severe dry spells during the rainy season or to the occurrence of relatively short rainy seasons. The area is characterised by hot wet summers and dry cold winters, with annual rainfall ranging from 700 to 900 mm with about 80 % falling between November and March. The soils are predominantly acidic sandy loams, derived from granite (Nyamapfene 1991), classified as Lixisols (FAO 1998). The soils had $pH_{(water)}$ 5.3, 0.65 % organic C, 0.21 % total N, 8 mg kg^{-1} mineral N, 54 mg available P kg^{-1}. The soil also had 0.20, 0.84, and 0.41 me/100 g of K, Ca and Mg, respectively, and 14 % clay, 9 % silt and 77 % sand.

6.3.2 Characteristics of the vermiculite-cattle manure composts

The VCM co-composts used in the study were produced by mixing cattle manure collected from MUAST cattle kraal with vermiculite from a mine in Buhera at 0, 10, 20 and 30 % vermiculite on a w/w basis. The mixtures were aerobically composted in 1 m^3 perforated wooden bins for 72 days as detailed in Chapter 3 and Pisa et al. (2020). The chemical composition of the co-composts is given in Table 4.1.

6.3.3 Trial establishment and management

The land used for this study was ploughed and disked to obtain a fine tilth, using tractor-drawn implements before the first rains. The experiment was set up in a randomized complete block design (RCBD) with 6 treatments, in 3 blocks (replicates). Blocking was done according to slope. The VCM co-composts of 0 (manure only), 10, 20 and 30 % vermiculite were applied at 5 t ha^{-1} to respective plots, as in Chapter 5. Two controls were included; no soil fertility amendment as negative control and recommended fertiliser as the positive control. A rate of 5 t ha^{-1} of compost was chosen to represent the average rate smallholder farmers apply (Zingore et al., 2007, 2011). The blocks were separated by 1.50 m while the plots (4 m x 5 m) within a block were 1.0 m apart. In this study the composts were used as basal fertilizer to emulate the smallholder farmer, who spreads composts or stockpiled cattle manure on their fields in place of basal fertilisers. The composts were broadcast and incorporated into the soil using hand hoes to a depth of 0 - 15 cm. Basal fertiliser (7 N: 14 P_2O_5: 7 K_2O) was broadcast at planting to supply FAO (2006) recommended rate of 35 kg P_2O_5, 17.5 kg N and 14.5 kg K ha^{-1} to the positive control, while an unamended soil was included as a negative control. The basal fertiliser and composts were all applied at planting.

The maize (*Zea mays* L.) variety, SC 513, was planted at an intra-row spacing of 0.3 m and interrow spacing of 0.9 m to achieve a plant population of approximately 37 000 plants per hectare. A single seed was placed at each planting station, on moist soil. All treatments, except the negative control, were fertilised with ammonium nitrate as top dressing at 120 kg N ha^{-1} split applied at three and six weeks after emergence (WAE), as in Chapter 5. Weeds were removed by hand-hoes while pests were chemically controlled using combination of Chlorantraniliprole and Lambda-Cyhalothrin for leaf-hoppers and Fall Army Worm, respectively, following regular scouting. Rainfall data was collected throughout the season. The experiment was repeated on the same plots in the 2017/2018 season.

6.3.4 Soil analysis

Soil samples were collected from each experimental plot before and after each growing season from the 0 - 15 cm depth and analysed for pH, electrical conductivity, organic carbon, available P and total N. Soil texture was determined before planting in the first season using the hydrometer method after dispersing using sodium hexa-meta-phosphate (Anderson and Ingram, 1993). Soil pH was measured in 0.1 M $CaCl_2$ method in a 1:5 soil: solution ratio, while organic carbon was determined using the modified Walkley-Black method, with external heating (Anderson and Ingram, 1993). Total exchangeable cations were extracted from soil samples using 1 M ammonium acetate. The amounts of exchangeable potassium (K), magnesium (Mg), calcium (Ca) and sodium (Na) in the extract were determined by flame photometry (Na and K) and atomic absorption spectrophotometry (Ca and Mg) (Okalebo *et al.,* 2002). Total soil N was measured calorimetrically at a wavelength of 650 nm after wet digestion using concentrated sulphuric acid and hydrogen peroxide (Okalebo *et al.,* 2002). Available P was determined colorimetrically at a wavelength of 400nm after extraction with sodium bicarbonate followed by colour development with ammonium molybdate/antimony potassium tartrate solution.

6.3.5 Determination of maize growth and yield parameters

Crop establishment (plant stand) was determined 2 weeks after emergence by counting the number of established plants and calculating the percentage to total planted. Leaf numbers were counted and plant heights were measured at 2, 4, 6, 8, 10, and 14 WAE. One row from each side of the plot was used as a border row and five plants were randomly selected from the net plot of 3 middle rows (9 m^2) and marked with twine to be used as experimental units for all the growth parameters. Care was taken to make sure each chosen plant had adjacent plants on all four sides. A tape measure was used to measure the plant heights from the ground level to the last leaf.

Yield parameters (cob number, cob weight, shelling out and grain yield) were determined from the net plot (the 3 middle rows of each plot) of 9 m^2 and grain yield was expressed per hectare at 10 % moisture content. Mean cob weight was determined soon after harvesting by weighing total harvested cobs per net plot. Maize was hand shelled and mean grain weight and percent shelling out determined. Shelling out was calculated using the equation;

$$Shelling\ out\ \% = \frac{Mean\ grain\ weight\ (kg)}{Mean\ cob\ weight\ (kg)} * 100 \qquad (6.1)$$

Grain yield per hectare was calculated as;

$$Yield\ kg/Ha = \frac{10\ 000}{9} * net\ grain\ weight\ (kg) \qquad (6.2)$$

6.3.6 Statistical analysis

Genstat 14 Statistical package(www.Genstat.co.uk) was used for data analysis. One-way analysis of variance was used to analysed data and $LSD_{0.05} = t_{0.05}$ x SE0.05), plus Tukey's Honesty test at α = 0.05 were used to separate means where necessary. Sigma Plot version 10 was used to draw graphs to show patterns for leaf number, plant height and yield per hectare

6.4 Results

6.4.1 Rainfall

Normal to above normal rains were received during the 2016/17 season (1126.7 mm) with most rain received in December which coincided well with planting. The 2017/18 season received much lower rainfall amounts (550 mm) than normal between October and December (Figure 6.1). The season was characterised by a dry spell from 22 December to 10 January, which had a negative effect on crop emergence such that re-sowing had to be done in

January.

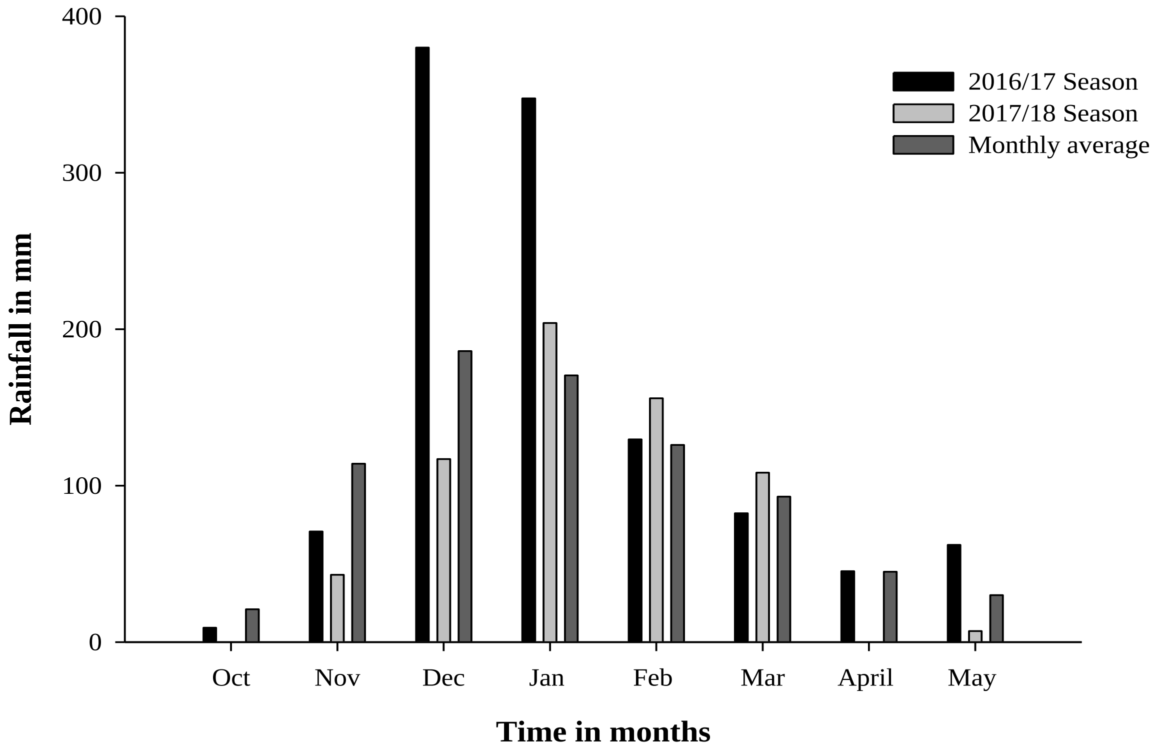

Figure 6.1: Rainfall received during the maize growing season in the 2016/17 and 2017/18 seasons.

6.4.2 Maize establishment, growth and yield

Maize establishment percent was significantly lower ($p < 0.05$) in the negative control (<80 %) than all the other treatments which had 92-98 % in the 2016/17 and 87 - 89 % in the 2017/18 season (Table 6.1). Besides the negative control, there were no significant difference among all the other treatments, including the positive control.

Table 6.1: Effects of VCM co-composts on of maize (*Zea mays* L) establishment (%) at 2 WAE. (Data points are the mean of the three replicates).

Season	No Fert	Rec Fert	0 % VCM	10 % VCM	20 % VCM	30 % VCM	LSD ($p<0.05$)
2016/17	77.5^{a}	91.7^{b}	93.3^{b}	93.3^{b}	96.7^{b}	97.7^{b}	9.61
2017/18	76.7^{a}	88.3^{b}	88.3^{b}	89.2^{b}	86.5^{b}	88.7^{b}	5.36

Values in the same row, followed by the same superscript alphabetical letters are not significantly different at $p<0.05$ according to Tukey's HSD. (Data points are the mean of the three replicates). The 0 % VCM, 10 % VCM, 20 % VCM and 30 % VCM represent composts from mixtures of cattle manure with 0, 10, 20 and 30 % vermiculite while No Fert and Rec Fert means no fertiliser was applied and recommended fertiliser was applied respectively.

In both seasons leaf number and plant height did not differ among treatments during the first 4 weeks after emergence. After 6 weeks, the negative control treatment had significantly lower number of leaves and plant height than the recommended fertiliser and 30 % VCM treatments (Figure 6.2) in both seasons. There were no significant differences in leaf number and plant height amongst the treatments that received a soil fertility amendment, including the positive control, in both seasons.

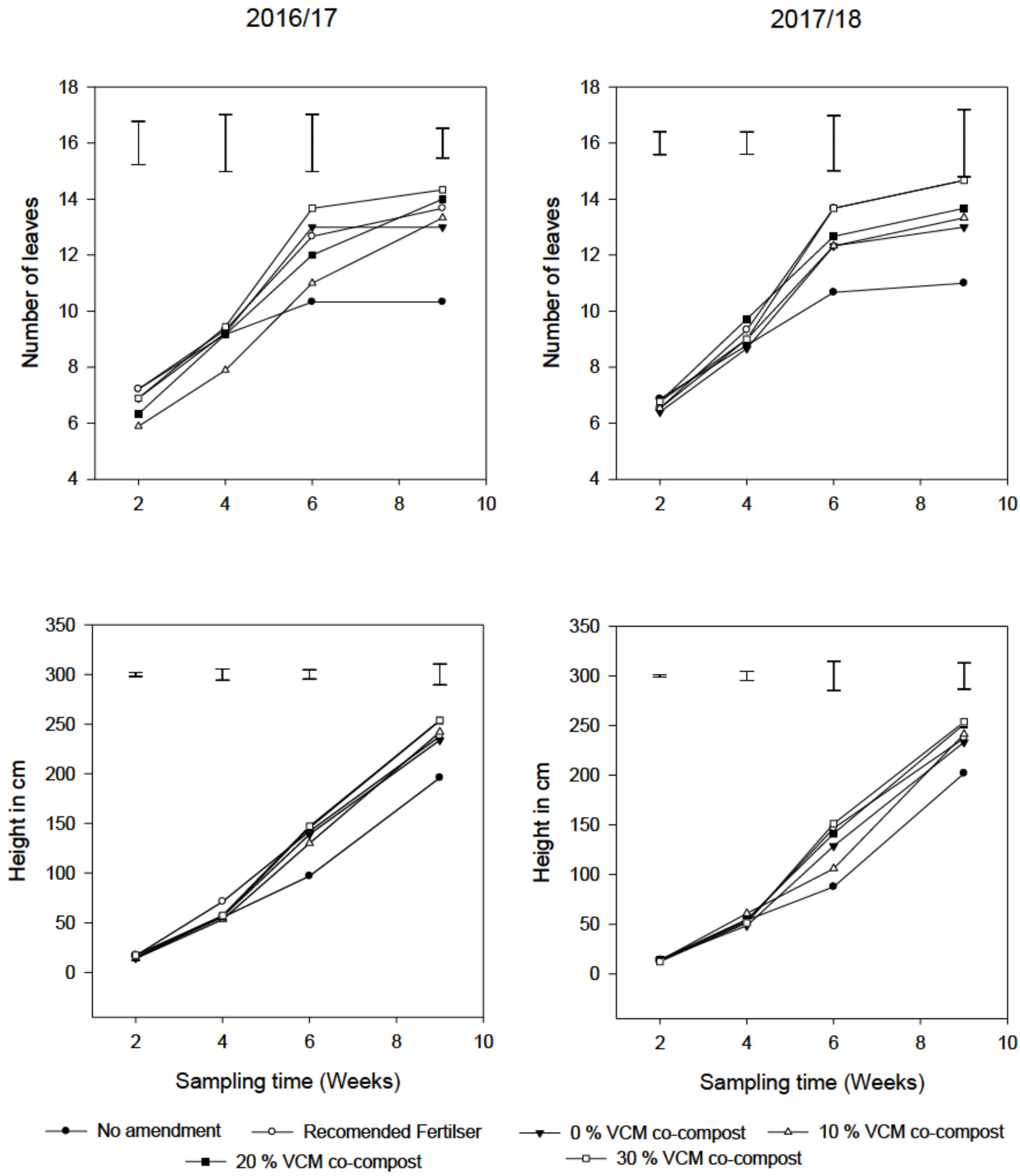

Figure 6.2: Leaf number and plant height of maize (*Zea mays* L) grown on soil treated with VCM co-composts during the 2016-2017 and 2017-2018 seasons. (Data points are the mean of the three replicates).

Significant differences ($p < 0.05$) were observed among the treatments for all the yield parameters (Table 6.2). In both seasons the negative control treatment recorded the least number of cobs, cob weight, shelling percent per plot and grain yield. Number of cobs in the plots that were treated with soil amendment did not differ significantly. The negative control treatment, had significantly lower number of cobs than the recommended fertiliser and the 20 % VCM treatments in the 2016/17 season and the 30 % VCM treatment in the 2017/18 season (Table 6.2).

Cob weight significantly increased with increase in proportion of vermiculite in the compost, with the highest in the 30 % VCM compost treatment, which did not differ significantly from the recommended fertiliser and 20 % VCM compost treatments in the 2016/17 season. The same trend was observed in the second season. In 2017/18 season however, the 20 % VCM treatment had lower cob weight than both the recommended fertiliser and the 30 % VCM treatments (Table 6.2). Though the cob weight for the 10 and 20 % VCM treatments did not differ, the shelling percent differed significantly between the treatments.

In the 2016/17 season the shelling percent of the 10 % VCM treatment was significantly higher (93.5 %) than all other treatments. In the second season, shelling percent differed significantly among all treatments, with the negative control recording the least and recommended fertiliser the highest, and was not different from the 20 and 30 % VCM treatments. The shelling percent from the 10 % VCM treatment was significantly lower than all the other plots, except the negative control.

Table 6.2: Effects of VCM co-composts on of selected maize (*Zea mays* L) yield parameters

	2016/17 season			2017/18 season		
Treatment	No. of cobs/ plot	Cob weight (kg/plot)	Shelling %	No. of cobs/ net plot	Cob weight (kg/plot	Shelling %
No Fert	30.7^{a}	3.93^{a}	83.9^{a}	31.0^{a}	5.48^{a}	67.5^{a}
Rec. fert.	41.3^{b}	7.10^{c}	87.6^{a}	37.0^{ab}	7.75^{d}	88.2^{d}
0 % VCM	35.3^{ab}	6.73^{b}	84.0^{a}	35.3^{ab}	6.10^{b}	83.3^{c}
10 % VCM	35.7^{ab}	6.67^{b}	93.5^{b}	37.7^{ab}	7.15^{c}	78.8^{b}
20 % VCM	39.7^{b}	7.42^{c}	87.0^{a}	34.7^{ab}	7.20^{c}	86.3^{cd}
30 % VCM	34.0^{ab}	7.45^{c}	86.6^{a}	40.0^{b}	8.07^{d}	84.8^{cd}
LSD	5.75	0.35	4.84	7.30	0.39	3.87

Results are for measurements done on a net plot of 9 m^2. Values in the same column, followed by the same superscript alphabetical letters are not significantly different at p<0.05 according to Tukey's HSD. (Data points are the mean of the three replicates). The 0 % VCM, 10 % VCM, 20 % VCM and 30 % VCM represent composts from mixtures of cattle manure with 0, 10, 20 and 30 % vermiculite while No Fert and Rec Fert means no fertiliser was applied and recommended fertiliser was applied respectively.

Maize grain yield (t ha^{-1}) was significantly different amongst treatments in both seasons ($p < 0.05$). For both seasons the negative control treatment had significantly lower yield than all compost treatments and the positive control (Figure 6.3). It is important to note that the negative control treatment recorded yields of 2.75 and 3.49 t ha^{-1} in the 2016/17 and 2017/18 seasons, respectively. The 0 % VCM compost had significantly lower yield than all other VCM co-compost treatments and the positive control (Figure 6.3). The other VCM composts and positive control were not significantly different in the 2016/17 season, while in the 2017/18 season, the grain yield increased with increase in proportion of vermiculite in the compost, with only the 30 % VCM co-compost treatment having similar yield to the positive control.

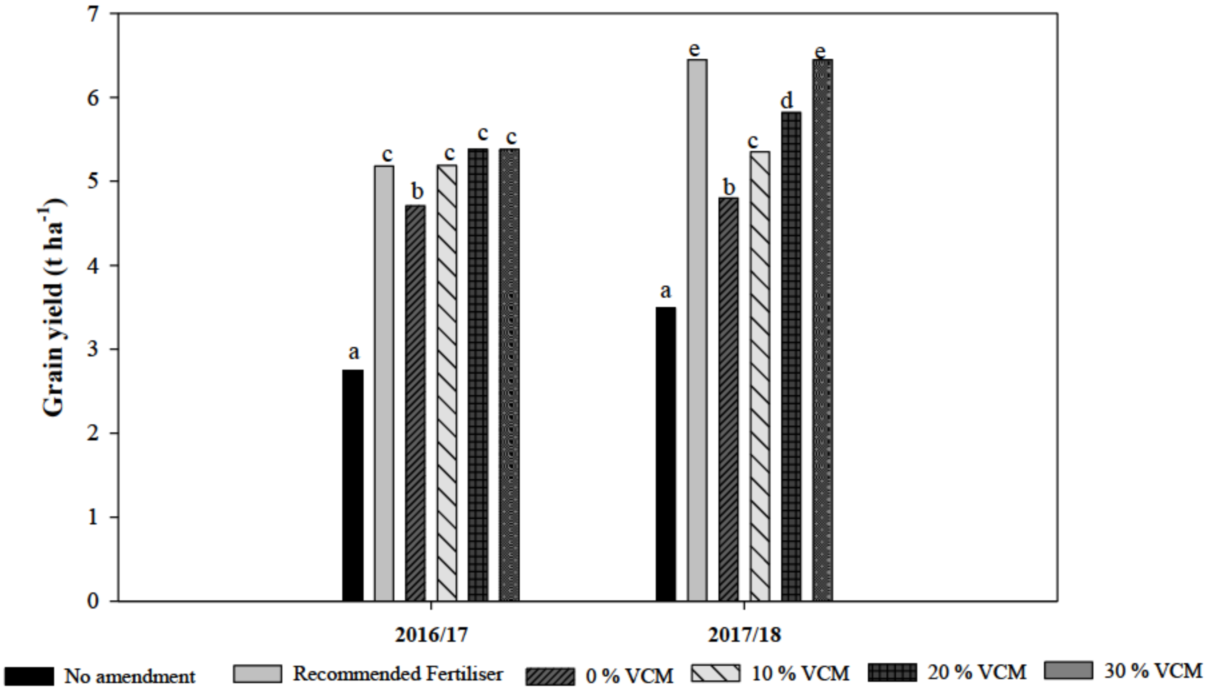

Figure 6.3: Effects of the application of VCM co-composts on maize (*Zea mays* L) grain yield (t ha^{-1}) during the 2016-2017 and 2017-2018 seasons. (Data points are the mean of the three replicates).

6.4.3 Soil properties

In both seasons the controls (negative and positive) recorded significantly lower pH than all the plots that were treated with VCM co-compost ($p < 0.05$; Table 6.3). Soil pH in the 0 % VCM treatment was significantly lower than 10 % and 20 % VCM co-composts treatments in 2016/17, while in 2017/18 season there were no significant differences among compost treatments. Electrical conductivity differed significantly among treatments in the first season with the 0 % VCM compost treatment having the highest EC (116.7 µS cm^{-1}) and the negative control having the lowest (50 µS cm^{-1}). All treatments with vermiculite in the co-compost did not differ from the negative control. In the second season, however, electrical conductivity did not differ among all treatments.

Soil organic C was significantly lower than the VCM composts treatments in both the negative and positive control treatments and highest in the 0 % VCM compost in the 2016/17 season (Table 6.3). The OC content in the plots that received the 10, 20 and 30 % VCM co-compost did not differ significantly in both seasons. However, in the 2017/18 season, organic C in the 0 % VCM compost treatment was significantly higher than both control treatments and the 30 % VCM co-compost treatment. Only the 20 % VCM had significantly higher N content than the negative control treatment in the 2016/17season. In the 2017/18 season, only the 30 % VCM treatment had significantly higher total N than all the other treatments (Table 6.3).

Treatments with compost had significantly higher available P than the negative control in the 2016/17 while they did not differ from the positive control. In the 2017/18 season, however, the 0 % and 30 % VCM treatments had significantly higher available P than both the negative and the positive controls (Table 6.3). In both seasons there were no significant differences in exchangeable K for all the treatments that received fertility amendment. The negative control had significantly lower exchangeable K than the positive control (both seasons) and the manure only compost (0 % VCM) treatment in the 2017/18 season (Table 6.3). Treatments with co-compost had higher exchangeable Ca and Mg than the negative control in both seasons (Table 6.3). Both Ca and Mg in soil increased with an increase in proportion of vermiculite in co-composts in both seasons. All composts with vermiculite had more Ca than both controls, which did not significantly differ from the 0 % VCM co-compost. The 30 % VCM co-compost treatment had the highest Mg content, with 107 and 90 mg kg^{-1} in 2016/17 and 2017/18 seasons respectively.

Table 6.3: Selected soil properties after harvest of maize (*Zea mays* L)

	Treatment	pH	EC	OC	TN	Available P	K	Ca	Mg
			µS cm^{-1}	%	----------mg kg^{-1}----------				
	No Fert	5.23^{a}	50^{a}	0.33^{a}	274^{a}	372^{a}	40^{a}	99.4^{a}	48.9^{a}
2016/17	Rec Fert	5.37^{a}	83.3^{b}	0.45^{a}	280^{ab}	461^{ab}	55^{b}	101^{a}	70.6^{b}
	0 % VCM	5.49^{b}	116.7^{c}	1.01^{c}	285^{ab}	508^{b}	50^{ab}	104^{ab}	83.9^{bc}
	10 % VCM	5.73^{c}	56.7^{ab}	0.85^{b}	293^{ab}	498^{b}	46.1^{ab}	111^{b}	86.1^{c}
	20 % VCM	5.69^{c}	53.3^{a}	0.85^{b}	295^{b}	502^{b}	58.9^{b}	115^{b}	88.9^{c}
	30 % VCM	5.60^{bc}	73.3^{ab}	0.75^{b}	293^{ab}	564^{b}	47.8^{ab}	114^{b}	107^{d}
	LSD	0.16	29.7	0.13	18.5	91.7	10.9	10.7	13.4
	No Fert	5.26^{a}	76.7	0.59^{a}	303^{a}	459^{a}	42.2^{a}	87.8^{a}	50.6^{a}
2017/18	Rec Fert	5.34^{a}	83.3	0.67^{a}	295^{a}	547^{a}	53.3^{b}	90.0^{a}	75.0^{b}
	0 % VCM	5.62^{b}	91.7	1.34^{c}	287^{a}	585^{b}	52.8^{b}	99.4^{ab}	75.0^{b}
	10 % VCM	5.71^{b}	73.3	1.12^{bc}	281^{a}	554^{ab}	47.2^{ab}	123^{b}	83.9^{c}
	20 % VCM	5.63^{b}	85.0	1.04^{bc}	271^{a}	563^{ab}	46.7^{ab}	112^{b}	82.2^{c}
	30 % VCM	5.60^{b}	80.0	1.02^{b}	319^{b}	592^{b}	47.2^{ab}	118^{b}	90.0^{c}
	LSD	0.18	20.7	0.26	43.7	37.2	7.50	17.3	6.57

Values in the same column followed by the same superscript alphabetical letters are not significantly different at $p<0.05$ according to Tukey's HSD. (Data points are the mean of the three replicates). The 0 % VCM, 10 % VCM, 20 % VCM and 30 % VCM represent composts from mixtures of cattle manure with 0, 10, 20 and 30 % vermiculite while No Fert and Rec Fert means no fertiliser was applied and recommended fertiliser was applied respectively.

6.5 Discussion

Maize establishment, growth and yield

In both seasons, maize seed emerged and established well for all the fertility amendment treatments indicating that the amendments did not have phytotoxic compounds, such as the propionic, acetic and butyric acid, which hinder germination and seed emergence. Tiquia et al., (1996) and Tiquia and Tam (1998), reported that the application of immature composts inhibits seed germination, emergence and plant growth due to phytotoxic compounds. The composts used in this study were stable and mature as shown in Chapter 3 and Pisa et al. (2020). The maize plants in the negative control plots grew slower than those from other plots due to nutrient deficiencies as they had to make use of the little residual soil nutrients.

Nutrient uptake in the negative control plots could have been compromised as evidenced by the poor plant growth and low yields in both seasons. In the plots with amendments, maize growth was good, as a result of greater nutrient uptake due to improved nutrient availability. Growth and yield in the plots that received VCM were comparable to those that received the recommended fertilizer, indicating that VCM co-composts were as effective for maize growth as the basal compound fertiliser 7:14:7 (N: P_2O_5: K_2O). The higher yield components (cob number, cob weight per plot) in plots that received fertility amendment, than the negative control, were due to adequate nutrient supply.

Maize yields were as high as 6 t ha^{-1} for the positive control and the 30 % VCM composts in the second season and were close to the yield potential of 8 t ha^{-1} for the Seed-Co 513 variety used. These yields were much higher than what farmers usually harvest. This could be due to the fact that in this particular study the recommended 120 Kg N ha^{-1} was higher than what most smallholder farmers can afford to apply. Yields recorded in the negative control were however greater than the average yields in the smallholder (SH) sector of Zimbabwe which are less than 1.5 t ha^{-1} (Mashingaidze, et al., 2009). This can be explained by the high level of management applied to experimental plots that are usually small and were kept weed free, reducing competition for residual soil nutrients. Pest control was also optimum.

Grain yield from the VCM co-compost plots, especially the 30 % VCM compared well to the recommended fertilizer plots suggesting that application of the compost influenced maize yields in a similar manner to recommended fertilisers. Using the combination VCM co-compost as basal fertiliser and N fertiliser top-dressing resulted in good plant growth and improved maize yield. These results are similar to those reported by Eghball and Power (1999), who reported that annual compost application resulted in maize grain yields similar to those of the fertilizer treatment. Amanullah and Khan (2015) also concluded that a combination of 2 t ha^{-1} compost plus 120 kg N ha^{-1} increased maize yields. The increase in grain yield with an increase in the proportion of vermiculite in the co-composts, especially in the 2017/18 season, could be explained by greater availability of Ca and Mg from the composts and improved moisture retention. The leaching Ca and Mg was reduced by vermiculite and therefore were available for plant uptake. The same amount of nitrogen was applied to all the treatments receiving fertility amendment and thus any similarities or differences could be attributed to differences in mineralisation of N, in addition to increased Ca and Mg. Soil Mg was seen to increase with higher vermiculite proportions in the composts (Table 6.3). The availability of sufficient Mg is also important for increased uptake and utilisation of P (Mengel and Kirby 2001; Marschner 2002).

In the second season the amount of vermiculite in the soil had increased and thus its effects more pronounced. The residual effects of the first season, together with effects of the added composts in the second season, could have made the effects more pronounced in the second season. However, a number of laboratory studies indicate that the presence of vermiculite can induce N and K fixation (Douglas 1989; Fanning et al., 1989; Murashkina et al., 2007; Goli-Kalanpa et al., 2008; Najafi-Ghiri and Abtahi, 2013; Nieder et al., 2011; Portela et al., 2019), rendering these nutrients unavailable for plant uptake. It could also have been that the amount of vermiculite added with the composts was not high enough to induce significant fixation that would render the nutrients unavailable. Jayabalakrishnan (2007) reported improved sunflower yields and nutrient (NPK) availability when 5 t ha^{-1} of vermiculite was applied to soil and attributed this to enhanced CEC and the physical environment especially WHC of the sandy soils, resulting in increased crop productivity. Results in this trial were similar to this observation as shown by increased soil NPK with an increase in vermiculite proportions in the VCM composts (Table 6.3). The composts with vermiculite also contributed through its high available Mg and P, which contribute to initial root development and nutrient supply especially P for the emerging plants. The higher the vermiculite in co-compost resulted in greater soil available P (Table 6.3).

The higher yield observed with the 20 and 30 % VCM compost treatment contradicted the dry matter and nutrient uptake results in Chapter 5 which were lower than the positive control and the 0 and 10 % VCM compost treatments. This could be due to the differing conditions especially on availability of water. The pot experiment received constant irrigation while in the field the maize crop depended on rainfall. The VCM composts could also have improved the soil physical condition, increased available water capacity of the sandy loam soil, and thereby increased crop growth and yield. In wetter season, 2016/17, there were no yield differences between treatments with vermiculite and the recommended fertilizer (Figure 6.3) suggesting that moisture was less important. In the drier season (2017/18), however, an increase in vermiculite content in the VCM composts resulted in an increase in yields. This suggests that vermiculite application is beneficial in drier years making moisture more important. This is further supported by the gravimetric water content results in the pot experiment which showed that the 20 and 30 % VCM composts retained more soil moisture (Table 5.5). Vermiculite is porous in nature and thus retains moisture in the interlayer spaces.

The co-composts were applied as basal fertiliser just like compound D (7:14:7; N: P_2O_5: K_2O), and were therefore the sole external source of P in plots to which VCM co-composts were applied. Phosphorus is very important for improving crop growth and yield (Williamson et al., 2001; Wu et al., 2005). At an application rate of 5 t ha^{-1}, all the VCM co-compost supplied the same amount of P as the recommended inorganic basal fertilizer used fertilizer.

All the composts initially had between 0.24 – 0.36 % total P meaning application at 5 t ha^{-1} supplied 12- 18 kg P ha^{-1} similar to that applied by 250 kg ha^{-1} of Compound D (7:14:7; N: P_2O_5: K_2O). The application of 0, 10 and 20 % VCM co-compost as basal presented the required amount of P (35 kg P_2O_5), which is the optimum required for maize production (FAO, 2006). The P in the composts, however, was in the organic form and could only be released with compost decomposition. The application of the organic materials could, however, have enhanced the bioavailability of P due to increasing pH and added humic acids, which have a greater affinity for Al and Fe oxides than PO_4. The higher soil pH in the compost treatments than the negative and positive controls suggested that P was relatively more available due to lower precipitation with solution Fe and Al and fixation on oxide surfaces, at pH >5.5 (Price, 2006; Barrow, 2017; Penn and Camberato, 2019). Greater P availability supports good root development, which ensures adequate nutrient and water uptake. The soils used in the study were of medium acidity (pH =5.3) according to Zimbabwean classification and therefore application of composts could have improved P bioavailability by decreasing the P-sorption efficiency of the soil and P-buffering capacity (Azeez and Averbeke, 2011). Sato and Comerford, (2005) and Rupa et al., (2001) observed a decrease in P sorption with increases in pH from 4.7 to 7.0. In addition to increased increasing nutrient availability, the VCM composts could also have increased the soil physical condition, increased available water capacity of the sandy loam soil, and thereby increased crop growth and yield.

The application of vermiculite also increased soil Mg and Ca content and improved physical environment of the soil resulting in increased in maize productivity (Page et al., 1979; Jayabalakrishnan, 2007). Higher crop establishment, growth and yield in the composts with vermiculite could have been increased due to increased water holding capacity, improved root development and improved nutrient uptake. Although vermiculite is known to fix ammonium-N and K, this effect was not evident when the vermiculite was added as components (up to 30 %) of co-composts with cattle manure.

Soil properties

The application VCM co-composts resulted in an increase in soil pH to within the optimum pH range 5.5 to 6.5 (Table 6.3) for maize production (Islam et al., 1980; Köpp et al., 2011), while the controls had a pH of about 5.3. The composts used had pH >7.0, which resulted in the liming effect observed. Application of composts is responsible for the increase in soil pH through the addition of organic anions such as malate and citrate in organic material. Yan et al. (1996) demonstrated that pH increase upon addition of organic anions was attributed to the decarboxylation process. Application of compost has been reported to reduce exchangeable Al in soil due the chelation and/or precipitation of Al by organic materials (van den Berghe and Hue 1999). Cattle manure composts also contain appreciable amounts of carbonates (Eghball, 1999) which neutralise acidity and raise pH. The vermiculite applied in the co-compost could also have influenced the increase in soil pH change. van Straaten, (2006) reported that vermiculite application has a liming effect on soils, due to the adsorption of H^+ ions from solutions on to the negatively charged surface. The increase in soil pH could have increased P availability and uptake increasing yield. Although the pH was lower, in the recommended fertiliser plots, than the VCM compost treatments, the high growth and yield were mainly due to the application of plant nutrient in their available forms of at critical growth periods.

The higher soil OC in the plots with 0 % VCM than those with higher proportions of vermiculite, could be explained by the concentration of organic C added as part of the compost, which was lower at higher proportion of vermiculite. Application of the composts increased SOM content, which enhances soil structure via aggregate stability (Diacono and Montemurro, 2010) improves water infiltration and enhances water holding capacity. Furthermore, the presence of vermiculite improved soil condition, enhancing water holding. In sandy soils, compost helps in water retention thereby reducing drainage of water to below the root zone, which could have ensured that plant get enough water and nutrients. Soil moisture was not monitored in this study. However, with below minimum expected rainfall received in the 2017/18 season (550 mm), the grain yield increased with increasing vermiculite content unlike the 2016/17 season harvest, which had received above normal rains (1126 mm) of rain. Organic matter and vermiculite in the co-compost could have improved water retention in the root zone and thus effective water use.

The higher exchangeable soil Ca in the VCM co-compost treatments was explained by high of calcium concentrations of the initial co-composts. Vermiculite based composts could have retained Ca and Mg from decomposing organic matter in the soil due to high CEC, reducing their susceptibility to leaching. The increase in exchangeable soil Mg with increase in proportion of vermiculite in the co-compost was also attributed to the high Mg content in the VCM co-composts, which originated from the vermiculite.The vermiculite used in this trial was a magnesium-alumunium-iron silicate clay with a suggested structural formula, $(Mg,Fe^{2+},Fe^{3+})_3[(Al,Si)_4O_{10}](OH)_2{\cdot}4H_2O)$ (Fleisher and Madarion 1991, Jayabalakrishnan, 2007). Furthermore, increased CEC with the application of VCM co-compost could have also reduced Mg losses via leaching.

6.6 Conclusion

The application of cattle manure co-compost with 20 and 30 % vermiculite increased maize growth and yield similarly to that of the recommended rate of inorganic fertiliser. Soil amended with 20 and 30 % VCM compost after harvest had improved pH, SOM and available P, Ca and Mg. Exchangeable K however decreased with increasing vermiculite. The similarity in growth and yield between 20 and 30 % VCM co-compost treatment and recommended fertilisers means that farmers can substitute basal inorganic fertilisers with 20 and 30 % VCM co-composts and get improved maize yields of up to 6 t ha^{-1}. Though maize yields from the 0 % VCM and 10 % VCM co-compost treatments did not match those of recommended fertilisers, the yields from these treatments can be considered high enough to improve food security at household level in smallholder farming areas, when compared to the negative control. Smallholder farmers can therefore co-compost cattle manure with 20-30 % vermiculite and get improved soil fertility and yields. Further studies should focus on effects of applying these composts, on physical soil parameters such as bulk density, porosity, water holding, root growth, which could contribute in the improved growth of crops.

CHAPTER 7: GENERAL DISCUSION, CONCLUSIONS AND RECOMMENDATIONS

7.1 General Discussion

Soils in smallholder settings are generally poor resulting in low yields and food insecurity. Application of inorganic fertilisers is limited by the high prices, resulting in farmers applying suboptimal quantities (Wuta and Nyamugafata, 2002; Zingore 2006). Organic manures, especially after composting, are used as the sole fertilisers or to supplement inorganic fertilisers. Most smallholder farmers apply the organic manures as basal applications followed by N fertiliser top dressing (Zingore et al., 2011). However, nitrogen losses occur during composting and inclusion of vermiculite in the composting mixtures could reduce these losses. Vermiculite inclusion in composting can be used especially where large quantities of vermiculite waste occur. Vermiculite, however is known to fix K and NH_4^+, affecting their availability for plant uptake (Neider et al., 2011). This effect may be reduced by the co-composting with animal manure. The quality and fertiliser value of vermiculite-cattle manure composts is not clearly understood. The general objective of this study was to determine the quality and fertiliser value of vermiculite-cattle manure composts for maize (*Zea mays* L.) production on sandy loam soils in Zimbabwe.

Composting transforms organic materials into stable organic fertilisers (Zhao et al., 2019; Gao et al., 2019) useful in improving soil fertility and environmental sustainability (Awasthi et al., 2017; Wang et al., 2017). Nutrient loss during composting, reduces the agronomic value of the composts (Latifah et al., 2015). In this study inclusion of vermiculite in the composting of cattle manure resulted in improved performance as all composts managed to get into the thermophilic phase allowing the final product to be pathogen and weed free. The decomposition process was enhanced due to improved aeration and water holding capacity. Vermiculite inclusion at 20 and 30 % in the composting of cattle manure improved nitrogen retention. Total N increased with an increase in vermiculite. The NH_4^+:NO_3^- and C:N ratio decreased with the addition of vermiculite to composting cattle manure. A reduction in mineral N, with increasing vermiculite content suggests ammonium fixation. The higher N retention observed in treatments with more vermiculite supports the fixation phenomenom.

Potassium concentration in the final compost decreased with increasing vermiculite, a similar trend to NH_4^+ concentration. Both of these ions are prone to fixation by vermiculite minerals. Fixation of K increased with increasing vermiculite content in composts. The composts that initially had lower K and ammonium concentration, 20 and 30 % VCM composts, were seen to have higher fixation capacity. This could mean that fixation sites were not saturated during composting and therefore they could fix added K/ NH_4^+. Inclusion of vermiculite reduced exchangeable K while reserve K increased with increase in vermiculite. Reserve K was however low based on the classification by Elephant et al. (2019). The initial K fixation is important when K is applied to sandy and sandy loam soils as it prevents leaching losses by adding the K to the non-exchangeable pool, which can be used later when solution and exchangeable pools have been depleted.

Moderate fixation of K and low reserve K in soil amended with the 10, 20 and 30 % VCM composts suggests that application of these composts results in K^+ and NH_4^+ retention that may not be released during the growing season for plant use thereby increasing K/ NH_4^+ fertiliser needed compared with composts without vermiculite. The application of these vermiculite-based composts in sandy loam soils can result in fixation of added ammonium as the mechanism of ammonium fixation is similar to that of K fixation and can result in initial

N deficiency as N is made unavailable for plant uptake. Kowalenko and Cameron, (1976), Kowalenko (1978), Chantigny et al., (2004) and Rider et al., (2006) observed that 32 - 59 % of the added NH_4^+ is fixed within a short period of time in soils with high phyllosilicate clays. Ammonium and potassium fixation and release plays an important role for fertilizer N efficiency (Steffens and Sparks 1999; Juang et al., 2001; Nieder et al., 2011) as it impacts the indigenous soil K and N supply towards crop nutrient uptake. Initial reduction in exchangeable K reduces losses via leaching especially if the rains come soon after fertiliser application. Fixed K^+ / NH_4^+ can be released when soil exchangeable and solution K^+ / NH_4^+ are depleted improves K availability during the growing season.

Inclusion of vermiculite in composting of cattle manure resulted in an increase in nutrient retention in composts and application of these composts to resulted in K fixation (and possibly ammonium-N) and low reserve K. The overall effects of the improved nutrient availability in VCM composts, K^+ / NH_4^+ fixation and reserve K necessitated the need to determine the effects of increasing vermiculite content in co-composts with cattle manure on early maize growth, nutrient uptake and selected soil quality parameters under irrigated conditions. The application of vermiculite cattle manure compost on a sandy loam soil showed an improvement in early maize growth, plant nutrient uptake, and dry matter yield, and selected soil quality parameters after harvest. Dry matter yield decreased with increasing vermiculite content and this can be explained by the reduction in N and K uptake as vermiculite increased. Nitrogen was provided by both the composts and the 120 kg N kg^{-1} applied as inorganic fertiliser while the K was solely provided by the composts. The uptake of K was in the order positive control > 0 % VCM > 30 % VCM = 20 % VCM =10 % VCM > negative control. A similar trend is observed with initial K in the composts with the 0 % VCM composts having significantly more K than the composts with vermiculite. The fact that K and N uptake decreased with vermiculite inclusion, necessitate the need for extra care when using vermiculite so as not to induce fixation of K^+ and NH_4^+.

The effect of increasing the proportions of vermiculite in VCM co-compost on maize growth and yield and soil chemical properties under dryland field conditions was investigated as the study on early growth and nutrient uptake was done under a controlled environment. While the pot trial revealed that the 0 and 10 % VCM composts had significantly better early pant growth, dry matter yield and nutrient uptake at 10 WAE than the 20 and 30 % VCM composts, cob and grain yield was higher with the 20 and 30 % VCM composts under field conditions. In the field other variables would affect the response of maize to VCM composts application. This could be due to the differing conditions especially on availability of water. The pot experiment received constant irrigation while in the field the maize crop depended on rainfall. The VCM composts improved the soil physical condition, increased available water capacity of the sandy loam soil, and thereby increased crop growth and yield. In the second pot trial, where water was restricted. application of VCM improved water retention. The presence of vermiculite in the composts further enhanced water retention as supported by an increased water content as vermiculite content increased. These results highlight that where rainfall is limited (dryland crop production), moisture storage is more important and the highest proportion of vermiculite, tested would be more desirable. However, where moisture is not limiting, nutrients are more limiting and the lowest proportion of vermiculite is desirable.

Application of the VCM composts with 20 and 30 % vermiculite resulted in high maize grain yield which was comparable to the recommended fertiliser regime. Even though the uptake of N, and K was significatly lower in 20 and 30 % VCM composts treatments than the recommended fertiliser in the pot trial, Ca and Mg uptake were much higher and this could explain why grain yield for the 30% VCM treatmenst in the field trial was comparable to the recommeded fertiliser. Soil Mg was also seen to be increase with higher vermiculite proportions in the composts. The availability of sufficient Mg is also important for increased uptake and utilisation of P (Mengel and Kirby 2001; Marschner 2002). Application of VCM significantly improved yields compared to the negative control and thus their use as basal fertiliser can be an alternative to inorganic basal fertilisers for smallholder farmers. Yields recorded in the negative control were however greater than the average yields in the smallholder (SH) sector of Zimbabwe which are less than 1.5 t ha^{-1}, (Mashingaidze, et al., 2009). This can be explained by the high level of management applied to experimental plots that are usually small and are kept weed reducing competition for residual soil nutrients. Pest control was also optimum.

The application of composts has been reported to increase soil organic matter. Soil organic matter decreased with increasing vermiculite and this could be explained by the concentration of organic C, added as part of the compost, which was lower at higher proportion of vermiculite. Application of the composts increased SOM content, which enhances soil structure via aggregate stability, (Diacono and Montemurro, 2010) improves water infiltration and enhances water holding capacity. The increase in SOC and clay through vermiculite, increased nutrient and water-holding capacity, especially beneficial under dryland conditions. The higher nutrient retention with increased vermiculite in the compost, could be a result of increased CEC due to vermiculite and the organic matter. The higher nutrient retention was supported by the lower N leaching as vermiculite composition in the compost increased. This behaviour of nutrient retention and water holding is particularly important on sandy soils in smallholder areas where low and erratic rainfall is experienced. In addition to providing N and K and organic matter the composts provide other essential nutrients including phosphorus in addition to affecting soil pH. The composts used in the study had pH >7.0, resulting in a liming effect. Application of composts is responsible for the increase in soil pH through the addition of organic anions such as malate and citrate in organic material. The increase in soil pH could have increased P availability and uptake thus increasing yield.

The VCM composts also supplied Ca and Mg. The higher exchangeable soil Ca after application of VCM co-compost treatments was explained by high of calcium concentrations of the initial co-composts which increased with increasing vermiculite. The increase in exchangeable soil Mg with increase in proportion of vermiculite in the co-compost was attributed to the high Mg content in the VCM co-composts, which originated from the vermiculite. The vermiculite used in this trial was a magnesium-alumunium-iron silicate clay. The Ca: Mg ratios of 1.67, 1.2, 1.2 and 0.1 for the 0, 10, 20 and 30 % vermiculite composts, respectively, suggest that the composts could upset the Ca:Mg ratio of soil which should be above 2. This thus necessitates careful management in order not to upset the Ca:Mg ratio of soils, which could lead to poor Ca uptake.

The compost produced in this study was therefore of high agronomic value and had the potential to improve crop production. Smallholder farmers, especially those close to vermiculite mines, can therefore be encouraged to apply vermiculite to the cattle manure during stockpiling as a way of reducing nutrient losses.

7.2 Conclusions

1. Vermiculite inclusion at 20 and 30 % in the composting of cattle manure improved nitrogen retention, and reduced mineral N content, as percentage of initial N added, NH_4^+:NO_3^- ratio and C:N ratio.

2. Inclusion of vermiculite reduced exchangeable K while increasing fixed and reserve K in the VCM composts and soils amended with these composts, which may also apply to ammonium-N.
3. The application of 0 and 10 % vermiculite cattle manure compost on a sandy loam soil showed an improvement in early maize growth, plant nutrient uptake, and dry matter yield, water retention and selected soil quality parameters after harvest of irrigated maize.
4. The application of 20 and 30 % vermiculite cattle manure compost on a sandy loam soil improves cob and grain yields and selected soil quality parameters after harvest of dryland maize.
5. Application of VCM co-composts can improve maize yields by providing essential nutrients and improving soil fertility thus provide farmers with an alternative that is less detrimental to the environment than inorganic fertilizer, and also improves soil organic matter.

7.3 Recommendations

Soil fertility is key to improved crop productivity and consequently household and nutrient security in the smallholder farming sector of Zimbabwe. The lack of quality organic resources can be addressed by mixing cattle manure with vermiculite to improve the agronomic value of the resultant compost, which can be applied to soil and assist in the retention of nutrients especially N and K. Cattle manure and vermiculite mixtures with 20 or 30 % vermiculite are recommended for reduction of N loss and improving compost characteristics. Under irrigated land, the use 0 and 10 % VCM compost of would be recommended while under dryland condition 20 and 30 % VCM composts are recommended as basal fertilisers.

7.4 Further Studies

1. Effects of these composts as sole sources of N on crop productivity needs to be evaluated, since that is likely to be the more prevalent practice under smallholder farm conditions
2. Further studies should focus on effects of applying these composts on physical soil parameters such as bulk density, porosity, water holding capacity, root growth, which could contribute in the improved growth of crops
3. More work needs to be done on the effects of vermiculite cattle manure co-composts on the availability of micronutrients and nutrient uptake under field condition while monitoring soil moisture.
4. The scope of this study was limited to one soil type therefore the research can be replicated on other soil types like heavy soils.
5. The economic viability of vermiculite inclusion in cattle manure composting needs to be explored.

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