EVALUATION OF A PERI-URBAN SMALLHOLDER FARMERS' SOIL AMENDMENT PRACTICES ON SOIL QUALITY AND CROP GROWTH, YIELD AND QUALITY

By

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DECLARATION

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ABSTRACT

Peri-urban, smallholder farmers surrounding Cape Town, which are the main producers of fresh vegetables in the region, are generally not producing at their optimum level due to lack of agronomic support, marginal sandy soils and socio-economic constraints. The aim of this study was to evaluate the soil amendment practices of an organic smallholder farmer from Raithby, near Stellenbosch, in comparison with potential alternative organic and chemical amendments on soil fertility and vegetable crop growth, yield and quality and economic profitability.

During the first winter field trial, the farmer's routine soil amendment practice of adding 10 t/ha of commercially bought compost was compared with three alternative organic amendment practices and a commercial chemical fertilizer programme on broccoli production. Two on-farm produced composts, composted plant and animal waste (CW) and composted waste containing 20% biochar (CB), and the commercial compost (CC) were applied at typical smallholder application rate of 10 t/ha. The CW was also applied at broccoli N requirement equivalent to 22 t/ha (CWCR). These organic treatments were compared with a control soil (C) and a chemical fertilizer (CF) programme designed specifically for broccoli. There were no significant differences in soil quality at planting or at harvest (pH, EC, ECEC, plant available macro or micro-nutrients) or broccoli head nutrient content between treatments. However, the CF significantly ($p<0.05$) increased soil mineral N compared to all other treatments, whereas, CB significantly ($p<0.05$) enhanced soil C. Application of CF significantly ($p< 0.05$) increased broccoli yields (88% increase compared to CC) which was correlated with the higher soil mineral N, followed by CW (28% increase compared to CC). Application of CC, CB and CWCR resulted in non-significant changes in yield compared to the control, which was attributed to too much C being added to soil compared to N. Compared to the farmer's routine amendment practice (CC), the CF resulted in the greatest income increase (455%) followed by CW at 10 t/ha (151%).

During the second summer field trial, the effect of two composts, i.e., university compost (UC) and farmer's compost (FC), two commercial organic fertilizers, i.e., OF1 (blood and bone meal based) and OF2 (chicken manure based), and commercial chemical fertilizer (CF) programme was evaluated on green bean production. The commercial organic and mineral fertilizers were

applied at green bean N requirement rate of 158 kg N/ha. Whereas, the two composts were inadvertently applied at different N application rates relative to the commercial fertilizers (UC was added at 8.9 ton/ha (~49 kg N/ha), while FC was added at 17.8 ton/ha (~181 kg N/ha) due to a commercial laboratory providing incorrect elemental analysis of the composts prior to the field trial. All compost and fertilizer treatments significantly ($p < 0.05$) increased soil Bray II P contents above the critical value 25 mg/kg at planting except FC. The commercial organic fertilizers increased soil EC by a factor of 2-3, which resulted in lower bean plant survival. There were no significant differences in bean nutrient content between treatments, except for OF1 which contained significantly lower Mg content. Application of CF significantly ($p < 0.05$) increased (56% compared to control) green bean yields which was associated with a significantly ($p < 0.05$) higher (168% compared to control) cumulative soil mineral N, while the FC applied at 17.8 t/ha produced the second highest increase (37% compared to control) which was associated with higher (5%) number of plants that survived to harvest and the order was consistent in terms of economic feasibility.

The availability of mineral N was the main driver of crop yields and size of economic yield per plant in this study. Composts, especially commercial composts with low inherent N content, are not reliable sources of mineral N for intensive crop production. The commercial organic fertilizers, although better sources of mineral N, were prohibitively expensive and decreased plant survival. The organic smallholder farmer is likely to generate more income when he produces his own compost using animal and plant waste and applily the on-farm produced compost at N requirement of the crop in production rather than buying composts or organic fertilizers. The study also indicated that the farmer would generate much higher income, especially in winter when organic N mineralisation is slowest, if he would use a chemical fertilizer programme for both model crops.

OPSOMMING

Kleinhoewe kleinboere rondom Kaapstad is hoofsaaklik verantwoordelik vir die produksie van vars groente in hierdie streek. Weens die gebrek aan agronomiese ondersteuning, marginale sanderige gronde en sosiale- ekonomiese beperkings, produseer hulle nie op hul optimale vlakke nie. Hierdie studie vergelyk die invloed van grondverbeteringspraktyke van 'n organiese kleinboerdery, van Raithby naby Stellenbosch, met potensiële alternatiewe organiese en chemiese toevoegings, op grondvrugbaarheid en oesopbrengs, asook ekonomiese winsgewendheid.

Gedurende die eerste winter se veldproef, was die boer se gewone grondverbeteringspraktykte om 10t/ha van ŉ kommersiële gekoopte kompos toe te dien. Tesame met die is drie alternatiewe organiese grondverbeteringspraktyke met ŉ kommersiële chemiese bemestingsprogram op broccoli produksie vergelyk. Twee plaaslik (op die kleinhoewe) geproduseerde komposte, wat plant en diere-afval (CW) bevat en gekomposteerde plant- en diere-afval wat 20% Biochar (CB) bevat, en kommersiële kompos (CC) was teen 10t/ha toegedien. Die CW het ook aan broccoli se stikstofbehoefte vereiste van 22t/ha (CWCR) voldoen. Hierdie organiese behandeling was met 'n kontrole grond (C) en 'n chemiese kunsmis (CF) program wat spesiaal vir broccoli ontwerp is,vergelyk. Daar was geen beduidende verskil op die grondgehalte tydens oes (pH, EC, ECEC, plantbeskikbare voedingstowwe, (makro- of mikro-voedingstowwe) of voedingstowwe in die broccolikop se inhoud tussen behandelinge gekry nie. Hoewel, die CF 'n beduidende verhoogte grondmineraal N-inhoud in vergelyking met all die ander behandelings, gehad het, terwyl CB tot ŉ aansienlike ($p< 0.05$) verbeterde grond C-inhoud aanleiding gegee het. Toepassing van CF het aansienlik ($p< 0.05$) die opbrengs van broccoli verhoog (88% verhoging in vergelyking met CC) wat met hoër grond minerale N gekorreleer was, gevolg deur CW (28% verhoging in vergelyking met CC). Toepasing van CC, CB en CWCR het egter geen beduidende bydra tot opbrengs gehad nie, wat toegeskryf is aan te veel C en te min N wat aan grond in hierdie behandelings toegevoeg is. In vergelyking met die boer se gewone grondvebeteringspraktyk (CC), het CF 'n baie hoër inkomste getoon (455%) gevolg deur CW teen 10 t/ha (151%).

Tydens die tweede (somer) veldproef, was die effek van die twee komposte, naamlik universiteitskompos (UC) en boerekompos (FC), twee kommersiële organiese

bemestingstowwe, OF1 (bloed- en beenmeel gebaseerd) en OF2 (hoendermis gebaseerd), en kommersiële chemiese kunsmis (CF) -program op die produksie van groenboontjies vergelyk. Die kommersiële organiese en minerale kunsmis was op ‘n groenbone se N-behoefte van 158 kg N/ha toegepas. Die twee komposte was per ongeluk op verskillende N vlakke in vergelyking met kommersiële kunsmis (UC) toegedien. UC is teen 8.9 ton/ha (~49kg N/ha) toegedien, terwyl FC teen 17.8 ton/ha toegedien is (~181 kg N/ha). Die fout was weens ŉ kommersiële laboratorium wat ŉ verkeerde elemente ontleding van die kompos vir die veldproef verskaf het. Alle kompos en kunsmisbehandelings het aansienlik ($p<0.05$) verhoogde grond Bray II P-inhoud bo die kritiese waarde tydens plant van 25 mg/kg behaal, behalwe FC. Die kommersiële organiese kunsmis verhoog die grond EC met ‘n faktor van 2-3, wat tot gevolg gehad het dat minder groenboontjie plante oorleef het. Daar was geen betekenisvolle verskille in die voedingstofinhoud van die groenbone nie, behalwe vir OF1 wat ŉ betekenvolle laer Mg-inhoud gehad het. Toepassing van CF het die opbrengs van groenbone aansienlik (56% in vergelyking met die kontrole) verhoog wat geassosieer was met ŉ aansienlike ($p<0.05$) hoër (168% met vergelyking met kontrole) kumulatiewe grondminerale N. Behandeling FC het teen 17.8 t/ha die tweede hoogste (37% vergelyking met kontrole) produksie behaal wat geassosieer was met (5%) meer plante wat oorleef het. Die volgorde was konsekwent in terme van ekonomiese lewensvatbaarheid.

Die beskikbaarheid van grondminerale N was die belangrikste vir oesopbrengs en die groote van die ekonomiese oprengs per plant in hierdie studie. Kompos, veral kommersiële kompos wat lae inherente N bevat, is nie voldoende vir intensiewe produksie nie. Kommersiële organiese kunsmis is ‘n goeie bron van minerale N, maar dit is baie duur en verlaag die saailinge se oorlewing weens ŉ hoë soutinhoud. Die organiese kleinboer, sal waarskynlik meer inkomste kan maak wanneer hy sy eie kompos met die gebruik van plant en diere-afvalmateriaal kan maak, en verseker dat dit die nodige N bevat, inplaas daarvan om kompos of organiese kompos te koop. Die studie het ook aangetoon dat die boer ŉ baie hoër inkomste kan genereer, veral in die winter wanneer organiese N mineralisasie stadig is, as hy van ŉ anorganiese bemestingsprogram vir albei die gewasse gebruik sal maak.

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CHAPTER 1

GENERAL INTRODUCTION AND RATIONALE

Smallholder farmers are generally defined as poor resource farmers that practice intensive mixed agricultural production with limited capital to sustain their low-income families. Despite socio-economic challenges faced by small scale farmers in South Africa, agricultural productivity is threatened by scarcity of water for irrigation especially in the Western Cape due to drought, declining soil fertility in smallholding farms as constrained by lack of capital to obtain suitable soil amendments for ameliorating the soil and lack of technical or extension support from government institutes (Averbeke et al. 2008; Moswetsi et al. 2017; Ncube 2017). However, small scale farming plays a significant role towards the economy of many Sub-Saharan countries, hence, improving agricultural productivity through promotion of small scale farming is part of the national development plan (NDP) of the South African government.

Furthermore, peri-urban smallholder farmers around Cape Town generally lack access to land tenure and finance capital (Mdlalo 2008), and thus they practice low-input cost organic agriculture on rented land. The main aim of this research project was to evaluate peri-urban organic smallholder farmer soil amendment practices on crop growth, yields and quality; and soil quality in comparison with commercial organic agriculture and conventional agricultural practices. Furthermore, the economic profitability of the organic smallholder farmer and commercial farming systems was compared to give both agronomic and economic recommendations on the practices of the farmer. Ultimately, this research aims to assist peri-urban small-holder farmers to farm more successfully in terms of profit and soil quality by choosing the most optimal practices.

In the first year of the study (2016), a late winter field trial was set-up in collaboration with the organic smallholder farmer, Aron Mabunda, where broccoli (*Brassica oleracea var. italica*) was grown in a smallholding farm outside of the village of Raithby, Western Cape Province, South Africa. The farmer's current amendment practice (i.e. purchased compost applied at 10 t/ha) was compared with typical commercial organic and intensive farmer practices. This included evaluation of compost produced from local plant and animal waste available to the farmer and composted waste with 20% biochar. The plant and animal waste compost was applied at typical smallholder farmer's application of 10 t/ha and at commercial organic farmer's application rate to evaluate its effect on crop growth. The reason for applying the on-farm produced compost at typical commercial organic farmer application rate was to compare the differences in soil and crop response to organic farmer amendments. The organic practices were compared to conventional practice of applying weekly chemical fertilizer programme designed for broccoli.

In the second year (2017) of the study, a late summer field trial was conducted in the smallholding farm in collaboration with the smallholder farmer. The effects of two composts, two commercial organic fertilizers and a chemical fertilizer programme were evaluated on soil quality parameters and green bean (*Phaseolus vulgaris*) growth, yield and quality. The commercial organic and chemical fertilizers were applied at green bean N requirement of 120 kg N/ha, while the two composts were inadvertently applied at 49 and 181 kg N/ha because of incorrect compost elemental analyses obtained from a commercial laboratory prior to the trial.

A further aim of the study was to investigate the effect of the organic amendments used in both field trials on water holding capacity of the sandy loam soil at the field trial site and a sandy soil from the Cape Flats. A laboratory study was conducted using the application rates used in both field trials to evaluate the effect of the amendments and their respective application rates on soil water holding capacity. The specific aim of the study is to determine the application levels of organic amendments to realize a significant increase in soil water holding capacity, which is beneficial for crop production, especially in summer as drought is one of the major challenges during summer months in the Western Cape.

Since the South African dualistic farming sector is largely dominated by commercial farmers, financial and technical support has been given more to commercial farmers as they contribute more towards economic growth than smallholder farmers. This has led to lack of understanding of agronomic practices performed by smallholder farmers due to limited on-farm trials conducted in smallholding farms especially in the peri-urban region around Cape Town since the region is mainly dominated by commercial farmers. However, agronomic practices of smallholder farmers in the Eastern Cape and Limpopo provinces have been evaluated adequately, thus, the work done helps to close the gap in knowledge since smallholder farmers are likely to face similar socio-economic challenges but the variations in climate, soils and agronomic practices suggests that similar work needs to be conducted in the Western Cape.

This thesis is divided into five chapters, namely: (1) General introduction and rationale, (2) Literature review, (3) Winter broccoli field trial, (4) Summer bean field trial and (5) General conclusions and recommendations. Chapter 2 of this thesis focuses on challenges faced by smallholder farmers in South Africa and the agronomic practices that the farmers practice to adjust to the challenges that they are facing to realize maximum profit. Additionally, effect of the employed agronomic practices on soil quality and crop productivity is explored. The two experimental chapters (i.e. Chapter 3 and 4) address the objectives of the study with Chapter 3 discussing the results obtained in the late winter field trial while Chapter 4 discusses the results obtained in the late summer field trial. Lastly, Chapter 5 draws conclusions and gives recommendations for smallholder farmers and researchers while highlighting potential for future research.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Human efforts to produce ever-greater amounts of food to ensure food security for the growing population size in the world has proved to have detrimental impact on the environment. This detrimental impact is associated with the overuse of agrochemicals which run-off to water storage reserves and contaminate fresh water while intensive use of tillage implements promotes emission of greenhouse gases from the tilled soil and tillage machineries to the atmosphere, and distracts soil structure to such an extent that it becomes susceptible to erosion. In 1798, Thomas Robert Malthus suggested that population growth would exceed food production leading to famine. He reasoned that human population was growing exponentially while food production or supply was growing arithmetically. Hence without population control, the population would be reduced by catastrophes such as famine. This meant that ways of improving food production are required to protect human life from tragedies such as malnutrition and starvation.

One of the greatest human achievements towards food security occurred between the 1930's and 1960's when a set of research, development and technology initiatives increased food production significantly especially in Asia, America and Europe (Vanlauwe et al., 2001). This set of research, development and technology is referred to as the Green Revolution. During the green revolution, new varieties of crops that could perform well under adverse conditions were introduced and the use of chemicals such as inorganic fertilizers and pesticides was intensified to improve agricultural production in all parts of the world. However, green revolution practices did not significantly improve agricultural production in many African countries and this is attributed to lack of research and funds for obtaining chemicals and expensive high yielding crop varieties in most African countries (Vanlauwe et al., 2001).

Even though many studies show that green revolution practices (intensive use of agrochemicals) did not significantly improve agricultural productivity in most African countries, most commercial farmers have adopted the use of pesticides and fertilizers especially in South Africa as most commercial farmers export their products to generate greater income.

A study conducted in Cape Flats region in the Western Cape indicated that contaminants such as nitrates, chlorides and fluorides were detected to be at elevated levels in the Cape Flats aquifer and the contamination was due to application of agrochemicals (Adelana and Xu 2006). Whereas, another study conducted in three intensive agricultural areas of the Western Cape (Hex River Valley, Grabouw and Piketberg) which looked at levels of endosulfan in storage water reserves indicated that two areas out of three; namely: Hex River Valley and Grabouw had endosulfan concentrations which exceeded the drinking water standard and the elevated endosulfan concentration was due to application of pesticides in agricultural fields (Dalvie et al. 2003). This indicates that methods of fertilization and control of pests that work in harmony with the environment rather than against it need to be assessed and implemented.

The South African agricultural sector is dualistic in nature, consisting of poor-resource smallholder farmers that contribute 10% to the marketed agricultural output and developed commercial farmers that supply 90% of the country's marketed agricultural output (Moswetsi et al. 2017). Moswetsi et al. (2017) further suggest that due to a decline in the number of commercial farmers associated with persistent drought that the country is experiencing, smallholder farmers role in national agricultural production is critical as there is less estimated risk with smallholding relative to large scale farming. According to a report issued out by the Western Cape Government (n.d.) most smallholder farmers in the Western Cape are located in the Cape Flats which is regarded as the peri-urban region of Cape Town. The report further states that peri-urban farmers around Cape Town contribute 100 000 tons of fresh vegetables annually to the city's agricultural output and this helps to reduce food prices since less transport costs are covered which serves to mitigate climate change due to reduction of greenhouse gas emissions associated with use of fuel when transporting the agricultural products from smallholding. However, agricultural production of the peri-urban farmers located in the Cape Flats is under threat due to contamination of the Cape Flats aquifer since the aquifer supplies approximately 18 billion litres of water to the farmers and the city as whole (Adelana and Xu 2006). Additionally, there is excessive pressure put on the municipality to prioritise development of informal settlements surrounding the Cape Town area, hence little attention is paid to peri-urban smallholder farmers such that there is no proper sanitation, waste collection services or storm water infrastructure at the farming areas. Consequently, peri-urban smallholder farmers should be self-sufficient in controlling waste and dealing with adverse climatic conditions by using integrated waste management practices.

This chapter will evaluate effect of the smallholder farmer's farming practises on soil quality and crop productivity with limited compromise of the natural environment. This review will focus on challenges faced by smallholder farmers and provide possible sustainable solutions.

2.2 SUSTAINABLE FARMING METHODS

South African smallholder farmers are generally producing below their optimum potential due to declining soil fertility and inadequate management of water during irrigation associated with lack of agronomic support, scientific knowledge and financial constraints (Moswetsi et al. 2017). In the context of peri-urban smallholder farmers of the Western Cape, well drained sandy soils that dominate the farming area occupied by smallholder farmers requires excellent nutrient management as these soils tend to lose nutrients easily due to their low cation ion exchange capacity and low water storage capacity. Persistent drought and estimated erratic climatic conditions due to rising sea levels pose a threat to agricultural productivity of well drained sandy soils located in the peri-urban farming area around Cape Town as it is estimated that the area will receive high intensity rainfall events in a short duration of time (Western Cape Government 2016). Consequently, peri-urban smallholder farmers are advised to fertilize their soil with organic amendments produced from available organic waste since these farmers are in a highly dense populated area. Secondly, smallholder farmers can use crop residues obtained from harvest to fertilize their soils. The use of organic amendments for fertilization has a potential to improve cation exchange capacity, water holding and storage capacity of sandy soils, and promote sustainable crop production while mitigating climate change associated with integrated waste management through use of organic amendments. However, there are also some detrimental effects on crop production, such as N immobilization, if organic residues are of a low quality.

Organic residues from plant material contain relatively low amount of nutrients that will require mineralisation before they become plant available (Palm et al. 2001; Vanlauwe et al. 2002; Diaz et al. 2007). Subsequently, very slow nutrient release or net immobilisation from direct incorporation of crop residues leads to nutrient deficiencies that may negatively affect crop productivity. Furthermore, incorporation of crop residues especially fresh material can transfer pests and diseases from one cropping season to another, especially if the two crops that have sequential seasons host the same pests. Additionally, decomposition of fresh material from direct application of crop residues may introduce pathogens that might as well feed on roots of cultivated crops in the field.

The arguments put forward indicate that sustainable farming methods that promote use of organic amendments through integrated waste management need to be evaluated as they have potential to positively and negatively affect crop production.

2.2.1 Production of biochar

Biochar is a carbon rich product obtained when biomass, such as wood, manure and crop residues, is burned in a closed container with limited or complete absence of oxygen with a main goal of producing biofuels and the process is called pyrolysis (Lehmann and Joseph, 2009; and Sika, 2012). The process is very old as it was used to obtain phosphorus and sulfuric acid from pyrite, however, there is a growing interest in its use as it can be used to thermally degrade organic waste materials to produce biofuels and carbon-rich char that can be used as soil amendment to sequester carbon into the soil thereby managing waste and lowering greenhouse gas emission to the atmosphere (Zeelie, 2012). The process can also be used to thermally degrade synthetic polymers such as plastic waste to produce useful plastic or petroleum. Lehmann and Joseph (2009) indicate that type of biochar produced during a pyrolysis process is dependent on the organic materials used and the temperatures that prevail during thermal degradation of the material, and that the variation in types of biochar makes it difficult to characterize its crystal structure. For example, use of fine materials such as lawn clippings would yield fine particles of biochar as opposed to use of wood which would yield coarse biochar. Correspondingly, elevated temperatures would produce finer particles of biochar while low temperature would yield coarse biochar particles.

To understand the effect that biochar has on soil properties when applied as a soil amendment, a thorough investigation of chemical and physical properties of biochar needs to be executed as the characteristics would greatly affect soil biological, chemical and physical properties. The following subsections will evaluate the effect of temperature and type of material added in a pyrolysis process on chemical and physical characteristics of biochar produced. A further investigation will look at how variations in biochar affect soil properties.

2.2.1.1 Effect of temperature on the pyrolysis process

Since pyrolysis process involves thermal degradation of organic waste materials to produce bio-crude oil and biochar, temperature plays a crucial role in degrading the materials and it significantly influences the quantity and quality of the end-products of the process. Herath et al. (2013) indicated that elevated temperatures yield finer particles of biochar while low thermal degradation of the material during pyrolysis process will produce coarse particles of biochar provided that similar organic materials are thermally decomposed at different temperatures. This indicates that different temperatures yield distinct types of biochar both chemically and physically, the variations will result to differences in soil response to biochar application. Hence, it will be difficult to characterize biochar and give recommendations on how and when it should be applied as its characteristic will differ from time to time. Studies also found that high temperatures result in biochar particles having lower surface area compared with low temperatures which means that porosity of high temperature produced biochar would be greater (Brown et al., 2006 and Lehmann and Joseph, 2009). Depending on application rate of biochar to soil, physical and chemical characteristics of biochar will influence soil properties.

2.2.1.2 Effect of biomass on biochar production

Lehmann and Joseph (2009) stated that the chemical composition of biochar mainly depends on the organic materials added to the system before the process of thermal degradation and different organic materials added usually undergo thermal degradation at different temperatures. Various temperatures at which different organic materials would start to undergo thermal degradation will influence the stability of the end-product of the process. A study conducted by Sjöström (1993) indicated that different carbonaceous materials will thermally degrade at different temperatures, namely: cellulose is degraded at 240-350°C, hemicelluloses at 200°C while lignin will thermally decompose at 280-500°C. This indicates that the type of organic material added in a pyrolysis system and the temperature that prevails throughout the process will have a significant effect on the type of biochar produced.

Lehmann and Joseph (2009) noted that during thermal degradation of biological waste materials: oxygen, hydrogen, nitrogen and sulphur are removed from the material while 90% of carbon is retained in biochar whereas the remaining 10% of carbon reacts with steam in the system to form carbon monoxide. Carbon monoxide produced during the process of pyrolysis is usually used to fire up gas stoves for domestic purposes. Lee et al. (2013) points out that chemical composition and structural stability of biochar is not necessarily the same as the material from which biochar is made from. This means that even though biomass is usually composed of chemical substances that are produced during the process of photosynthesis, biochar does not necessarily contain the end-products of photosynthesis and the structure will depend on the portion of plant that was used during pyrolysis. For example, biochar that was produced from woody materials such as the plant stem will differ structurally from the one that was produced from leaves.

Many studies indicate that it is not only the type of biomass added and temperature prevailing in a pyrolysis system that determine the chemical and physical characteristics of biochar that will be produced by the process, other factors include: heating rate, pressure purge gas and particle size (Lehmann and Joseph, 2009; and Lee et al., 2013). However, for the scope of the work done in this research, smallholder farmers would only be able to control temperature of the process and type of biomass they add as other system parameters require highly sophisticated systems that would be economically unfeasible for small scale production.

2.2.1.3 Agronomical benefits offered by use of biochar and its constraints

Biochar addition to soil has benefits of improving soil chemical and physical properties while it also functions to sequester carbon into the soil thereby limiting greenhouse gas emission. Lehmann and Joseph (2009) indicated that specific surface area is the most principal factor that determines the role that biochar would play when applied to soil. Specific surface area of soil particles influences most vital functions for fertility, including water holding capacity of soils, aeration, cation exchange capacity and microbial activity.

Brady and Weil (2008) pointed out that sandy soils tend to have low water holding capacity compared with loamy or clayey soils as sand particles are known to have low specific surface area of about 0.01-0.1 m^2/g while clay particles have a relatively high specific surface area ranging between 5-750 m^2/g. This indicates that biochar would have positive effect on many characteristics of both sandy and clayey soils as sandy soil is known to have low water holding capacity while clayey soils tend to have relatively low aeration status. Lehmann and Joseph (2009) pointed out that biochar addition to sandy soils has a potential to improve water holding capacity since biochar particles have a higher specific surface area relative to sand particles while biochar addition would improve aeration status of clayey soils as biochar particles have relatively lower particle surface area compared to clay particles. This therefore means that nutrient availability will then be improved in both clayey and sandy soils as improved aeration status in clayey soils would promote mineralisation of organic nutrients while improved water holding capacity would promote availability of nutrients in soil solution for plant uptake. Consequently, biochar can be used to limit soil erosion in fields that are susceptible to erosion by wind or water due to biochar's structural features and the ability to increase surface charges in soil (Jien and Wang, 2013).

On the contrary, many scientific studies elaborate that biochar addition to soils may over-lime the soil such that soil pH increases to levels that make most nutrients to be unavailable for plant uptake and may elevate molybdenum toxicity as molybdenum becomes more labile at alkaline soil pH (Beesley et al. 2011; Sika 2012). Additionally, it is well known that biochar application to soils has potential detrimental impact of immobilizing nitrogen since its surface charges have affinity to adsorb and fix N in nitrate form (NO_3-N). A meta data analysis study conducted by Thu et al. (2017) showed that short term studies performed on biochar application from 2010-2015 suggest that application of biochar complimented with chemical fertilizers reduces soil inorganic nitrogen while application of biochar with other organic amendments induces mineralisation of organic N thereby increasing soil inorganic N. These observations imply that blending biochar with other organic amendments such as compost or organic fertilizers might have positive effect on mineralisation of N when biochar is utilized as a soil amendment.

Singh et al. (2014) suggested that the adoption of biochar as soil amendment in Australia has been slow due to contrasting results in terms of crop productivity due to application of biochar. The contrasting observations are due to different biochar used in numerous studies and they are also partly due to environmental conditions at which studies were conducted. Unless a certain technology development shows consistent results in terms of improving crop yields and profits, farmers will be reluctant to adopt certain technologies as they must protect their businesses from catastrophic practices.

2.2.1.4 Environmental benefits of the pyrolysis process and its constraints

Production of biochar through the pyrolysis process functions to reduce greenhouse gas emissions to the atmosphere while use of biochar as a soil amendment serve to sequester carbon into the soil. Brady and Weil (2008) pointed out that soil is the most efficient terrestrial ecosystem that can function to store carbon instead of allowing carbon dioxide emissions to the atmosphere as elevated levels of greenhouse gases in the atmosphere have resulted to global warming. Since biochar is a highly stable carbonaceous material, applying it to soil would have a major environmental benefit of storing carbon in soil thereby reducing the level of greenhouse gases in the atmosphere. Accordingly, the main idea of applying biochar into soil is attributed to potential of soil to store carbon for a long period of time mitigating greenhouse gas emissions and thereby reducing climate change (Singh et al. 2014).

Biochar has vast beneficial effects on the environment that include the following: rehabilitation of acid soils in mining field and mitigating climate change through reduction of greenhouse gas emissions. Due to biochar's adsorbing features and its liming effect, biochar can be applied to soils that have been contaminated with toxic chemicals such as petroleum to allow biochar to adsorb contaminates and render them ineffective in soil as a biological habitat. Furthermore, biochar can be applied in acid soils in mining fields to rehabilitate pyrite affected soils (Singh et al. 2014; Jien and Wang 2013; Botha 2016). Affinity and capacity of biochar to adsorb and store organic molecules towards its surfaces has initiated the use of biochar in low-cost agricultural water treatments such as water polluted during wine making (Botha 2016; Singh et al. 2014).

In contrast to biochar's adsorbing features, application of biochar to herbicide treated fields may render the herbicide ineffective in preventing the growth of weeds as biochar tends to adsorb organic molecules in soils (Singh et al. 2014). In view of use of biochar for rehabilitation of acid soils, many scientific studies have indicated that use of biochar as a soil amendment may over-lime the soil to a level that induces molybdenum toxicity (Beesley et al. 2011; Lehmann and Joseph 2009; Sika 2012). Furthermore, application of pure biochar to soil also immobilizes nitrogen and this a major challenge in crop production. For these reasons, it has been proposed in the agricultural sector that various methods of adding value to biochar should be investigated for better agronomic use. Such methods include incorporating biochar into a composting process to render its negative effects ineffective when applied to soil (Dias et al. 2010; Sika 2012; Botha 2016). Additionally, contaminants that may form part of the biomass used during the pyrolysis process such as polyaromatic hydrocarbons, toxic metals, other organic and inorganic contaminants may still prevail in biochar produced at the end of pyrolysis (Singh et al. 2014). Therefore, application of biochar with contaminants to soil will cause accumulation of toxic substances in soil that will eventually become detrimental in crop production and to soil as a natural habitat. Lehmann and Joseph (2009) pointed out that due to variations in biochar nutrient composition and differences in production costs of biochar as different technology uses different temperature, economic feasibility of biochar production is one the main constraints that results in biochar technology to remain in a fledging state. Admittedly, it is more economically feasible for farmer's to produce biochar at small scale for their own use as there is unreliable market for this product as a soil amendment due to its contrasting effects on soil fertility and crop productivity (Singh et al. 2014).

In summary, biochar production offers vast beneficial effects such as mitigation of climate change, rehabilitation of pyrite affected soils in mining sites, waste water treatment in agricultural fields, reducing susceptibility of soils to erosion and other environmental benefits. However, financial feasibility of producing biochar at commercial scale is one of the major limiting factors in marketing the product. This financial constraint is due to variations in technology used to produce biochar, farmer's reluctance to adopt biochar as soil amendment attributed to contrasting effects of biochar on crop productivity and variation in chemical composition of the product which would affect its influence on soil.

2.2.2 Production of compost

Integrated solid waste management practices have been introduced by government, industries and business institutions due to alarming environmental impact that landfill waste disposal has on natural habitat and water storage pollution. In South Africa, "reduce, re-use, recycle" phrase was introduced by government and private sector as an awareness for people as means of trying to promote integrated solid waste management. Diaz et al. (2007) pointed out that integrated solid waste management is a design of an operation that functions in harmony and efficiently with various complementing units that form part of the operation in managing solid waste. Various processes of turning waste into beneficial materials such as biochar, compost and other recycled products have been evaluated and are used around the world to sustain livelihoods of people in under-developed, developing and developed countries.

Composting is a practice of biodegrading organic waste materials in an aerobic natural or controlled environment to create humus like material called compost that can be used as soil amendment to improve soil fertility (Diaz et al. 2007; Brady and Weil, 2008). Microorganisms facilitate the process of decomposition of organic materials in a composting process. Therefore, the efficiency of decomposition of organic substrates in a compost pile depends on environmental conditions preferred by the prevailing microbes present in that compost pile. Accordingly, Brito et al. (2008) suggested that decomposition of organic materials during composting is influenced by temperature, moisture content of the pile, C/N ratio of the organic mixture, pH and the physical structure of raw biomass added as it determines aeration of the compost pile. However, temperature is known to be the most essential parameter that indicates decomposition of organic materials during a composting process. Brady and Weil (2008) pointed out that the composting process consists of three important phases, namely: (1) mesophilic phase- initial stage where readily available microbial food sources are decomposed causing a rise in temperature from ambient to ~40°C, (2) thermophilic phase- occurs after the mesophilic phase where temperature reaches 50-75°C due to microbial activity when more resistant carbon sources such as cellulose and lignin are undergoing decomposition and (3) curing phase- last stage where carbon decomposition has stabilized resulting in temperature decline to ambient. Duration of the composting phases is determined by environmental conditions prevailing in the composting system and the stability of the end-product is dependent on the stages of composting. Therefore, it is important to mix the compost piles frequently during the thermophilic stage as most pathogens and seeds die off at this stage.

2.2.2.1 Effect of internal and external environmental conditions of composting pile

Aeration, temperature and moisture content are the major environmental components that one would be able to manipulate when designing a composting system. Aeration is very important in thermophilic composting as it affects microbial activity in a composting pile. Aerobic conditions in a compost pile promote circulation of gases within the pile while anaerobic conditions inhibit microbial respiration which induces loss of nitrogen through denitrification as microbes will use nitrogen metabolites for respiratory purposes in the pile (Diaz et al. 2007;

Amlinger et al. 2003). In addition, temperature is the main factor that indicates efficiency of the composting process as optimal temperature of a composting pile reflects a concession of minimal nutrient loss and optimal inactivation of pathogens in the pile. Brito et al. (2008) suggested that composting temperature ranging between 45-55°C is considered to optimize composting efficiency while elevated temperatures exceeding 55°C destroys pathogens present in the biodegrading biomass. Despite the mentioned beneficial effects of elevated temperatures in a composting pile, elevated temperatures also induce volatilization of ammonia from N present in the system and leads to a loss of nitrogen which might promote nitrogen immobilization when compost is applied to soil. Furthermore, moisture content of the composting pile should not exceed 60% as moisture might inhibit elevation of temperatures such that the thermophilic stage is not reached by the pile (Brito et al. 2008; Diaz et al. 2007). Application of compost that did not reach a thermophilic phase that lasted for at least 15 days to soils might introduce pathogenic diseases that may affect crop production and soil fertility negatively.

External environmental factors play a role by either cooling down or warming up the composting pile and that can either be negative or positive depending on the prevailing conditions of the pile. For instance, if the composting process is conducted in atmospheric conditions and the pile heats up to temperatures above 65°C then, rain from the atmosphere would reduce temperatures thereby limiting loss of nitrogen to the atmosphere. Correspondingly, it is ideal to construct a composting pile in a tunnel in winter as that would allow the composting temperature to increase inducing efficient decomposition of the biomass while building a pile in a cold environment would reduce the efficiency of the composting process.

2.2.2.2 Effect biomass mixture on the composting efficiency

The composting process involves the use organic materials, thoroughly mixed to obtain a certain C/N ratio and environmental conditions that are adequate for survival of microorganisms which induce biodegradation of the biomass using enzymes. In the agricultural sector, biomass is generated from crop fields in the form of crop residues while huge amounts of animal excreta is generated from dairy and livestock production. Grasty and FAO (1999) pointed out that the global agricultural sector contributes 18% of greenhouse gases towards global warming with dairy and livestock production contributing elevated levels of methane. Consequently, use of organic materials such as crop residues, animal excreta and processed food waste as substrates or feedstock in composting is essential for reducing the escalating levels of greenhouse gas emissions to the atmosphere.

Substrates that are used to build a compost pile usually originate from biological activity such as photosynthesis or consumer biomass (Diaz et al. 2007). Subsequently, it is vital for one to assess the mixing ratio of substrates that are used to build a compost pile as biomass characteristics would have an influence on readily available source of energy for microbes and the environmental conditions existing within the compost pile. Diaz et al. (2007) suggested that compost piles should always have higher ratio of loose fragments (i.e. plant material) than dense material (i.e. animal excreta). Crop residues are usually fibrous and contain small amount of nutrients compared with animal excreta which is usually highly nutritious and dense. This means that in order to obtain adequate environmental conditions in a compost pile there should be greater volume of plant biomass than animal excreta. In contrast, adding high amount of animal excreta into a compost pile may result in anaerobic conditions that might promote emission of ammonia from the pile due to the fact that microbes will reduce nitrogen metabolites for respiratory purposes when oxygen circulation is inhibited in the pile (Al Naddaf et al. 2011). It is essential to understand the composition of organic molecules of crop residues incorporated into a compost pile as it determines the efficiency of microbes to decompose the substrates.

Dias et al. (2010) pointed out that carbon to nitrogen content is one of the most important parameters to consider when mixing different substrates to build a compost pile. C/N ratio is an indicator of source of energy for microbes as microbes would decompose readily available feedstock such as proteins and sugars during the mesophilic phase of the composting process while they will degrade much more stable carbon sources such as cellulose or lignin during the thermophilic phase. Thus, it is essential to understand the composition of substrates added in a compost pile as C/N ratio ranging between 25-30 is considered optimal for microbial activity.

2.2.2.3 Agronomic benefits of using compost and its constraints

There are three main reasons why we compost fresh biomass before application to soil and they are: (1) to reduce phytotoxic features of fresh organic substrates, (2) to inactivate pathogens that may be present in fresh biomass by exposing the litter to thermophilic conditions and (3) to produce a humus-like soil amendment that is free of pathogens and diseases (Diaz et al. 2007). Therefore, recycled organic wastes that does not fulfil the features of a mature compost put forward by (Diaz et al. 2007) should be regarded as immature.

Application of a mature compost to soil can improve water holding capacity of a soil, nutrient content and soil structure which functions to reduce susceptibility of soil to erosion. Due to compost porous structure, application of compost to sandy or clayey soil would improve water holding capacity of sandy soil by reducing the pore sizes between sand particles such that water would adhere more to reduced pores while in clayey soils compost would increase pore sizes thereby increasing the storage capacity of a clayey soil. Consequently, improved soil water holding capacity would result in improved nutrient use by crops as dissolved nutrients would remain much longer in sandy soil solution instead of leaching while ammonia emissions would be reduced in clayey soil that would have resulted due to water logging given that storage capacity of clayey soil was not improved (Roy et al. 2010). Additionally, improved soil structure results in elevated storage capacity of soil which could function to reduce susceptibility of soil to erosion as structure-less soils are usually prone to soil erosion by water and wind (Jien and Wang 2013; Herath et al. 2013). Improved soil conditions promote good crop growth as aeration and water content would be adequate for proper root development.

However, many scientific studies show that use of compost in crop production is threatened by the slow release of nutrients and immobilization of nutrients such that they become deficient in plant tissues (Cambardella et al. 2003). Deficiency of nutrients in crops reduces yields, plants become prone to diseases and pest, and crop quality may be reduced such that farmer’s do not realize income by the end of the growing season. Additionally, compost production and its application to soil is a labour-intensive practice that would have negative financial implications when one wants to apply it on a large scale. Henceforth, many scientific studies suggest that application of organic amendments in small scale farming could alleviate crop yields thereby making smallholder famers generate more income especially if they produce compost on farm as there would be less financial implications associated with that.

2.2.2.4 Environmental benefits of using compost and its constraints

Since composting involves the use of waste materials that would probably end up in a landfill, the practice of composting reduces environmental pollution such as soil contamination and water pollution in dams, rivers and lakes due to deposition of substances from landfill sites in water storage systems which would lead to eutrophication, disturbing ecological systems that exists in fresh water. Additionally, waste disposed in landfills undergoes biodegradation due to microbial activity which induces emission of greenhouse gases to the atmosphere and that contributes towards global warming. Composting organic waste materials instead of disposing them in landfills reduces air, water and soil pollution while recycling nutrients that can be used to sustain crop growth in agricultural fields (Thanh et al. 2015; Diaz et al. 2007). However, production and application of biochar to soil reduces greenhouse gas emission to a greater extent relative to composting since the gases are collected for use. Thus, blending compost with biochar has been suggested as a form of improving the stability of compost which reduce greenhouse gas emissions in soil while supplying plants with adequate amount of nutrients.

However, environmental conditions that prevail in a compost pile determine the fate of greenhouse gas emissions from the pile to the atmosphere (Diaz et al. 2007b; Brady and Weil, 2008). For example, if anaerobic conditions prevail in a compost pile oxygen becomes deficient for microbial respiration such that microbes use nitrate present in the biomass for respiratory purposes, likewise, nitrogen content will be reduced in compost and ammonia will be released to the atmosphere. Financial feasibility is another major constraint that limits adoption of compost production by farmers and in the business sector as a whole. Diaz et al. (2007) pointed out that commercialization of compost production has been slow due to variations in compost quality because of differences in biomass used for composting and limited market for compost.

2.2.3 Potential for sustainable farming methods in African countries

According to Bationo (2003) the African continent has approximately 340 million people with 50% of this population size living in rural areas. At least 14% of children under the age of 5 years die due to malnutrition and other opportunistic diseases that target weak immune systems while 28% of the population is chronically hungry with life expectancy of only 54 years. Kplovie et al. (2016) reported an increment of life expectancy in Africa to 61 years. However, it remains the lowest in the world with Europe, North and South America having highly significant life expectancies compared to other continents. Since half of the African population is found in rural areas, direct dependence on locally produced agricultural products is the main form of consumption due to limited infrastructure for transportation of foods from supermarkets in urban areas to rural areas. Therefore, rural development is essential for improving livelihoods of people in the African continent as half of the population would be able to contribute towards the economy. Bationo (2003) pointed that agricultural development is dawdled by the following factors: (1) low soil fertility and removal of fertilizer subsidies, (2) over dependence on rainfall attributed to under-developed infrastructure in rural areas, (3) inadequate extension services and research, (4) inconsistent policies and land tenure, and (5) insufficient market because most smallholder farmers are in rural areas and that results to high post-harvest losses. Low soil fertility and removal of fertilizer subsidies factor indicates that intervention through sustainable farming methods is required to improve agricultural productivity in Africa.

2.3 CONCLUSIONS

This review indicates that thorough investigation of fertilization using organic and inorganic fertilizers in crop production has been conducted intensively throughout the world. The disadvantages and advantages of both farming methods have been outlined for different environments under various farming methods. The most important reason of supplying nutrients through a chemical fertilization programme is because the crop is supplied with the required amounts of plant-usable nutrients at a specific phenological growth stage. This has advantages in terms of not only maximising crop yields and quality, but also improving crop nutrient-use efficiency. While application of organic amendments helps to increase SOM, CEC and soil water holding capacity that also functions to reduce susceptibility of soil to erosion. However, nutrient management is quite difficult in organic farms since organic amendments need to mineralise from organic form to mineral form since the plants absorb and assimilate nutrients dissolved in soil water that are in mineral form.

The difficulty brought by application of organic amendments in nutrient management requires extensive studies that seek to optimize nutrient management when organic amendments are used as a form of fertilization. This is required mostly in smallholding farms since it is generally more economically feasible to apply organic amendments in small scale farming because the practice is labour intensive. Additionally, it is very important to compare the effect of organic amendments with chemical fertilizers since smallholder farmers perceive that the practice of applying chemical fertilizers is expensive compared to organic amendments while it is not always the case. There is a huge gap in understanding soil fertility and plant nutrition within the society as there is a myth that organically treated crops are more nutritious than crops treated with mineral fertilizers while crops absorb mineral nutrients dissolved in soil solution.

Furthermore, this study will help transfer scientific knowledge from the researchers to the smallholder farmer while the researchers will be learning indigenous practical methods that the smallholder farmer utilizes on farm. This could help incorporate the smallholder farmer’s indigenous knowledge systems into scientific research which would help in making scientific research applicable to the society. Lastly, this study will function to give the farmer agronomic support which is one of the major constraints for smallholding in the region as the province is dominated by large scale commercial farmers.

CHAPTER 3

WINTER FIELD TRIAL: COMPARISON OF COMPOSTS AND CHEMICAL AMENDMENTS ON BROCCOLI PRODUCTION AND SOIL QUALITY

3.1 INTRODUCTION

Smallholder farmers are generally defined as farmers who practice intensive diversified production on marginal land with limited natural resources and capital (Ncube 2017). This statement suggests that smallholder farmers utilize accessible resources to optimize their production to realize maximum income. Additionally, poor urban and peri-urban smallholder farmers around Cape Town in the province of the Western Cape are faced with poverty, high family dependency, lack of sufficient land, security of tenure, and lack of financing options (Mdlalo 2008). These socio-economic factors negatively affect the production of the small-holding sector in the region and in most parts of the country.

Consequently, smallholder farmers tend to fertilize their soils with easily accessible or relatively cheap soil amendments such as kraal manure, organic waste materials or compost. These types of soil amendments utilized by smallholder farmers release nutrients slowly compared to chemical fertilizers as they depend on microbial decomposition to mineralise organically bound nutrients. This has implications on crop performance and productivity as undernourishment of crops negatively affects yields. Additionally, water availability for irrigation is one of the major constraints faced by the South African agricultural sector with only less than 10% of the arable land being irrigated (Moswetsi et al. 2017). Therefore, application of organic amendments to soil may assist to alleviate water problems in the long run as elevated soil organic matter helps to retain more water in the soil, however, nutrient management should be the major concern especially in the Western Cape region as the soils are mainly sandy with low cation exchange capacity. Subsequently, Moswetsi et al. (2017) suggests that financial support provided by South African government and non-governmental organizations (NGO's) for smallholder farmers should be accompanied by agronomic support as there is very little progress in efforts to help farmers to be more productive.

There is limited knowledge of the types of amendments that are used by smallholder farmers and the effect that the amendments would have on crop growth due to lack of agronomic support for smallholder farmers. This gap in knowledge requires a thorough evaluation of smallholder farmers agronomic practices to provide sound agronomic recommendations that will help smallholder farmers to farm more successfully.

Consequently, a peri-urban smallholder farmer who practices organic agriculture on the outskirts of Cape Town was selected for the study. The smallholder farmer was routinely using a commercially available compost and he was applying it at the rate of 10 t/ha per cropping season, but was interested in producing his own compost. Therefore, two types of composts (composted green and animal waste, and 20% pine biochar containing compost) were produced using readily available organic materials to compare their effect on soil quality and crop response relative to the farmer's normal amendment (i.e. commercial compost). The farmer selected broccoli (*Brassica oleracea var. italica*) as a model crop since the first field trial was conducted in late winter and the farmer had a market for the crop when it matures. Broccoli is one of the most essential cool season crops that belong to the brassicas family and is well known for its anticancer properties (Omirou et al. 2009). The commercial compost, and two on-farm produced composts were applied at the farmer's usual rate of 10 t/ha. The on-farm produced composted waste was also applied at 22 t/ha which was equivalent to broccoli N requirement. The organic compost treatments were further compared with a commercial chemical fertilizer programme designed for broccoli.

The main objective of this experimental chapter is to evaluate the smallholder farmers current farming practices in comparison with alternative organic and chemical farming practices, in terms of crop production, soil quality and economic profitability. This experimental chapter has the following specific objectives:

- To evaluate the effect of on-farm produced composts, commercial available compost and chemical fertilizer on the growth, yield and quality of broccoli; and soil quality.
- To determine the effect of on-farm produced composts and commercial available compost on water-holding capacity of a sandy loam soil from the smallholding farm and a sandy soil from the Cape Flats.
- To perform a basic marginal analysis of the various organic and chemical soil amendment practices.

3.2 MATERIALS AND METHODS

3.2.1 Compost Production and Characterization

It was decided to produce two types of composts using locally available materials in order to compare this to the farmer's current practice of buying commercial compost (CC) and applying it at 10 t per ha. The first compost was made using only plant and animal waste (CW), and second compost was made with locally available pine wood biochar (CB). Biochar was selected as it is reputed to increase soil water holding capacity and breaks down more slowly than fresh residues.

3.2.1.1 Compost Production

Lawn clippings (from the university grounds), wheat straw and cattle manure were obtained from Welgevallen Experimental Farm of Stellenbosch University for making the composts. These materials were selected as they are also readily available to smallholder farmers in the area. Slow pyrolysis pine wood biochar was obtained from a local producer, S&P Carbon Ltd in the Eastern Cape. Pine biochar is the most commonly available type of biochar on the South African market, as it is typically made from pine sawmill waste. The biochar had been previously described and characterized by Sika and Hardie (2014). Kikuyu grass cuttings were also transported from the smallholding farm near Raithby (where the field trial was to be conducted) to Welgevallen Experimental Farm. The compost was produced at Welgevallen so that the composting process could be closely monitored. Grass (lawn clippings and kikuyu grass), wheat straw and cattle manure were mixed thoroughly to reach a C to N ratio of 27:1 as a C/N that is between 25-30 is recommended for efficient breakdown of organic materials during a composting process (Table 3.1). This C/N ratio was obtained by determining moisture, C and N content of the materials before mixing and calculate the required mass of each material required to obtain a C/N ratio of 27. After thoroughly mixing the raw materials to form a single pile, the composting pile was divided into two unequal piles (one with estimated mass of 40 kg and the other with 20 kg of the mixture) and to the smaller pile 20% of pine wood biochar was added on a dry mass basis. The composting piles were composted for three months under atmospheric conditions and they were overturned on weekly basis to allow uniform breakdown of the materials for the first two months. The piles were also irrigated on weekly basis to promote microbial activity throughout the composting process. The following parameters were measured to monitor the composting process: moisture content, temperature and dehydrogenase enzyme activity.

Table 3.1: Carbon to nitrogen ratio of the materials used for composting and their respective bulk densities used for estimating mixing contents to obtain dry 60 kg compost mixture with a C/N ratio of 27:1.

Composting material	C/N Ratio	Wet BD (kg/L)	Dry BD (kg/L)	Mixture (%) for C/N ratio of 27:1	Wet equivalent volume for 60 kg of dry compost (L)
Cattle Manure	15:1	0.695	0.259	45	388.49
Grass	13:1	0.086	0.032	35	2441.86
Wheat Straw	80:1	0.074	0.018	20	1621.62

3.2.1.2 Compost Characterization

Compost moisture content was measured on weekly basis until the end of the thermophilic phase by subsampling the piles three times and drying the samples in an oven at 60°C for 24 hours to determine the amount of moisture lost during drying. Temperature was measured on weekly basis throughout the composting process by inserting a long temperature probe in all sides of the pile and the readings were averaged to obtain the average temperature of each pile. Triplicate samples were collected using subsampling method from each composting pile for determination of dehydrogenase activity on day: 5, 30, 60 and 90. These days were chosen because they represent the three important stages in a composting process, namely: oxidative, thermophilic and maturation stage. These samples were also used to determine C and N content to monitor biodegradation of the composting materials. Electrical conductivity (EC) and pH were also measured from samples collected on the above-mentioned days to monitor the conditions for active microbes in the compost piles. Germination Index (G.I) and C/N ratio were measured on samples collected during termination of the composting process and these parameters were also measured on samples obtained from commercial compost used by the farmer to evaluate maturity of the three composts. The following subsections explain how each of the parameters were measured.

3.2.1.2.1 Electrical conductivity and pH

Dry compost sample was sieved with a 2 mm sieve and 5g of sieved compost was mixed with 50 ml of deionised water (1:10 w/v), the mixture was shaken for 30 minutes (Jindo et al. 2012). After shaking, the mixture stood for 10 minutes then pH and electrical conductivity (EC) were determined with the use of Metrohm 827 lab pH meter and a Jenway 4510 EC meter, respectively.

3.2.1.2.2 Proximate analysis, total C and N

Proximate analysis is a thermogravimetric method of determining moisture content, ash content, fixed and volatile matter content in biological compounds (Sweeten et al. 2003; Williams et al. 2001; Botha 2016). Proximate analysis is an indicator of the amount of energy stored in biological compounds or solids. According to Williams et al. (2001) and Botha (2016), the ASTM standard method points out that moisture content of biological solids should be determined after drying the substance at 105°C, volatile matter after burning at 900°C in an inert atmosphere while fixed carbon is the mass lost at 750°C in aerobic conditions. Ash content is the amount of material left after moisture content, volatile matter and fixed carbon is determined. Proximate analysis is a widely used method to determine the amount of energy stored in organic solids and it is determined in the form of moisture content, ash content, fixed carbon and volatile matter (Sweeten et al. 2003; Williams et al. 2001). Moisture content is usually disregarded when proximate analysis of a compost is evaluated as compost application is estimated on dry matter basis because nutritional quality of a compost is determined on a dry compost sample.

Total C and N content in compost samples were measured using the dry combustion as described by Nelson and Sommers (1982) () with the aid of EuroVector Analyser. The C/N ratio is regarded as one of the most vital factors that play a crucial role in the biodegradation of organic substrates in a composting process since it indicates carbon and nitrogen content which are sources of energy for microbes in a biological system. Venglovsky et al. (2005) pointed out that a C/N ratio of 25-30 is regarded as the ideal C/N ratio for biodegradation of organic materials in a composting system, but the author further argues that a C/N ratio ranging between 20-35 should be considered acceptable during a composting process. Initial C/N ratio that is below 20:1 is known to promote volatilization of nitrogen as ammonia into the atmosphere thereby forfeiting compost quality by decreasing N content while initial compost C/N ratio exceeding 35:1 is known to slow the degradation process as microbes are supplied with too much carbon source to decompose.

3.2.1.2.3 Dehydrogenase Activity

Dehydrogenase enzymes are involved in many biochemical processes in biological systems and are thus routinely used as indicator of oxidative biological activity (Kumar et al. 2013). Dehydrogenase activity was measured per the method explained by Tabatabai (1994)which makes use of an electron acceptor (triphenyl tetrazolium chloride) which was reduced to triphenylformazan.

Air-dried compost was sieved through a sieve of less than 2 mm in diameter and 6 g of compost was mixed with 0.06 g of $CaCO_3$, the sample was dispensed into three different test tubes and each test tube contained 1 g of the mixture of compost with $CaCO_3$. Thereafter, 1ml of 3% of TTC was added in each test tube and 2.5 ml of deionised water was added. The samples were thoroughly mixed using a glass rode and then they were left in an incubator for 24 hours at 37°C. After 24 hours, the samples were removed from an incubator and 100 ml of methanol was added in each test tube in 10 ml portions to allow development of the red colour formed by the formazan. The red extract was filtered through a cotton wool into a 100 ml volumetric flask to the endpoint and the absorbance of the red extract was determined in a spectrophotometer at a wavelength of 485 nm. Absorbance was converted to concentration of TPF produced by preparing a calibration curve with a correlation coefficient of 95-100%. The TPF calibration curve was prepared by diluting 10 ml of TPF standard solution (1 mg TPF/ml) with methanol to 100 ml in a volumetric flask and pipetting 5, 10, 15 and 20 ml from the diluted TPF solution into four different volumetric flasks and diluting them with methanol to 100 ml. The red colour intensity from the prepared TPF standard solutions which contained 500, 1000, 1500 and 2000 ug TPF ml^{-1} was measured in the spectrophotometer at 485 nm wavelength as described for the samples with methanol as a blank.

3.2.1.2.4 Germination Index

Germination index is a maturity test based on seed germination and initial growth stages of plants using an extract from the compost (Urpilainen et al. 2005 and Zucconi et al. 1981). This method indicates phytotoxicity of the compost at various stages of the composting process and the compost is considered mature when the G.I is 60% or greater when compared with seeds germinated in deionised water which should be regarded as the control (Diaz et al, 2007) . Many scientific studies have used this method as an indicator of compost maturity (Diaz et al. 2007; Kumar et al. 2013).

Germination index was performed according to the adapted method ofZucconi et al. (1981). Five grams of air-dried compost (<2 mm) was mixed with 50 ml (1:10 w:v) in a centrifuge cube and they were placed in reciprocal shaker for 1 hour. The centrifuge cubes were removed from a reciprocal shaker after 1 hour and the centrifuge cubes were centrifuged at 3000 rpm for 15 minutes, the supernant was then filtered through a Whatman No 6 filter paper into an extraction bottle. Wheat seeds (*T. aestivum*) were placed on top of cotton plug in a petri dish, 10 wheat seeds were used for G.I. In each petri dish, 10 ml of the supernats from the compost samples (commercial compost, waste material compost and 20% pine biochar compost) were added and 10 ml of deionised water was added to the control petri dish. All the samples were replicated three times and the petri dishes were left inside the laboratory cupboard to limit evaporation of the liquid for three days. After three days, the total length of the radicle was measured using a 15 cm ruler and for the seeds that did not germinate the radicle length was considered to be 0. Germination index is given as percentage according to the following equation:

$$G.I\ (\%) = \frac{Total\ length\ of\ roots\ on\ the\ compost\ extracts}{Total\ length\ of\ roots\ on\ the\ deionised\ water\ dish} \times 100\%$$

3.2.1.2.5 Maturity Indices and Elemental composition

Maturity of the compost piles was determined by making use of C/N ratio method explained by Neyla et al. (2009) and wheat seed germination index method explained by Diaz et al. (2007). Total elemental composition (N, P, K, Ca, Mg, Na, Mn, Cu, Zn, Fe) was determined by treating the compost samples with an acid as done for plant samples when performing wet digestion method (Jindo et al. 2012) and the concentrations of the nutrients were obtained by Inductively Coupled Plasma Spectroscopy.

3.2.2 Effect of on-farm produced compost, commercial compost and chemical fertilizer on broccoli growth, yield and quality; and soil quality

3.2.2.1 Site description

The broccoli field trial was conducted on a small-holding farm located near Raithby, a small village located approximately 15 km south of Stellenbosch. The Raithby small-holding farm is located at latitude 34° 01' S and longitude 18° 47' E, at an altitude of 95 m above sea level. The area has a warm temperate, sub-humid with a mean annual temperature of 16.6°C and an average rainfall of 650 mm received mainly during the winter months (June-August). The sandy soil at the site is relatively shallow (40-50 cm) and is classified as Wasbank soil form in the Lynedoch family (Soil Classification Working Group 1991). This indicates that this land is not suitable for deep rooted crops. The field was previously left fallow with Kikuyu grass (*Pennisetum clandestinum*) growing there for several years. The textural analysis of soil from the farm was performed using a pipette method (Gee and Bauder 1986). Table 3.2 below, shows preliminary soil analysis results for a sample that was obtained when the site was first visited which was used for designing the field trial.

Table 3.2: Baseline soil chemical and physical properties before the establishment of the experimental field trial

Carbon (%)	Nitrogen (%)	pH		EC (mS/m)	Bray II-P (mg/kg)	Textural fractions (%)		
		H_2O	KCl			Sand	Silt	Clay
1.4	0.12	6.94	6.43	0.049	55.74	75	10	15

3.2.2.2 Field trial experimental design

Broccoli (*Brassica oleracea var. italica*) was selected as the field trial crop since the trial was conducted during winter (Jul.-Oct. 2016) and there was a strong demand for broccoli by the smallholder farmer's regular clients. The smallholder farmer's routine soil fertility amendment practice (application of commercial compost (CC) at 10 t/ha) was compared to three alternative organic amendment practices, a commercial chemical fertilizer programme for broccoli and a control treatment (Table 3.3). The three alternative organic amendment treatments made use of the composted waste (CW) and composted biochar (CB) that were produced at the university experimental farm (Section 3.2.1.1). The composted farm waste was applied at 10 t/ha (CW) and at a rate of 300 kg N/ha (CWCR) according to the typical N needs of broccoli, while the composted biochar was applied at 10 t/ha (Table 3.3). Experimental treatments of the field trial were replicated three times and laid out in a randomized completely blocked design with plots sizes of 4 m^2 (Figure 3.1). A randomized completely blocked design was used to block the fertilizer from interfering or contaminating the organic amendment treatments or the control. Chemical fertilizer was applied on three experimental plots that were on the lower edge of the whole experimental plot as the experimental site was slightly sloping ((Figure 3.1 and (Figure 3.2).

Two weeks prior to transplanting of broccoli seedlings the three types of composts were applied at their respective application rates to allow the soil to buffer to the changes brought by amendments before planting. Composted biochar (CB) was applied at an application rate of 10 tons per hectare, composted waste (CW) was applied at 10 tons per hectare and 300 kg N per hectare (~22 tons/hectare, abbreviated CWCR) and the commercial compost (CC) was applied at 10 tons per hectare (Table 3.3). Commercial fertilizer (CF) was obtained from Yara Cape Ltd and applied according to an 11-week fertilizer programme designed specifically for broccoli production by YARA (Table 3.4). The first application of chemical fertilizer was applied a week before transplanting broccoli seedlings according to the fertilizer programme (Table 3.4). The experimental plot was irrigated automatically for 1 hour per day using micro jets. The scheduling of the irrigation system was decided upon measuring the time it takes for the waterfront in the soil profile to reach the effective rooting depth of 30 cm meters for vegetables production.

Table 3.3: Experimental treatments, their application rates and macro nutrients input.

Treatment name	Treatment abbreviation	Application rate	Amount of macro nutrients applied (kg/ha)					
			N	P	K	Ca	Mg	S
Control	C	0	0	0	0	0	0	0
Commercial Compost	CC	10 t/ha	68	20	14	217	19	-
Chemical Fertilizer	CF	188 kg N/ha	188	68	171	123	11	47
Composted Biochar	CB	10 t/ha	162	36	95	274	35	-
Composted Waste	CW	10 t/ha	169	37	108	277	31	-
Composted Waste (Commercial Rate)	CWCR	22 t/ha	300	82	238	478	68	-

Table 3.4: Weekly applications of YARA chemical fertilizer products and the amount of macro nutrients supplied by each application.

Time	Product name	Application rate (kg/ha)	Macro nutrients supplied (kg/ha)					
			N	P	K	Ca	Mg	S
Before planting	Superstart	300	23.4	23.4	23.3	30	3.4	19.3
Week 1	Turbo 31	100	19.5	1.9	9.8	1.8	0.0	0.9
Week 2	Turbo 31	100	19.5	1.9	9.8	1.8	0.0	0.9
Week 3	Nitrabor	125	19.3	0.0	0.0	22.9	0.0	0.0
Week 4	Superstart	300	23.4	23.4	23.3	30	3.4	19.3
Week 5	Nitrabor	100	15.4	0.0	0.0	18.3	0.0	0.0
Week 6	TopUp	125	13.9	4.6	27.5	0.0	1.1	1.6
Week 7	Nitrabor	100	15.4	0.0	0.0	18.3	0.0	0.0
Week 8	TopUp	125	13.9	4.6	27.5	0.0	1.1	1.6
Week 9	TopUp	125	13.9	4.6	27.5	0.0	1.1	1.6
Week 10	TopUp	100	11.1	3.7	22.0	0.0	0.9	1.3

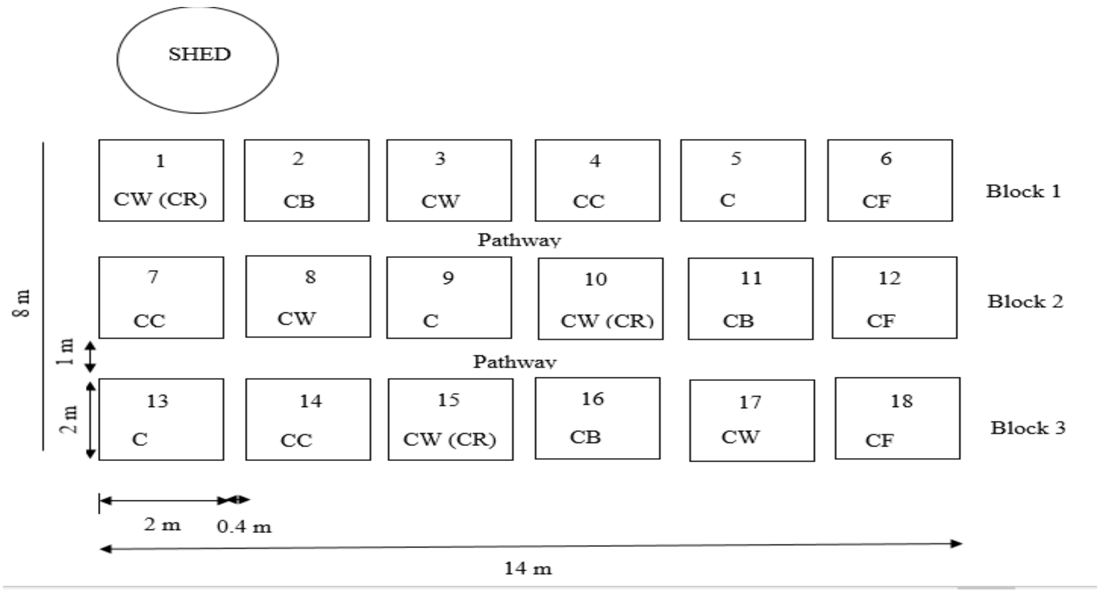

Figure 3.1: Plan of the experimental layout with six triplicated treatments.

Figure 3.2: Photograph of the experimental plot at planting.

A pathway of 1 m between blocks and on the edges of the blocks was left fallow to limit interactions between blocks and edge-effect from weeds or farmers production. Only 2 m × 1.5 m of the treated 2 m x 2 m plots was planted with broccoli (at a row and inter row spacing of 0.3). An amended 2 m × 0.5 m buffer strip was left unplanted in each treatment plot so that soil respiration could be measured apart from the broccoli root respiration.

A composite soil sample was taken from each of the experimental plots at planting to determine soil fertility status brought by the application of the amendments at the start of the field trial. Soil samples were collected on weekly basis during the growing season of broccoli to measure mineral N (nitrate and ammonium ion) content in soil during the first 12 weeks when broccoli requires the most N (Schonhof et al. 2007; Omirou et al. 2009; Louis 2011). Soil samples were also collected at harvest from each experimental plot to evaluate change brought by uptake of nutrients by plants and leaching of nutrients due to percolation of water. Pest control was performed according to organic farming practices on all the treatments according to the farmer's normal practice. This involved applying neem oil for controlling aphids and commercial organic insect spray containing pyrethroids for controlling caterpillars that were feeding on broccoli leaves. Weeding was performed by manual labour on all the treatments according to the farmer's routine practices. Broccoli yields and nutritional quality was determined when the crop reached maturity. Marginal analysis of each treatment was also performed once the crops had been sold.

3.2.2.3 Determination of soil chemical and physical properties

3.2.2.3.1 Soil pH and Electrical Conductivity

Soil samples dried at 105°C for 24 hours were sieved with a 2 mm sieve and 10 g of sieved soil was mixed with 25 ml of deionised water (1:2.5 w/v) and the mixture agitated for 30 minutes (AgriLASA 2004; Soil Survey Staff 2014). After shaking, the mixture was left to stand for 10 minutes then pH and electrical conductivity (EC) were determined with the use of Metrohm 827 lab pH meter and a Jenway 4510 EC meter, respectively. For soil pH, 1 M KCl was also used as described to determine soil pH that accounts for exchangeable acidity.

3.2.2.3.2 Plant available macro and micro nutrients

Plant available P was determined using the Bray II method that was developed by Bray and Kurtz (1945). This method of extraction for P is based on the effect of H^+ on solubilizing soil P and the ability of F^- (added in a form of NH_4F) to lower the activity of Al^{3+}, Fe^{2+} and Ca^{2+} on exchange sites to complex with P because that would result in underestimation of P. Bray II solution was prepared by dissolving 2.22 g NH_4F with 19.5 ml of 32% concentrated HCl in 2 L volumetric flask with 1 L deionized water and filling up the flask to the mark with deionized water. Oven dried 2 mm sieved soil samples that were obtained at planting and at harvest were weighed into 100 ml plastic bottles, and they were mixed with Bray II solution in 1:8 (w/v) soil to solution ratio. The 100 ml bottles were agitated for a minute and the mixtures were filtered through a Whatman no. 40 filter paper into extraction bottles. Colour development was performed by treating 20 ml of each extract obtained from each treatment replicate with 10 ml boric acid-molybdate reagent and 10 ml reducing agent solution, then filling up the 50 ml volumetric flask used for colour development with deionized water to the mark as described by (AgriLASA 2004). Samples stood for 20 minutes to allow colour development and the extracts were then transferred into 2 ml cuvettes, colour intensity was then measured at a wavelength of 660 nm on a Jenway Spectrophotometer. Results were obtained as absorbance and they were converted by preparing calibration standards. Calibration standards were prepared by dissolving 0,439 g of KH_2PO4 in a 1 L volumetric flask that contained 400 ml deionized water and adding 4.4 ml concentrated H_2SO_4, diluting the mixture with deionized water to the mark. From the prepared stock solution contained 100 mg P/L; 0, 2, 4, 6, 8 and 10 ml was then pipetted into six different 100 ml volumetric flasks and then the flasks were filled with deionized to the mark. The same procedure for colour development was performed on 20 ml of each working standard and the samples were read in a spectrophotometer after 20 minutes of colour development by using a blank (0 mg P/L) to zero the spectrophotometer. A calibration curve that had a correlation coefficient of 95-100% was used to convert the results from absorbance to concentration (mg P/L) and using the mass of soil and volume of the extracting solution (Bray 2) results were converted to mg P/kg soil.

Exchangeable basic cations (Ca, Mg, Na and K) were extracted with ammonium acetate in 1:10 (w/v) soil to ammonium acetate solution ratio as described by Thomas (1982) while plant-available micronutrients were extracted with Di-ammonium EDTA in a 1:2 (w/v) soil to Di-ammonium EDTA ratio as described by Whitney (1998). Ammonium acetate and Di-ammonium EDTA extracts were analysed using Inductively Coupled Plasma Mass Spectroscopy (ICP-MS).

3.2.2.3.3 Loss on ignition, total carbon and nitrogen

Loss on ignition is a widely used method for determining total soil organic matter (SOM) (Konare et al. 2010). To determine SOM for each treatment replicate, 2 g of soil was weighed into a weighed and labelled platinum dish. Platinum dishes that contained soil were re-weighed with the soil and inside, then they were placed in a muffle furnace set to 550°C for 4 hours. After 4 hours, the platinum dishes were taken out into a desiccator to cool to room temperature for one hour and the dishes weighed again. The difference in mass loss represented organic matter that was degraded at 550°C. This method was used for samples at planting and the ones that was obtained at harvest, because the aim was to measure the amount of OM that would have been degraded after one cropping season.

Total carbon and nitrogen content was determined for samples collected at planting using dry combustion method as explained by Nelson and Sommers (1982) with the aid of EuroVector Elemental Analyser. This was performed to evaluate change brought by the application of the amendments compared to the control (i.e. no application of any amendment) as it would influence microbial activity and consequently that would affect how nutrients are mineralised over time, especially nitrogen.

3.2.2.3.4 Nitrogen mineralisation

Nitrogen mineralisation was determined on weekly basis as it was hypothesized that it would be one of the main limiting factors in the organic amendment treatments as it is known that composts mineralise N slowly, especially during winter (Brady and Weil, 2008). Samples were collected in the late afternoon (16:00) once a week to ensure similar time of day as this affects mineralisation dynamics. Collected samples were kept in a cooler box with ice from the farm to the lab and they were then immediately extracted with 2 M KCl to determine mineral N while at field moisture content. The moisture content of each sample was determined by drying some of the soil in the oven at 105°C for 24 hours and determining the change in mass. This was done to limit denitrification of nitrogen due to anaerobic bacteria that would consume N for metabolic purposes when the sample is kept in an airtight plastic in a warm environment.

Mineral N was determined using 2 M KCl in a 1:5 ratio (w/v) and shaking the mixture at 180 oscillations in a reciprocating shaker for 1 hour (Mulvaney 1996). The mixture was then filtered through a Whatman filter paper into an extraction bottle. A colorimetric method was used for determining mineral N (NH_4^+ and NO_3^+) as described by Mulvaney (1996) in the 2M KCl extracts. Colour development for ammonium ion was done by treating 0.2 ml of the KCl extract with ammonium test kit (Merck Pty (Ltd.), South Africa) while nitrate ion was done by treating 1.5 ml of the KCl extract with nitrate test kit (Merck Pty (Ltd.), South Africa). Colour intensity in ammonium treated extracts was measured in a Jenway 7315 spectrophotometer at a wavelength of 667 nm while that of nitrate treated extracts was measured at a wavelength of 540 nm according to Mulvaney (1996). Absorbance measurements obtained were calibrated by preparing a set of ammonium ion standards that contained 0, 2, 4, 6, 10, and 20 ug of NH_4^+-N, and that of nitrate ion which contained 0, 2, 4, 6, 8, 10 and 20 ug NO_3^--N. The first set of standards (i.e. NH_4^+-N working standards) were prepared by first making a standard solution of ammonium sulphate that contained 100 ug NH_4^+-N per ml of the solution. A solution of ammonium sulphate that contains 2 ug NH_4^+-N per ml of the solution was prepared from the 100 ug NH_4^+-N solution and then pipetting 0, 1, 2, 3, 5 and 10 ml of the prepared standard solution into six different 100 ml volumetric flasks that contain the same amount of 2 M KCl that was used for extraction. The same procedure that performed to prepare standards of NH_4^+-N was used for NO_3^--N, the exception was that potassium nitrate was used to prepare the standard solution instead of ammonium nitrate. The procedure that was performed on soil extracts was then performed on the standards from this point, 0.2 ml of NH_4^+-N standard solutions were treated with ammonium test kit and 1.5 ml of NO_3^--N standard solutions were treated with nitrate test kit. Colour development from the standards solution was measured in a spectrophotometer at a wavelength of 667 and 540 nm for respective ions (i.e. NH_4^+-N and NO_3^--N). Calibration curves that had a correlation coefficient from 95-100% were used for both ions to convert results from absorbance to concentration (mg/kg). The following digital images show the colour differences in extracts analysed for NH_4^+-N and NO_3^--N:

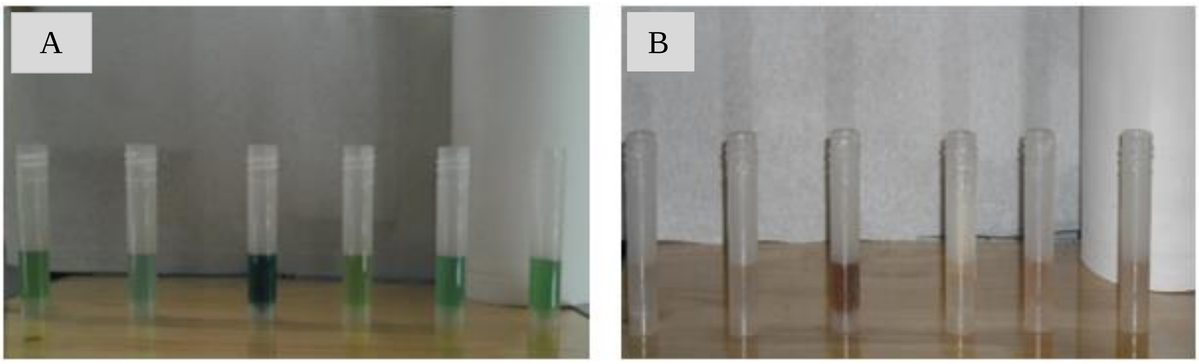

Figure 3.3: Digital images of 2 M KCl extracts treated with ammonium (A) and nitrate (B) test kits, respectively.

3.2.2.3.5 Soil Respiration

Soil is a natural habitat with a vast number of microorganisms, macrofauna and plants. These organisms co-exist with each other in soil as an ecosystem and they have various functions that could either benefit the soil as natural resource or their ecosystem. Carbon dioxide (CO_2) evolution (soil respiration) is usually measured in soil quality studies as an indicator of organic matter decomposition by microorganisms (Soil Survey Staff 2014). The soda lime method was used to measure cumulative carbon dioxide evolution from different plots treated with varying soil amendment and this method is known to be one of the most low-cost reliable methods of measuring carbon dioxide emission from the soil (Keith and Wong 2006).

The soda lime method entails weighing ±10 g of soda lime pellets [NaOH and $Ca(OH)_2$] (Merck Pty (Ltd.), South Africa), into a perforated plastic tube then fixing the pellets with fibre glass inside the tube and oven drying the fixed soda lime in plastic tube at 105°C for 14 hours. After 14 hours of oven drying, the perforated tubes weight was recorded, and they were placed in an airtight Ziploc bag then transported to the field. On farm, the tubes were removed from the Ziploc bag and they were hung inside a polyvinylchloride (PVC) chambers that had a height of approximately ±4 cm with a diameter of 12 cm. The PVC chambers were sealed on top with aerated tubes that contained an unknown amount of soda lime which were fixed in place with glass wool. The closing tubes were put in place to allow the chamber to exchange oxygen with the atmosphere while limiting atmospheric carbon dioxide from entering the chambers. Keith and Wong (2006) indicate that soda lime constituents (i.e. NaOH and $Ca(OH)_2$) react with CO_2 to form carbonates such as Na_2CO_3 and $CaCO_3$ which results in weight gain. The perforated tubes containing soda lime were replaced every two weeks with fresh tubes. The used traps were dried again for 14 hours at 105°C and they were weighed to determine mass gain. The difference in mass would then represent total carbon dioxide respired over weeks. To account for handling errors, which could either result to overestimation or underestimation of CO_2 evolution, three blank chambers with weighed perforated soda lime tubes inside were placed on the experimental plot with closed lids on both ends of the chambers. The blank chamber's perforated tubes were also weighed with perforated tubes that were placed on the treated plots and their weight gain was subtracted from the difference obtained from treatments perforated tubes as a handling error.

3.2.2.4 Determination of crop response parameters

Chlorophyll content index was measured to monitor plant response to N mineralisation/immobilization as influenced by the different soil amendments applied. Chlorophyll content index (CCI) was measured using a CCM-200 plus chlorophyll meter (Opti-Sciences, Inc. 8 Winn Avenue, Hudson, USA) on ten leaves in each plot and the values were averaged to capture crop variations for each treatment replicate. The results from the chlorophyll meter were calibrated using a method described by Richardson et al. (2002) which involves collecting ten leafsamples that have a colour differences and rank the differences from 1-10, then measure the chlorophyll content index and extract each leaf sample with methanol after cleaning the leaves with 3% detergent and deionized water. The absorbance of extract was then measured in a spectrophotometer. Absorbance was converted to concentration using simultaneous equations developed and explained by Arnon (1949). A calibration curve was drawn on CCI results and chlorophyll concentration extracted from the leaf samples that were used for benchmarking the results. The model was well described by a linear model and a linear function was used to convert results from CCI to chlorophyll concentration.

Total broccoli fresh head weight yield was measured weekly from each treatment replicate and representative broccoli head samples were taken. Broccoli head samples were oven dried at 60°C for 24 hours and taken to Elsenburg Analytical Laboratory, where the samples were milled, and acid digested. Total mineral content of broccoli heads was determined in an Inductively Coupled Plasma Mass Spectroscopy (ICP-MS) to assess crop quality from different soil amendments. Marginal analysis was performed on crop yields obtained from each soil amendment treatment and this was done to evaluate economic profitability of each soil amendment treatment as it results to crop yields.

3.2.2.5 Soil Water-holding Capacity Laboratory Experiment

A soil water holding capacity experiment was conducted in the laboratory to evaluate the effect of the selected organic amendments on the water holding capacity of the sandy loam soil at the field trial site, and a sandy soil from the Cape Flats region. These two soils were selected as they are typical of soils used for vegetable production in the Cape Town peri-urban and urban regions. The sandy loam soil was collected from the smallholding were the field trial was conducted and the sandy soil was collected from a Kroonstad soil form (Soil Classification

Working Group, 1991) located in the Cape Flats in Brackenfell, Western Cape (33°53’42.67” S, 18°43’26.982”) (Table 3.5).

Table 3.5: Textural fractions of the soils used for soil water holding capacity.

Textural Class	Textural fractions (%)		
	Sand	Silt	Clay
Sandy Loam	75.0	10.0	15.0
Sandy	97.6	1.9	0.5

The organic amendments (composted biochar and composted waste) were applied at the same rates as the rates used in the field trial (Section 3.2.2.2) and pure pine biochar was also used as amendment applied at 10 t/ha. Thus, this experiment had six treatments, namely: control (C), biochar (B), commercial compost (CC), composted biochar (CB) and composted waste (CW) applied at 10/ha; and composted waste (CWCR) applied at 22 t/ha. The amendments were mixed with soil individually in 1 L beakers and the amended soils were packed in core rings fitted with filter on the bottom end to allow for infiltration of water, according to the method adapted from Cassel and Nielsen (1986). All the treatments were replicated three times. The core rings with various treatment replicates were weighed, their weights were recorded before they were left in water overnight to saturate. After saturation, the core rings were placed on freely drainable surface to allow the amended soils to freely drain for 24 hours. The core rings were weighed after drainage and the difference between dry weight, wet weight and water held by the filter paper (correction factor) was taken as water holding capacity as described by a method explained by Soil Survey Staff (2014).

3.2.3 Statistical and Marginal Analysis

The data obtained was statistically analysed using analysis of variance (ANOVA) for repeated measures which is a two-way ANOVA and where necessary a one-way ANOVA was used to analyse the results for statistical differences. Analysis of covariate (ANCOVA) was used for broccoli yields as crops did not grow uniformly in the field. The number of crops that broccoli heads were harvest from were used as a covariate in the analysis. The treatment means were compared using the Least Significant Difference range test at 95% confidence level. All statistical analyses were performed using R software package (version 3.2.3, University of Auckland, New Zealand).

Marginal analysis was performed by determining marginal rate of returns (MRR) of each experimental treatment relative to the smallholder farmer's normal soil amendment practices (i.e. application of commercial compost at 10 t/ha) as described by (Louis 2011). Marginal rate of returns was calculated by determining marginal net benefit of using a certain amendment relative to use commercial compost and dividing marginal benefit by marginal cost, which is essentially a comparison of variable costs of a certain soil amendment with commercial compost cost. Field price was used for each treatment and cost of labour was considered when costs were determined on per hectare basis. In principle, the following equation was used to determine MRR:

$$MRR = \frac{Net\ gain\ from\ treatment - Net\ gain\ from\ normal\ practice}{Cost\ of\ treatment - Cost\ of\ normal\ practice} \times 100\%$$

3.3 RESULTS AND DISCUSSION

3.3.1 Compost Production and Characterization

3.3.1.1 Compost production

Moisture content (Figure 3.4) and temperature (Figure 3.5) of the compost pile that contained 20% pine wood biochar (composted biochar treatment) were significantly lower than the one that did not contain biochar (composted waste treatment). This could partially be attributed to the fact that the composted waste only pile was physically larger than the 20% biochar compost pile. However, the lower temperature of the composted biochar pile could also be attributed to the recalcitrant nature of the black C contained in the biochar compared to fresh plant and animal waste materials used in the composted waste (Botha 2016). Biochar contains less labile C, thus, the composted biochar (CB) pile did not become as warm as the composted waste material (CW) pile due to lower microbial metabolic activity (Botha 2016). This observation is completely opposite to the observation of Jindo et al. (2012) who mixed poultry manure with biochar produced from oak leaves, and other bulking organic materials and observed that fine particles of biochar functioned to increase the temperature of the composting piles and aided to retain more water in the piles. The reason for this contrast may be due to the variations in biochar used on these two studies, the biochar used for this study was porous and loose as it was produced at 550°C with pine wood while (Jindo et al. 2012) used biochar derived from leaf material pyrolyzed at average temperature of 600°C which would have produced a finer biochar relative to the one used for this study. Moisture content started to increase gradually from day 35 to day 56 (Figure 3.4) and this indicates that the piles were becoming homogenous as they retained more water.

The composted waste (CW) pile reached a thermophilic temperature of 55°C-60°C (Figure 3.5) which helps in destroying seeds and pathogens (Diaz et al., 2007; Venglovsky et al., 2005) while the composting pile that contained pinewood biochar did not reach a minimum temperature 55°C for destroying pathogens. This could mean that application of composted biochar could potentially introduce pathogens which may harm plants during the growing season. Composted biochar (CB) pile reached a maximum temperature of 52°C which is representative of the thermophilic phase and the temperatures dropped as an indication of maturity. Composted waste pile reached a maximum temperature of 65°C which designates the thermophilic phase and then the temperature fluctuated which may be associated with the fact that the composting pile was larger and more difficult to turn. However, after the 49th day, the temperature of composted waste (CW) started to stabilize and decreased significantly which indicates maturation phase.

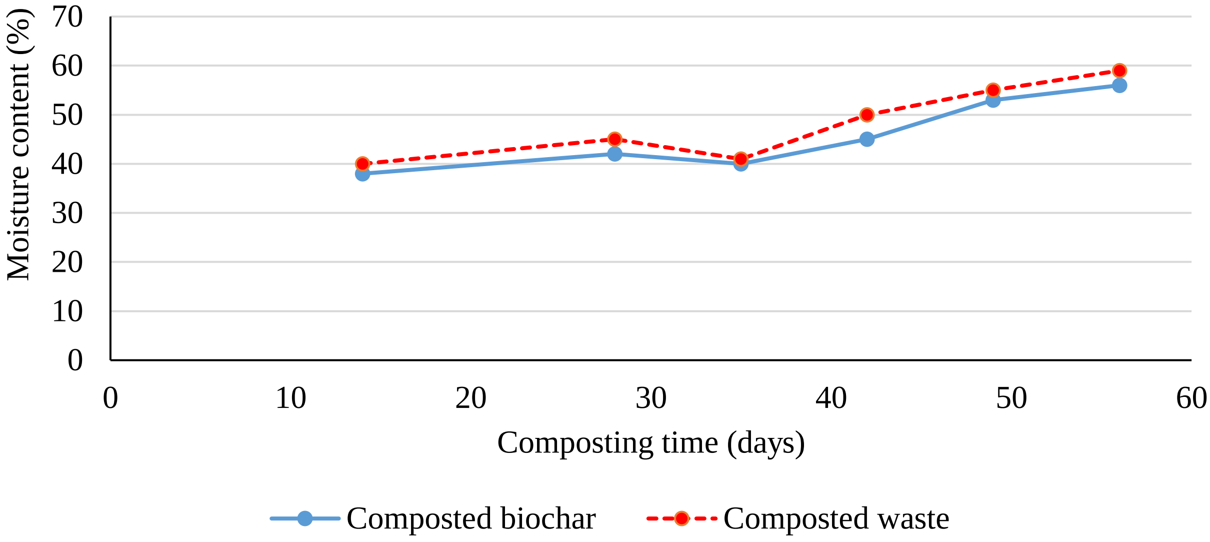

Figure 3.4: Moisture content of composted biochar (CB) and composted waste (CW) piles over the 3-month composting period.

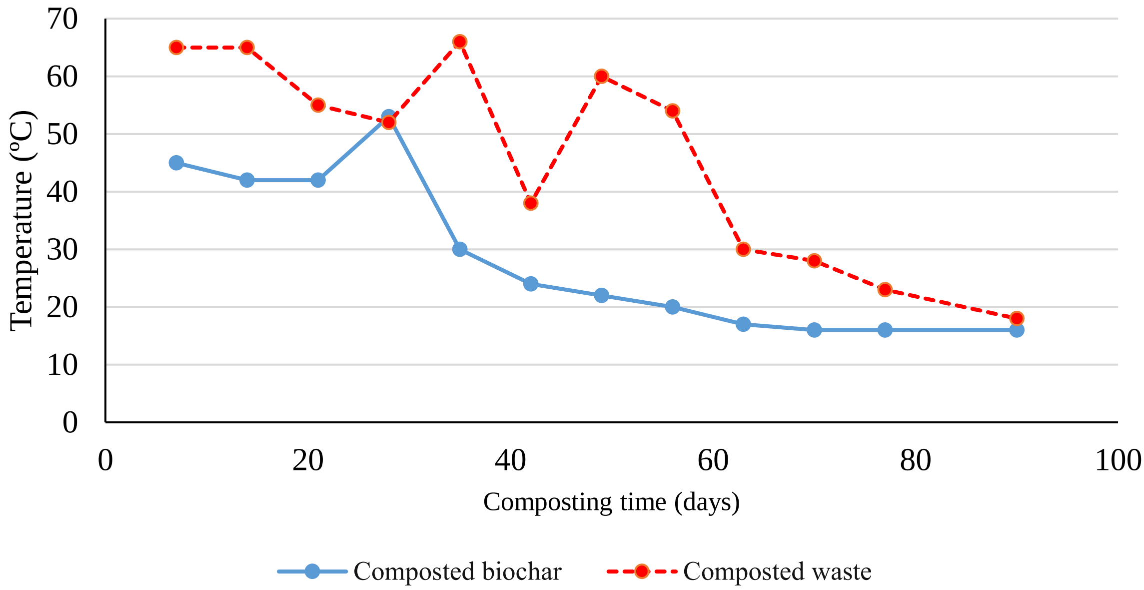

Figure 3.5: Weekly temperature measurements of the composted biochar and composted waste piles over the 3-month composting.

Weekly average moisture content and temperature results were not analysed statistically as the mean was calculated in the field and only the average was recorded, so the second factor (i.e. replicate) could not be provided for the software to analyse the results.

3.3.1.2 Compost Characterization
3.3.1.2.1 Compost pH and Electrical Conductivity

Compost pH steadily increased in both piles from day 5 to day 60 (thermophilic and mesophilic phase) and it decreased rapidly from day 60 to day 90 (maturation phase) (Figure 3.6). However, the compost pH was still within accepted levels of between 7.06-7.87 which is relatively neutral to slightly alkaline. Bertoldi et al. (1983) suggested that pH of a composting pile should range between 5.5-8 for optimum microbial degradation of organic substrates. The increment in compost pH from day 5 to day 60 may be closely attributed to ammonification of amino groups in the organic substrates. This occurs due to the release of OH^- ions from the carboxylic compounds into the solution during ammonification and that would function to increase pH (Amlinger et al. 2003). This increment in pH from day 5 to day 60 indicates the termination of the bio-oxidative stage (thermophilic and mesophilic) in both compost piles (CB and CW). The decrease in compost pH of both piles can be attributed to the nitrification process which follows ammonification process as microbes oxidize NH_4^+ to NO_2^- which is unstable and toxic so microbes would convert NO_2^- to NO_3^- while donating a proton (H^+) to the solution in the pile (Venglovsky et al. 2005; Botha 2016). This decrease in compost pH could also be attributed to accumulation of organic acids as the piles retained more moisture as time progressed since the materials became more homogenous which would then promote accumulation of fatty acids (Venglovsky et al. 2005; Neyla et al. 2009).

Electrical conductivity increased steadily from day 5 to day 30 (thermophilic phase), decreased rapidly from day 30 to day 60 (mesophilic phase) and steadily increased from day 60 to day 90 (maturation phase) in both compost piles (Figure 3.7). The increment in EC during the thermophilic phase in both compost piles could be attributed to the accumulation of salts as the microbes were rapidly decomposing the organic material while the decline in EC during the mesophilic phase could be ascribed to leaching of salts due to irrigation of compost piles or rain as composting was conducted in an open environment (Jindo et al. 2012; Botha 2016). The increment in EC during the final stages of the composting process (i.e. maturation phase) can be attributed to the accumulation of salts since the practice of irrigating the compost piles was ceased on day 56 and it can also be due to the fact that the compost piles were more homogenous at this stage and that encouraged retention of water in the compost piles such that less salts were leaching (Venglovsky et al. 2005).

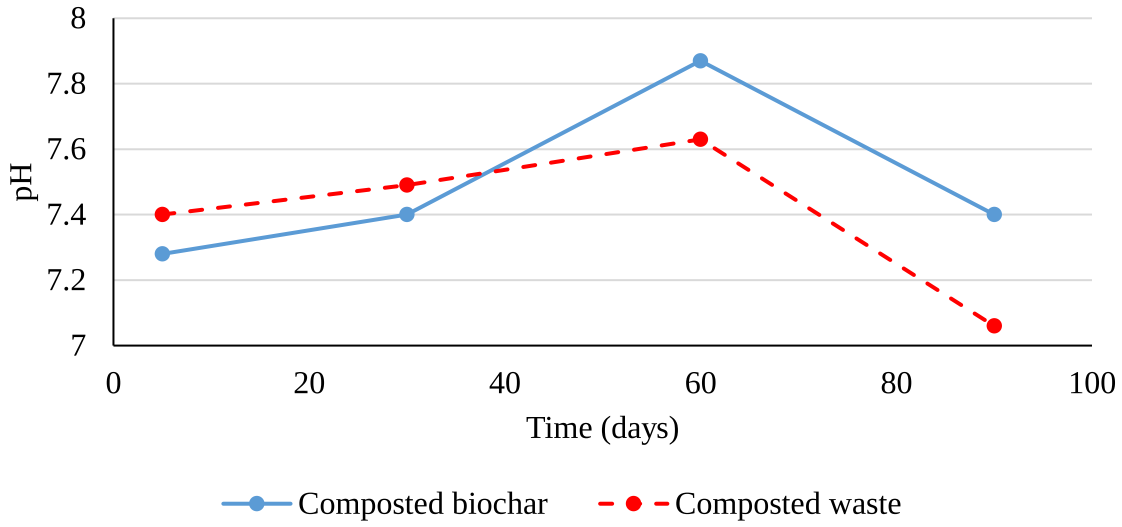

Figure 3.6: Compost pH of composted biochar and composted waste piles over the 3-month period.

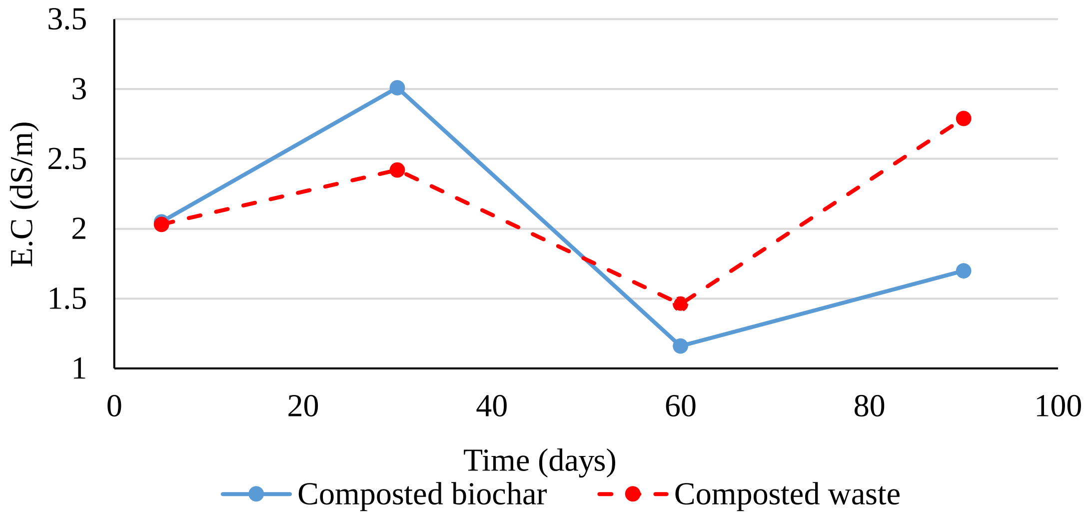

Figure 3.7: Electrical conductivity of composted biochar and composted waste piles over the 3-month composting period.

3.3.1.2.2 Dehydrogenase Activity

The dehydrogenase activity (DHA) in the compost increased steadily from day 5 to day 60 of the composting process (Figure 3.8), demonstrating the duration of the bio-oxidative process (thermophilic and mesophilic phases), and it later decreased gradually from day 60 to day 90 (maturation phase) of the composting process. Enzyme activity was significantly higher ($p<0.05$) in the composted waste (CW) pile compared to the composted biochar (CB) pile and this expected because biochar is a highly stable C source that undergoes decomposition very slowly (Diaz et al. 2007and Jindo et al., 2012). Dehydrogenase activity results from each of the two composting piles were significantly different ($p<0.05$) which indicates that microbes preferred fresh materials that contained labile carbon rather than highly stable materials such a biochar (Botha 2016). This could mean that biochar could slow down a composting process which would mean that the material should be composted longer to allow it to mature. Incorporation of biochar decreased DHA by 30.54 ug TPF/g dry compost on average ($p <0.05$). The time factor had a significant influence ($p< 0.05$) on DHA during the composting process and that indicates that DHA differs with various stages of the composting process.

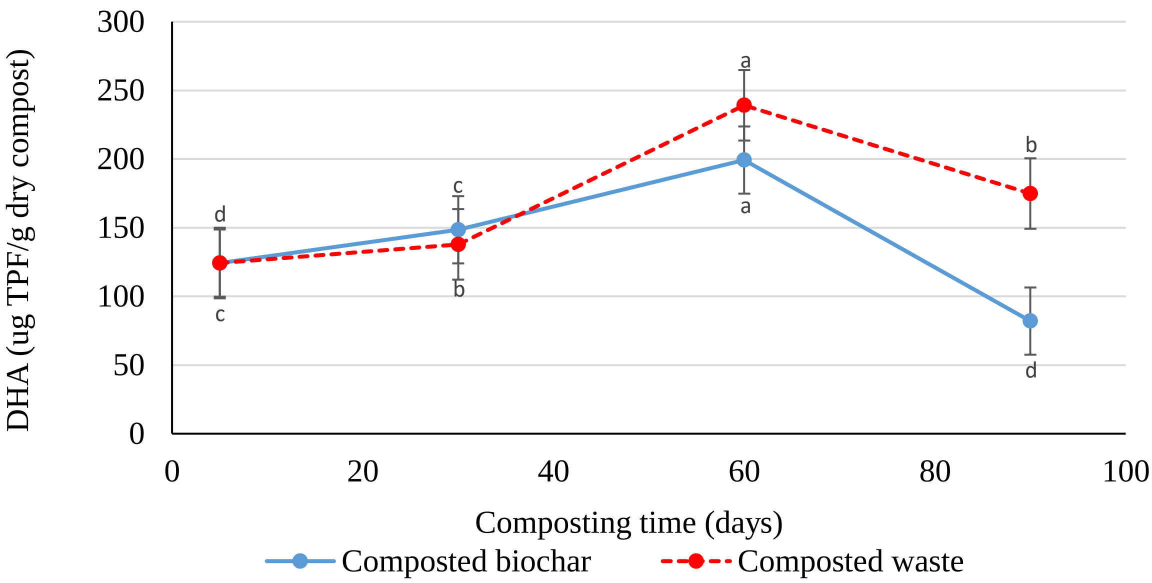

Figure 3.8: Dehydrogenase activity of composted biochar and composted waste over 3-month composting period. Statistical significant differences due to time of sampling are illustrated by letters of significance at p< 0.05.

3.3.1.2.3 Proximate analysis, total C and N

The volatile matter, fixed C and ash content of the two composts produced on farm and the commercial compost are shown in Table 3.6. The addition of 20% pinewood biochar resulted in a slight increase of fixed C in compost (Table 3.6). This can be attributed to the stability of carbon stored in biochar since it is highly stable and that would increase compost stability thereby increasing carbon sequestration in soil (Jindo et al. 2012). However, the difference in fixed C between CB and CW was insignificant as it was below 1% and that can be associated with low pine biochar's fixed C which was 51 % (Botha 2016).

Matthiessen et al. (2005) pointed out that volatile matter of an organic material is the easily degradable composition while ash content represents the mineral composition (i.e. highly stable material) of that organic material. Table 3.6 shows that the CC had the least degradable material as its volatile matter was 65% and 67% lower than that of CW and CB respectively. Notably, the CC had the highest ash content that amounted to 88.83% and this is beyond accepted levels in South Africa. According to South African Act no. 36 of 1947 a registered compost should only be sold if it contains less than 40% moisture content, less than 67% ash content and has a germination index of greater than 80%. The commercial compost used by the smallholder farmer contained 21% more ash content than the recommended ash amount.

Table 3.6: Proximate results of composted biochar and composted waste produced on-farm, and commercial compost used by the farmer

Compost name	Volatile Matter (%)	Fixed C (%)	Ash (%)
Composted Biochar	27.93	14.70	61.53
Composted Waste	26.57	13.92	63.33
Commercial Compost	9.20	2.06	88.83

The C/N ratio of both compost piles decreased from initial stages of the composting process to the termination of the process (Figure 3.9). However, addition of 20% pine wood biochar to CB pile increased the C/N ratio of the pile beyond the targeted C/N ratio ranging between 25-30 to 34:1 which still falls within accepted levels. Nevertheless, the wider C/N ratio of composted biochar pile might have contributed to lower enzyme activity (Figure 3.8) and temperature (Figure 3.5) of the pile during the composting process. The C/N ratio of the composted waste pile fell within the targeted range (25-30) at initial stages of composting and it decreased steadily until day 30 which signifies the end of the thermophilic phase and the decline was less pronounced from day 30 to day 60 which indicates that the material was stabilizing.

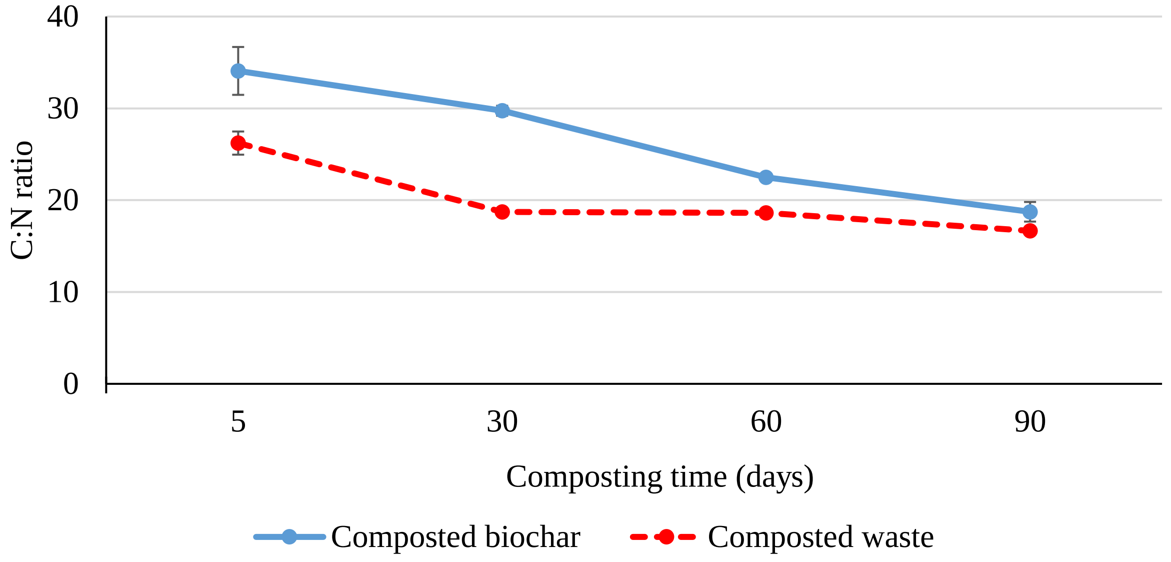

Figure 3.9: C/N ratio of composted biochar and composted waste piles over the 3-month composting period.

3.3.1.2.4 Maturity Indices and Elemental Composition

Germination Index and C/N ratio were used as maturity indices to compare compost maturity between the on-farm produced CB and CW and purchased commercial compost (CC) (Table 3.7). According to de Berltodi et al (1996) a mature compost has a germination index greater than 60% and a C/N ratio ranging from 10-20. According to these benchmarks, all the composts can be regarded as sufficiently mature (Table 3.7). It is clearly depicted that commercial compost had a slightly lower germination index and C/N ratio than the on-farm produced composts (Table 3.7).

Table 3.7: Maturity indices of the two on-farm produced composts (CB and CW) and commercial compost (CC) using the broccoli field trial

Type of compost	Germination Index (%)	C/N ratio
Composted Biochar	87.88	17.57
Composted Waste	84.85	17.32
Commercial Compost	82.66	13.21

The pH, EC and elemental composition of the on-farm produced composts (CB and CW) and commercial compost (CC) are shown in Table 3.8. The CB had a higher pH than the CW, which can be attributed to the alkaline nature of biochar (Botha 2016). The CC had a higher pH (8.2) and EC than that of on farm-produced composts (CB and CW), probably due to the amount of minerals (indicated by high ash content) present in CC.

Composted waste (CW) and composted biochar (CB) piles contained higher macronutrient contents that the CC (Table 3.8). The on-farm composts contained 1.62-1.69% N, whereas, the CC only contained 0.68% N. The low N content of the composts are of concern as that would directly affect N mineralisation. Palm (2001) demonstrated that organic amendments with N contents less than 2.5% results in N immobilization when added to soils and should be regarded as poor nutrient sources. The P content of the CC was also much lower (0.2% P) than compared to the CB (0.36% P) and CW (0.37% P) composts, as was the K content (Table 3.8).

Table 3.8: Compost pH, electrical conductivity (EC) and total elemental composition of the two on-farm produced composts (CB and CW) and commercial compost (CC) used in the broccoli field trial.

Compost	pH (H_2O)	EC (mS/m)	Macro nutrients (%)					Micro nutrients (mg/kg)					
			N	P	K	Ca	Mg	Na	Mn	Fe	Cu	Zn	B
CB	7.40	17.00	1.62	0.36	0.95	2.74	0.35	766	241	9620	21	132	27
CW	7.06	27.90	1.69	0.37	1.08	2.17	0.31	851	226	8510	19	117	22
CC	8.20	40.67	0.68	0.20	0.14	2.77	0.19	630	88	9828	29	119	25

3.3.1.3 Summary of the composting process and mature compost characterization

Compost production and characterization results indicated that incorporation of biochar in a composting process prolongs the time required for the compost to reach maturity as it decreases dehydrogenase activity since biochar is highly stable material such that microbes cannot use it as a source of carbon. Compost temperature and enzyme activity also indicated that CB pile was less degradable as compared to CW, and that is attributed to 20% pine wood biochar incorporated in CB. Proximate analysis and C/N ratio indicated that the mature CB contained slightly more fixed C and a slightly wider C/N ratio. However, both piles (CB and CW) matured after a period of 90 days as indicated by a germination index higher than 60% and C/N ratio lower than 20 (Mathur et al. 2012; Sweeten et al. 2003; Williams et al. 2001). Interestingly, the two on-farm produced composts (CB and CW) met the requirements stipulated by the South African Fertilizer Act no. 36 of 1947 which states that in order for a compost to be registered and sold commercially it should have less than 67% ash content and a germination index greater than 80%. Comparatively, the CC used by the smallholder farmer contained ash content that is beyond the accepted level and this will have implications on degradability and mineralisation efficiency of CC as ash content represents the inorganic or undegradable constituents contained in that compost.

3.3.2 Effect of soil amendments on soil properties and crop response

3.3.2.1 Laboratory Study: Soil Water Holding Capacity

All the organic amendments generally increased soil water holding capacity (WHC) of both sandy and sandy loam soils (Figure 3.10), increment ranging from 0.42-11.75% in sandy loam soil and 1.61-5.60% in sandy soil was obtained. However, only the CW applied at 10 and 22 t/ha on the sandy soil, and CW applied at 22 t/ha on sandy loam soil resulted to significant ($p < 0.05$) increases in WHC (Figure 3.10). The increment in WHC due to organic amendments can be attributed to an increase in SOM which functions to increase porosity and improve structure of the soil. This is in line with results obtained by Aggelides and Londra (2000) when they compared the effect of an organic amendment applied at different rates on two contrasting soils and observed an improvement in soil physiochemical properties. Among the amendments (B, CC, CB and CW) applied at 10 t/ha on the sandy loam soil, B yielded the most pronounced increase of WHC (Figure 3.10), which can be attributed to fine biochar particles relative to other amendments (Nada et al. 2012). However, biochar fine particles did not have the most pronounced effect on WHC of a sandy soil (Figure 3.10) and this might be due to high amount of macro pores that would be present in sandy soil preventing positive interaction between sand particles and biochar fine particles. An increment in soil water holding capacity has positive implications on nutrient-use efficiency by plants as 14 out of 16 plant essential nutrients are absorbed by plant roots through absorption of water from the soil.

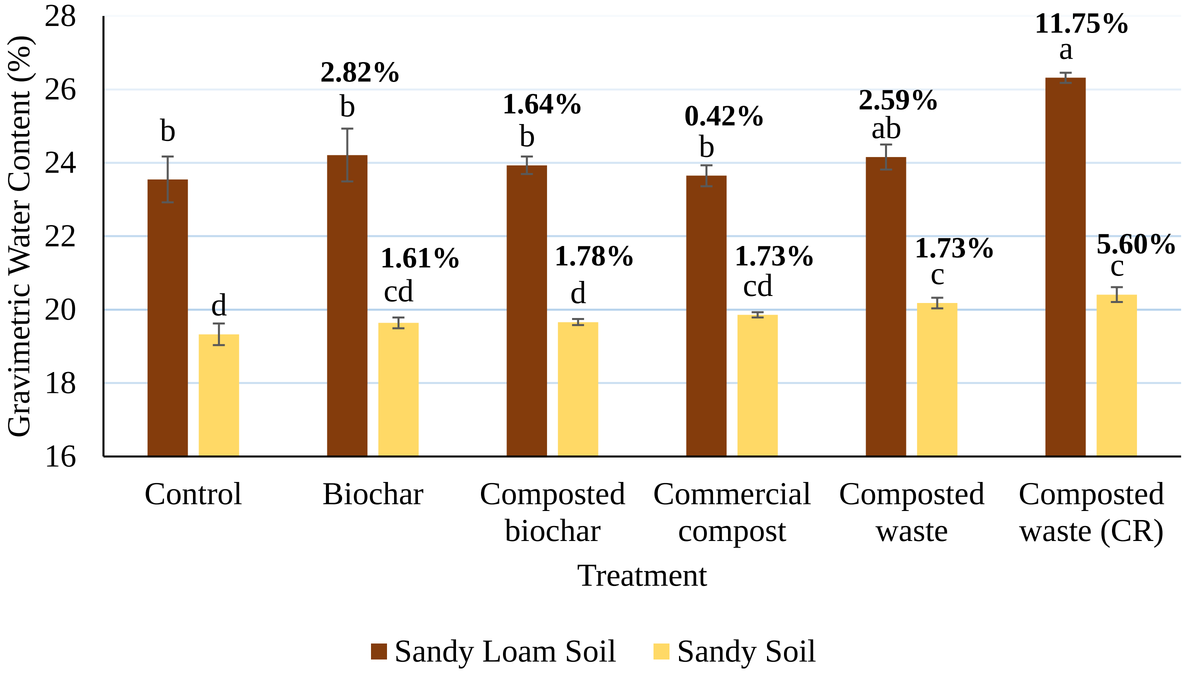

Figure 3.10: Soil water holding capacity of sandy and sandy loam soil amended with various organic amended at 10 and 22 t/ha. Statistical differences are represented by letters of significance tested using Tukey's t-test at p< 0.05.

3.3.2.2 Broccoli Field Trial

3.3.2.2.1 Soil pH, electrical conductivity and plant available nutrients

The organic amendments (CB, CC, CW and CWCR) and chemical fertilizer all increased soil pH measured in water and 1 M KCl, although the differences were not statistically significant (Table 3.9). Dixon (2006) states that the ideal soil pH (water) for broccoli production ranges from 5.8-6.5, however soil pH of up to 7 helps prevent soil-borne diseases and therefore the soil pH in all the amended plots and the control was ideal. The CW applied at 10 tons/ha resulted in the highest soil pH in deionized water and 1 M KCl (Table 3.9), even though the

CC on its own had the highest pH measured in water (Table 3.8). This higher soil pH due to application of CW compared to CC can be attributed to higher volatile matter in CW which is essentially a representative of easily degradable organic fraction. An increment in soil pH due to application of organic amendments can be attributed to adsorption of divalent cations to pH dependent sites on organic acid edges and the loss of exchanged H^+ with the solution through deep percolation (Mnkeni and Austin 2009; Ingrasamintelor et al. 2009; Abd Elrahman et al. 2012). While an increase in soil pH as a result of chemical fertilizer application to soil can be attributed to added divalent cations which would adsorb on exchange sites while H^+ would be dissociating from sites since elements that have higher ionic strength are mostly preferred (Ingrasamintelor et al. 2009). Additionally, inorganic phosphate ions ($H_2PO_4^-$ and $H_2PO_4^-$) added through application of chemical fertilizer could have reacted with hydrous oxides such as gibbsite ($Al(OH)_3$) in soil with phosphate ion replacing the hydroxyl group ($-OH^-$) which would then been released into the soil solution causing an increase in soil pH (Tisdale and Nelson 1958; Jones 2012).

Soil pH in water decreased slightly (0.03-0.38 pH units) from planting to harvest in untreated plots and plots treated with CF, CW and CWCR (Table 3.9). Soil pH decline was greatest in the control treatment when measured in deionized water and that can be attributed to leaching of nutrients by rainfall and irrigation, and uptake of nutrients by plants. The greatest decline in soil pH measured in KCl was observed on plots treated with CWCR that can be associated with high number of organic functional groups that would deprotonate when treated with a neutral salt such as KCl with K^+ replacing H^+ in organic functional groups thereby reducing solution pH. The decline in soil pH over time is a normal occurrence due to leaching of cations from soil because of winter rainfall and irrigation, biochemical processes such as mineralisation of N or decomposition of OM which results to deprotonation organic functional groups and plant uptake of basic cations (Brady and Weil, 2014). However, soil pH in plots treated with CC and CB increased from planting to harvest by 0.08 and 0.22 in water and increased by 0.17 and 0.02 in KCl in pH units, respectively. The liming ability of CC can be associated with CC's inherent pH (Table 3.8) and CC's ash content (Table 3.6) which is representative of mineral content that does not degrade easily while liming ability of CB can be attributed to pine wood biochar that the compost contained (Botha 2016). Electrical conductivity (EC) was not significantly affected by any of the soil amendments utilized in this study (Table 3.9 and Table

3.10). Electrical conductivity was within the accepted range for broccoli production in all the experimental treated plots as the threshold that results to 10% reduction in yield is reported to be greater than 120 mS/m (Brady and Weil, 2008).

Plant available P increased due to the application of both organic amendments and initial chemical fertilizer application, however, the increments were not statistically significant (Table 3.9 and Table 3.10). Plant available P was sufficient for broccoli production at planting as it was within the accepted threshold of 25-83 mg/kg in all the amended plots and the control (FSSA 2007). Application of CC, CF, CB, CW, and CWCR increased plant available P at planting relative to the control by 1.11, 19.94, 22.79, 23.26, and 25.06 mg/kg respectively (Table 3.9). These increments in plant available P are in line with P application rates as depicted on Table 3.3, however, plant available P in plots amended with CF was not in line with the seasonal P application for the growth of broccoli due to the fact that CF was applied on weekly basis and only 23.3 kg/ha was applied at the time of sampling when P was determined as illustrated on Table 3.4.

Exchangeable acidity declined in soil due to the application of amendments with the untreated plots having a highly significant soil exchangeable acidity ($p < 0.05$) compared to the treated plots while CC and CF significantly ($p < 0.05$) reduced soil exchangeable acidity (Table 3.9). Application of CC, CF, CB, CW, and CWCR resulted in reduction of exchangeable acidity in soil which amounted to 0.36, 0.35, 0.15, 0.20, and 0.25 $cmol_c$/kg respectively. The highest reduction in exchangeable acidity due to application of CC can be associated with the liming ability which is due to its inherent pH (Table 3.8) and high ash content (Table 3.6) while the second most noticeable decline in exchangeable acidity of soil treated with CF can be associated with displacement of adsorbed acidity (H^+) by readily available cations such that when exchangeable acidity was extracted with 1 M KCl most of it was already replaced by more preferred cations.

Plant essential cations (Ca, Mg and K) were in optimum levels in all treatments at broccoli planting for the growth of vegetables as recommended by FSSA (2007) (Table 3.9). Application of organic amendments and chemical fertilizer did not significantly increase plant available Ca and Mg content at planting (Table 3.9). Only plant available K was significantly ($p < 0.05$) increased by the application of composted waste at 22 tons per hectare (CWCR)

(Table 3.9) and this has implications on crop nutrition as K is one of the primary essential elements. The highly significant ($p< 0.05$) increase of K content due to application of CWCR can be attributed to the highest application of K by CWCR relative to other amendments (Table 3.3). At planting, application of CF, CB, CW and CWCR increased exchangeable K content by 7.8, 50.7, 140.4 and 198.9 mg/kg respectively relative to the control. Additionally, application of CC reduced extractable amount of Ca and Mg by 162 and 7.2 mg/kg respectively relative to the control and the application of CB did not increase extractable Ca content even though it increased exchangeable Mg by 25.2 mg/kg. This reduction of exchangeable Ca and Mg in CC amended plots may be attributed to the dilution of nutrients caused by addition of sand as depicted by the amount of ash contained in CC (Table 3.6). While the reduction of exchangeable Ca in CB amended plots can be due to the ability of biochar to strongly adsorb ions (fixation). Conversely, application of CF, CW and CWCR increased exchangeable Ca by 8, 180, 174 mg/kg respectively while Mg increased by 26.8, 42.0 and 88.8 mg/kg due to the respective amendments. These increments are consistent with individual nutrient application rates depicted in Table 3.3. This is in exception of application of composted waste at 10 t/ha which increased exchangeable Ca by 6 mg/kg more than the increment that is due to application of composted waste at 22 t/ha. |This can be attributed to an increment in pH dependent surface charges that would be more in CWCR which could have adsorbed more Ca, thus, an increment due to CWCR was lower than that due to CW. Plant essential cations generally decreased from time of broccoli planting to harvest, except for Ca and Mg in plots amended with CC and CB (Table 3.10). This can be attributed to the fact that CC and CB had high ash content and pH which means that basic cation carbonates could have dissolved over time due to acidification of the soil and biological activity.

There were no statistical significant ($p> 0.05$) differences between ECEC of plots amended with organic and chemical amendments compared to the control, and the differences in ECEC at the planting time of broccoli and harvest were statistically insignificant (Table 3.9 and Table 3.10). However, application of on-farm produced composts (CB, CW and CWCR) increased ECEC at planting by 0.20, 1.42 and 1.90 $cmol_c$/kg respectively while application of CC reduced ECEC by 1.22 $cmol_c$/kg. The increment in effective cation exchange capacity of soils amended with CB, CW and CWCR can be attributed to pH dependent charges that are present in organic matter (Sparks 2003; Sika 2012), while reduction of ECEC due to application of CC can be associated with high ash content of CC (Table 3.6) resulting a dilution effect. It is important to note that reduction of ECEC does not necessarily mean that application of CC reduced the ability of soil to hold nutrients, rather it indicates that soil (mainly sand) that was present in CC as ash content fixed cations such ECEC was low. Effective cation exchange capacity (ECEC) generally decreased from broccoli planting to harvest, except for plots amended with CC and CB (Table 3.10). This can be attributed to the ability of CC and CB to release cations over time as shown for Ca and Mg results which resulted in an increase in ECEC. The greatest reduction in ECEC from planting to harvest was observed on untreated and CF treated plots, this can be associated with the fact that no organic material was added to these plots.

There were no statistical significant differences between measured micro nutrients (Cu, Zn, Mn and Fe) between treatments, and the time factor also did not significantly influence micro nutrient contents (Table 3.9 and Table 3.10). According to Pais and Benton (1997) all the measured micro nutrients were within accepted level for the growth of plants. According to FSSA (2007) the soil contained adequate amount of Zn at planting, however, Zn content was inadequate for plant growth in CF amended plot at harvest (Table 3.10). The decline in Zn content over does not necessary have implications on broccoli field trial as no signs of Zn deficiency were observed, rather it has implications on the growth of crop that follows broccoli hence it is very important to monitor nutrients availability in a sound cropping system.

Table 3.9: Soil fertility status at broccoli planting in the compost and fertilizer treatments compared to the control. Statistical differences due to the treatments are presented by letters of significance at $p< 0.05$.

Treatment	pH (H_2O)	pH (KCl)	EC (mS/m)	P (mg/kg)	Exch. Acid (cmolc/kg)	Total elemental composition: Basic cations (cmolc/kg)				Total elemental composition: Micro elements (mg/kg)				ECEC (cmolc/kg)
						Ca	Mg	K	Na	Cu	Zn	Mn	Fe	
Control	6.57	5.98	0.074	49.94	0.76 a	7.09	1.18	0.34 b	0.10	0.96	3.15	4.31	36.3	9.47
Commercial Compost	6.76	6.22	0.074	51.05	0.40 b	6.28	1.12	0.34 b	0.11	0.68	2.47	3.26	34.6	8.25
Chemical Fertilizer	6.66	6.17	0.074	69.88	0.41 b	7.13	1.82	0.36 ab	0.11	2.07	2.79	3.51	48.3	9.83
Composted Biochar	6.78	6.31	0.072	72.73	0.61 ab	7.09	1.39	0.47 ab	0.11	1.16	2.09	2.71	45.4	9.67
Composted Waste	6.95	6.46	0.073	73.20	0.56 ab	7.99	1.53	0.70 ab	0.11	1.33	2.34	3.74	38.2	10.89
Composted Waste (CR)	6.59	6.15	0.073	75.00	0.51 ab	7.96	1.92	0.85 a	0.13	1.29	2.75	4.06	40.8	11.37

Table 3.10: Soil fertility status after broccoli harvest in the compost and fertilizer treatments compared to the control. Statistical differences due to the treatments are presented by letters of significance at p< 0.05.

Treatment	pH (H_2O)	pH (KCl)	EC (mS/m)	P (mg/kg)	Exch. Acid (cmolc/kg)	Total elemental composition: Basic cations (cmolc/kg)				Micro elements (mg/kg)				ECEC (cmolc/kg)
						Ca	Mg	K	Na	Cu	Zn	Mn	Fe	
Control	6.19	5.67	0.074	46.40	0.66	3.07	0.83	0.16 b	0.13	0.74	2.51	3.70	46.71	4.85
Commercial Compost	6.84	6.39	0.074	44.65	0.51	7.68	1.27	0.15 b	0.14	1.53	4.40	5.74	30.27	9.75
Chemical Fertilizer	6.41	5.94	0.073	68.60	0.46	4.92	0.70	0.47 a	0.13	0.79	1.65	2.58	53.86	6.68
Composted Biochar	7.00	6.33	0.073	75.35	0.63	9.71	1.55	0.24 ab	0.16	1.14	3.92	5.04	42.61	12.29
Composted Waste	6.92	6.32	0.074	62.79	0.58	7.15	1.12	0.33 ab	0.13	0.64	3.01	4.03	40.94	9.31
Composted Waste (CR)	6.34	5.78	0.072	61.34	0.53	7.31	1.94	0.36 ab	0.20	0.77	3.20	5.20	47.75	10.34

3.3.2.2.2 Total C and N at planting and changes in soil organic matter

Only the application of composted biochar (CB) significantly ($p < 0.05$) increased soil C content at planting compared to the control (Table 3.11). However, application of CW and CWCR also tended to increase soil C (0.69- 0.98%) relative to the control, whereas, the high ash containing CC lowered the soil C content, similar to what was observed with initial ECEC (Table 3.9). There were no significant differences in total soil N content at planting even though CB and CWCR added more N compared to other amendments (Table 3.11). Elevated soil C content of CB amended plots resulted in highly significant ($p < 0.05$) C/N ratio relative to CF, CC and the control while soil C content of CW and CWCR amended plots did not significantly differ from either. The C/N ratio results would be expected to influence soil respiration results as microbes largely depend on soil C content for energy and total soil N for metabolic processes while total C content and the stability of the carbonaceous material would be expected to affect SOM as stability and decomposition of SOM is dependent on source of C and its stability. Amlinger et al. (2003) pointed out that the C/N ratio is very important in determining the fate of N in soil with C/N< 12 promoting N mineralisation while C/N> 12 promotes N immobilisation.

Table 3.11: Soil total C and N content at broccoli planting in the compost and fertilizer treatments compared to the control. Statistical significant differences are illustrated by letters of significances at $p < 0.05$.

Treatment	C (%)	N (%)	C: N
Control	3.00 b	0.23	12.86 b
Commercial Compost	2.38 b	0.18	13.49 b
Chemical Fertilizer	3.05 b	0.22	14.09 b
Composted biochar	4.44 a	0.27	16.46 a
Composted waste	3.69 ab	0.23	15.83 ab
Composted waste (CWCR)	3.98 ab	0.25	15.70 ab

Application of organic amendments, except for CC, had a statistically significant ($p < 0.05$) effect on total soil organic matter (SOM) as determined by LOI, and there were significant ($p < 0.05$) differences in soil organic matter (SOM) at planting and harvest (Table 3.12). The results show that CB, CW and CWCR respectively increased SOM at planting by 55%, 39% and 51%

relative to the control (Table 3.12). Contrary, application of CC and CF did not significantly increase the amount of SOM. This insignificant increase in SOM may be due to low C content and high ash content of CC (Table 3.6) while CF only added solid minerals that would dissolve in soil water which means that no significant increase in SOM was expected. However, CB and CWCR biodegradation was not as efficient as other amendments as the percentage decrease in SOM in plots amended with CB and CWCR was 13.04% and 10.57% respectively. This could indicate that the material either suppressed microbial activity or was more difficult to degrade. This has implications on decomposition of SOM and mineralisation of nutrients. Kimetu and Lehmann (2010) pointed out that biodegradation of biochar in soil is relatively lower compared to other organic amendments because biochar is a highly stable carbonaceous material produced from thermal degradation of organic materials. Hence, percentage change in SOM was lower in CB amended plots among plots treated with 10 t/ha of organic materials and this has positive implications on carbon sequestration in soil. The lowest change in SOM on CWCR amended plots can be associated with insufficiency of microbes to biodegrade high amount of organic matter as CWCR was the highest application.

Table 3.12: Total SOM in plots treated with compost and chemical fertilizer compared to the untreated plots at broccoli planting and after harvest. Significant differences from Tukey t-test at p< 0.05 are indicated by different letters.

Treatment	SOM (%)		Relative change in SOM (%)
	At Planting	At Harvest	
Control	6.93 b	5.63 d	-18.79
Commercial Compost	8.90 b	5.85 d	-34.30
Chemical fertilizer	8.69 b	6.88 d	-20.76
Composted biochar	10.73 a	9.33 c	-13.04
Composted waste	9.61 a	7.16 cd	-25.48
Composted waste (CR)	10.48 a	9.37 c	-10.57

3.3.2.2.3 Soil Respiration

There were significant ($p < 0.05$) differences in soil respiration over time due to various treatments; the control treatment emitted significantly ($p < 0.05$) higher CO_2 than all the organic amendments, whereas, there were no significant differences between the control and CF treatment (Figure 3.11). Soil respiration significantly ($p < 0.01$) increased over time, likely due to an increase in daily temperatures from winter to spring (Figure 3.12).

Cumulative soil respiration data was normalized to total soil C content at planting to compare the relative decomposability of the substrates (Figure 3.13). Application of CC, CB, CW, and CWCR, respectively, resulted in significantly ($p < 0.05$) lower soil respiration relative to the control soil (Figure 3.13). This could mean that the soil microbes were not yet adjusted to the added organic substrates, or struggled to decompose the substrates due the somewhat wider C/N ratio (Table 3.11). The lower extent of soil respiration in the CB treatment can also be attributed to the recalcitrant nature of biochar (Lehmann and Joseph 2009; Botha 2016). It is possible that the application of CWCR could have added too much organic substrates that rendered microbes inefficient in breaking down the material yielding lower microbial respiration, and this corresponds with the smaller decrease in SOM on CWCR amended plots. The addition of CWCR also resulted in significantly higher soil water contents (Figure 3.10), which could have led to lower soil temperatures during the day (Hillel 2004) and low soil temperatures could have suppressed microbial activity. The lower soil respiration in the CC treatment can be associated with CC's relatively low content of easily degradable volatile matter (Table 3.6) and low inherent N content (Table 3.8). The lowest respiration rates of the CB and CWCR treatments also showed lowest relative losses in SOM during the field trial (Table 3.12). A correlation between cumulative soil respiration (Figure 3.13) and relative change in SOM (Table 3.12) was tested as both parameters measure degradability of SOM during the field trial. The test did not show any significant correlation relationship between the two parameters and the inconsistency can be associated with fact that soil respiration was measured on a buffer zone where there were no plants while LOI soil samples included root biomass as representative samples were collected in the whole experimental plot. However, the relatively small change in SOM on CB and CWCR amended plots can easily be associated with inhibition of soil respiration which indicates insufficiency of microbes to degrade SOM.

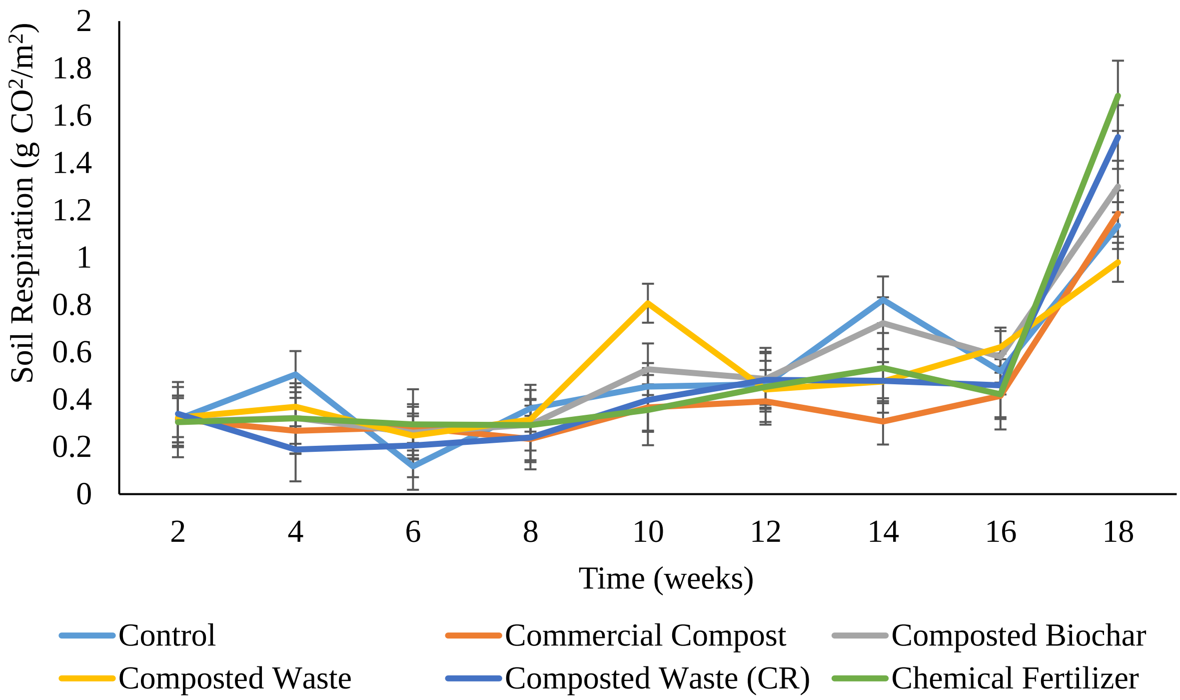

Figure 3.11: Effect of soil amendments on bimonthly cumulative soil respiration during the broccoli field trial. Error bars represent standard error of the means of n=3.

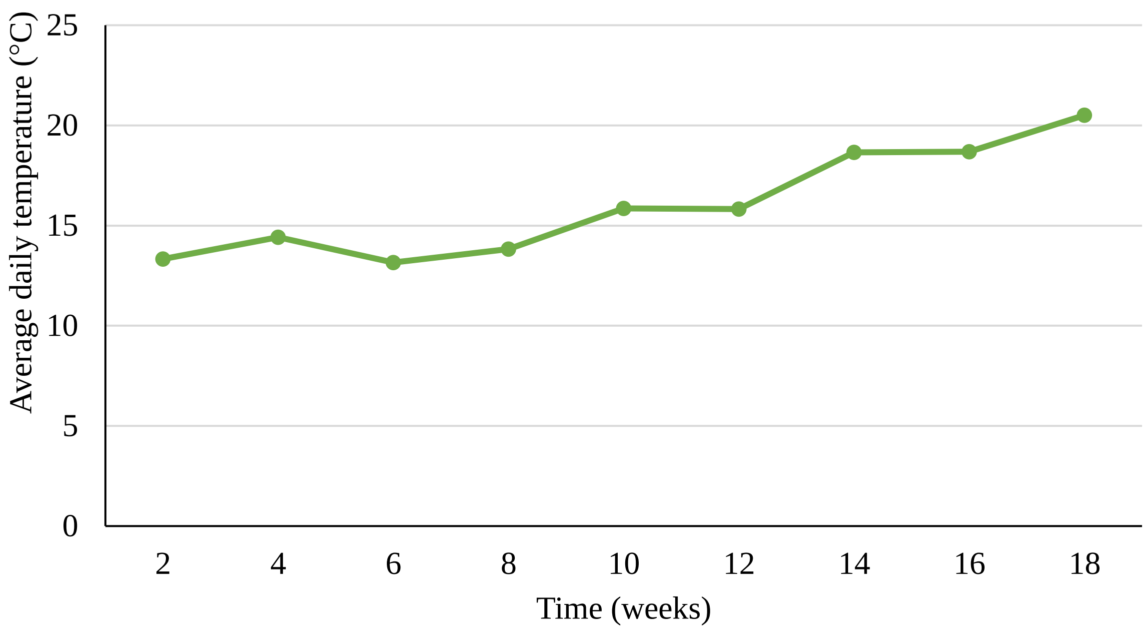

Figure 3.12: Average daily temperature during the growing period of broccoli.

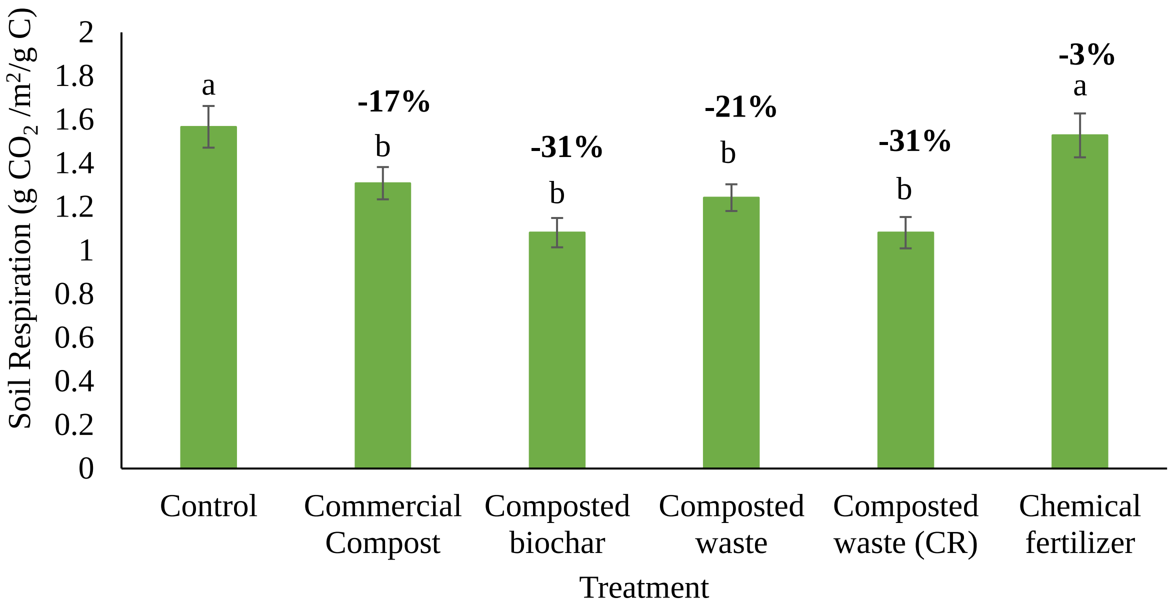

Figure 3.13: Effect of soil amendments on cumulative soil respiration normalised to total soil C content at planting. Statistical significant differences are illustrated by letters of significances at $p < 0.05$.

3.3.2.2.4 Nitrogen Mineralisation

The mineral N content of the soil during the first 11 weeks of the broccoli field trial is shown in Figure 3.14 (ammonium) and Figure 3.15 (nitrate). The chemical fertilizer had a highly significant ($p < 0.01$) effect on ammonium (Figure 3.14) and nitrate (Figure 3.15) contents compared to the control and the organic amendments. Additionally, the duration factor also had a significant effect on both ammonium and nitrate contents with ammonium content being significantly ($p < 0.05$) higher at weeks 3 and 6 on CF amended plots while nitrate content was significantly ($p < 0.05$) higher from week 5 to 7 on CF amended plots. The CF programme was applied on weekly basis to meet crop requirements, hence the higher applications at week 3 and 6 (Table 3.4) aim to supply sufficient mineral N during the two major growth stages of broccoli; namely: transplanting to spear initiation and initiation to maturity (Dixon 2006).

The exchangeable ammonium content was higher than nitrate content and this could be attributed to soil colloidal surfaces carrying a net negative charge that positively charged ions such as ammonium ion are attracted to while nitrate ions leach easily due to their net negative charge. Additionally, high ammonium content could be due to the fact that the first step of organic N transformation is ammonification which is essentially conversion of organic N (amides and amines) to ammonium ions followed by nitrification hence nitrate was always lower during the broccoli field trial (Amlinger et al. 2003). There was a net negative change in ammonium ions from planting to week 11 during the broccoli field trial (Figure 3.14), while there was net positive change in exchangeable nitrate ions (Figure 3.15). The net negative change in ammonium ions from planting to week eleven of the broccoli field trial amounted to 79%, 90%, 86%, 80%, 83%, and 80% for C, CC, CB, CF, CW and CWCR respectively. Net accumulation of nitrate ion amounted to 8%, 31%, 48%, 708%, 36%, and 3% on C, CC, CB, CF, CW, and CWCR plots respectively. The net decline of exchangeable ammonium on the untreated and treated plots can be associated with the uptake of mineral N by plants or microbes, leaching due winter rainfall and irrigation, and nitrification of ammonia to form nitrate.

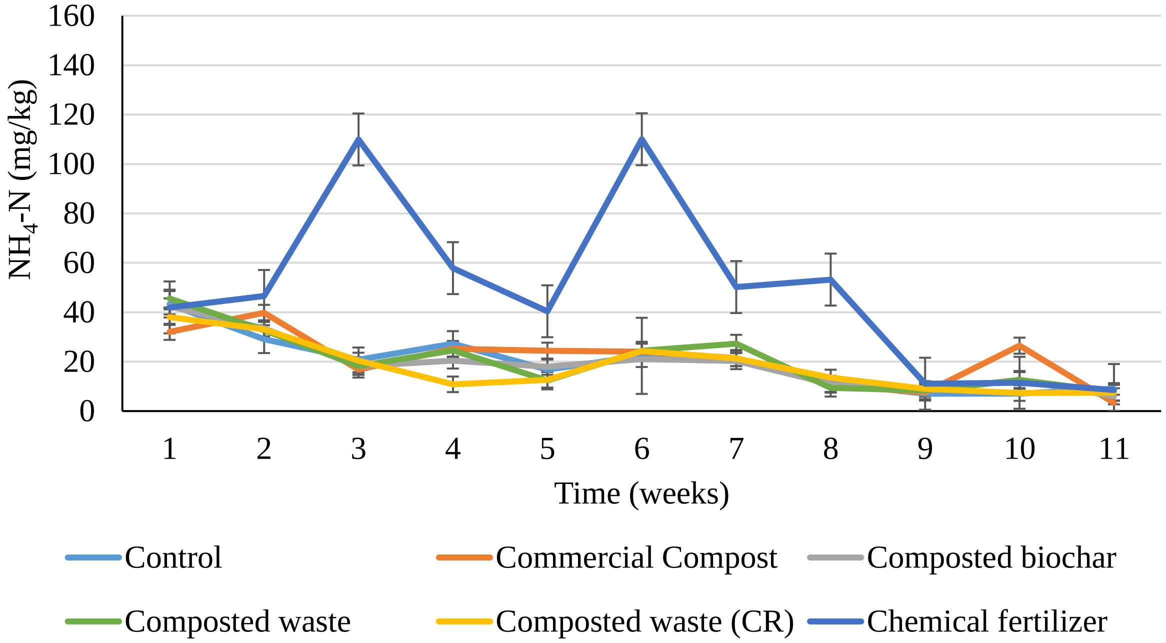

Figure 3.14: Effect of soil amendments on soil exchangeable ammonium content during the first eleven weeks of the broccoli growing period.

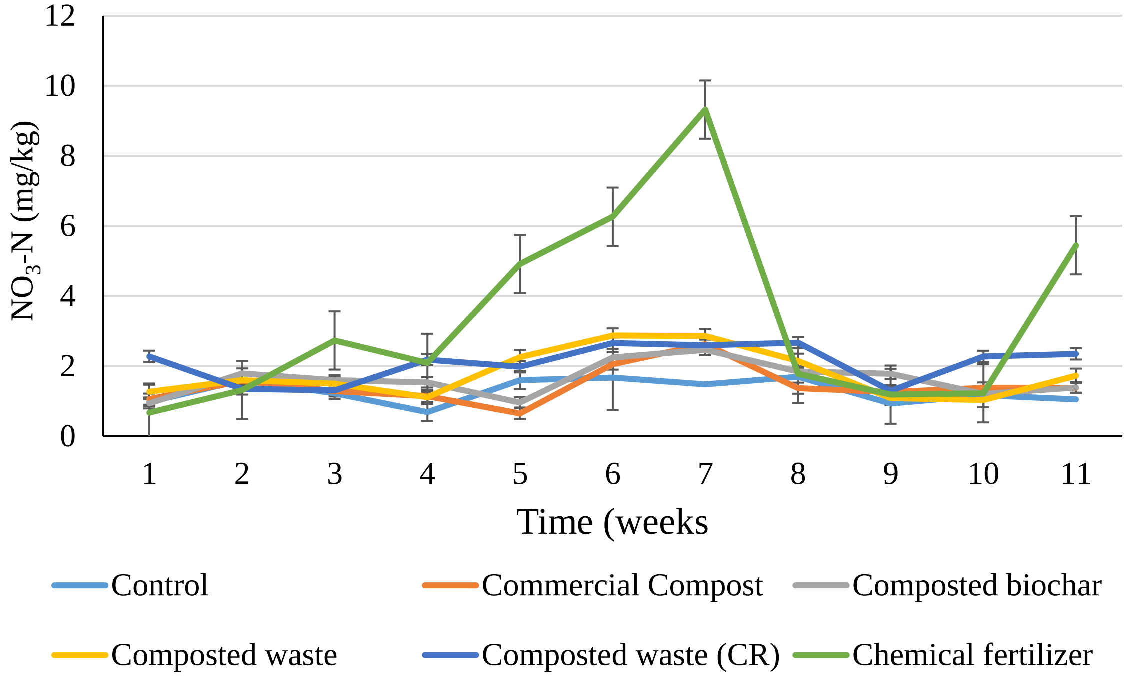

Figure 3.15: Effect of soil exchangeable nitrate content during the first eleven weeks of the broccoli growing period.

The amount of total soil mineral N measured weekly during the first 11 weeks is shown on Figure 3.16. There was an apparent net decline in soil mineral N in all the treatments over time (Figure 3.16). As previously discussed, the net decline cannot only be attributed to microbial or plant N immobilization as the system was not closed, it could also be due to leaching of N (Chesworth 2007). The net negative change in total mineral N from planting to week eleven of the broccoli growing period was found to be as follows in ascending order: 67% for CF, 68% for CC, 76% for CWCR, 77% for Control, 80% for CW and 83% for CB. The greatest net negative change in mineral N was obtained in the CB treatment which can be associated with the ability of biochar to immobilize mineral N such that it cannot be extracted with a strong salt (such as 2 M KCl) (Sika and Hardie 2014).

Cumulative total exchangeable mineral N was computed from soil mineral N measured from planting to the eleventh week of broccoli growing period (Figure 3.17). Application of CF significantly ($p < 0.01$) increased cumulative mineral N while application of organic amendments did not significantly increase mineral N relative to the control. The increments in cumulative mineral N due to the application of CC, CW and CF were 3%, 6% and 156% higher than the control, respectively. On the contrary, application of CB and CWCR resulted to 2% and 3% lower mineral N relative to the control, respectively (Figure 3.17). Soil C/N ratios at planting (Table 3.11) or C/N ratios of composts (Table 3.7) did not correlate with the cumulative mineral N of the organic treatments; CC had the lowest C/N ratios yet appeared to mineralise less N than CW. However, CC had the lowest inherent N content among the three composts (Table 3.8) which could account for the lower extent of N mineralisation compared to the other composts (Palm et al. 2001).

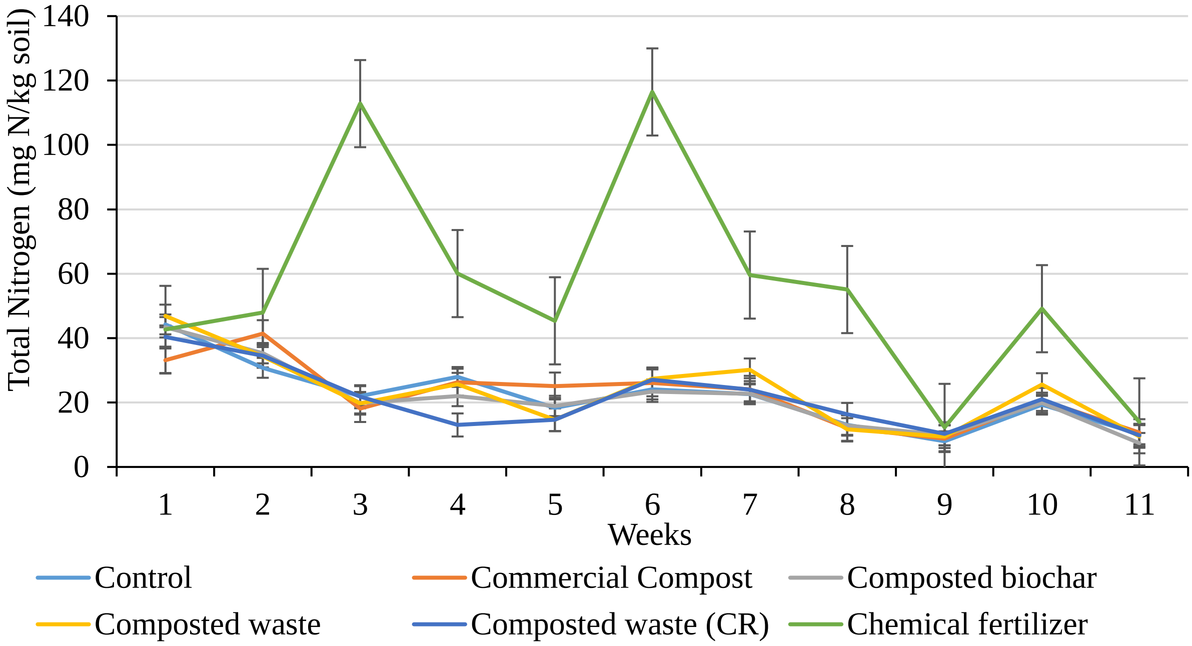

Figure 3.16: Effect of soil amendments on total exchangeable mineral N during the first eleven weeks of broccoli growing period.

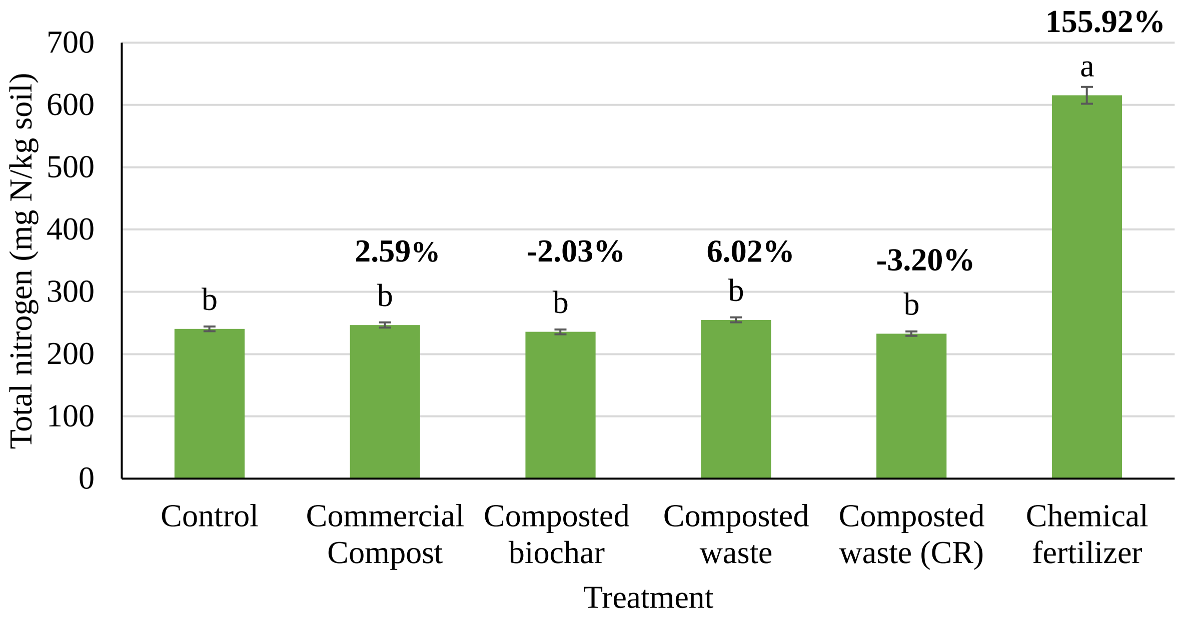

Figure 3.17: Effect of soil amendments on cumulative total soil mineral N (NH_4^+ and NO_3^-) during the first eleven weeks of broccoli growing period. Statistical significant differences are illustrated by letters of significances at $p < 0.05$.

3.3.2.2.5 Effect of soil amendments on crop response

3.3.2.2.5.1 Crop Vigour

Chlorophyll content significantly ($p < 0.05$) increased in all the treatment plots from time of seedling transplanting to harvest (Figure 3.18). The broccoli that was treated with chemical fertilizer had significantly ($p < 0.05$) higher chlorophyll content compared to all the organic amendments over time (Figure 3.18), which is attributed to the fact that chemical fertilizer supplied readily available nitrogen for plant uptake compared to organic amendments (Figure 3.17). These results are similar to the results obtained by Ouda and Mahadeen (2008) when they evaluated the effect of organic manure, inorganic fertilizer and their mixtures on growth of broccoli. The authors observed that the highest application rate of inorganic fertilizer resulted in higher chlorophyll content of broccoli leaves. Plots amended with composted waste applied at 10 t/ha (CW) had the second highest chlorophyll content after the chemical fertilizer treatment ($p < 0.05$) while plots amended with commercial compost had the least chlorophyll content on broccoli leaves. The increased chlorophyll content of broccoli leaves on CW treated plot can be attributed to higher plant available N compared to other organic amendments as shown on Figure 3.16 which was essentially attributed to the efficiency of microbes in decomposing and mineralizing organic substrates (Figure 3.13). Additionally, application of CW supplied more organic N (Table 3.8) among the amendments applied at 10 t/ha hence CW mineralised organic N more and promoted good crop vigour. On the contrary, CC supplied the least amount of N (Table 3.8) while application of CC reduced soil respiration (Figure 3.13) which inhibited N mineralisation (Figure 3.17) that led to poor crop vigour as indicated by leaf chlorophyll content (Figure 3.18).

Furthermore, average chlorophyll content was computed to evaluate the effect of the amendments on the development of the chlorophyll pigment based on leaf chlorophyll content measured (Figure 3.19). The average leaf chlorophyll content of broccoli plants treated with CF was significantly ($p< 0.05$) higher than for plants grown on plots treated with CC and CB (Figure 3.19). However, there were no significant differences in average leaf chlorophyll content between broccoli plants grown on untreated plots and plots treated with CW and CWCR. Based on the soil mineral N results (Figure 3.17), it was expected that the broccoli grown on plots amended with CB and CWCR would have lower chlorophyll content relative to CC but that did not occur (Figure 3.19). This could be due to the Mg content supplied by CB and CWCR which was double and fourfold that of CC (Table 3.3), and the fact that CWCR held more water than any of the amendments enhancing nutrient absorption (Figure 3.10).

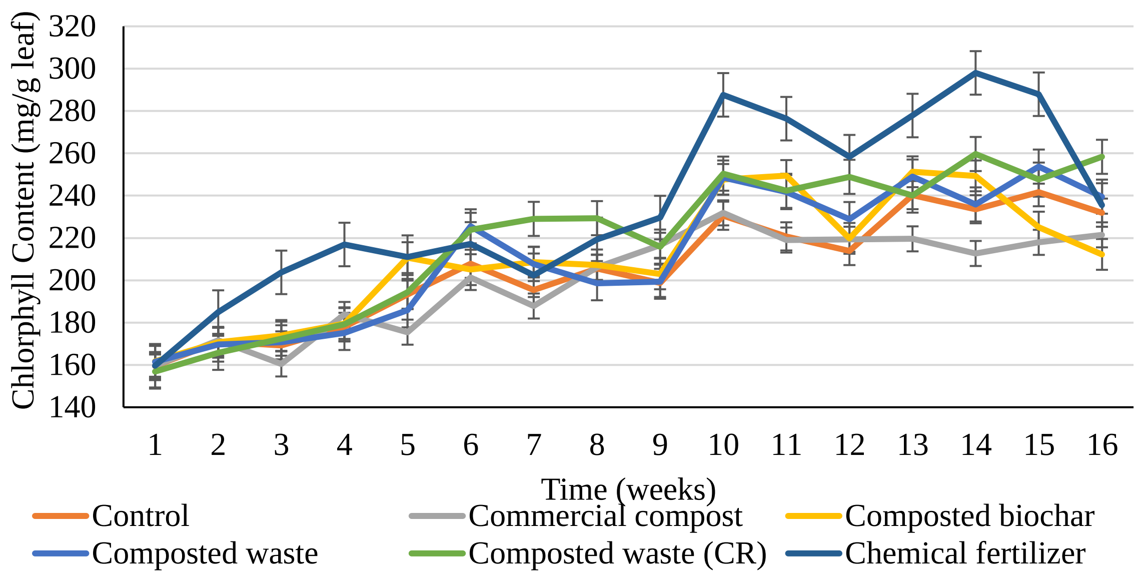

Figure 3.18: Effect of soil amendments on chlorophyll content of broccoli leaves during the growing period.

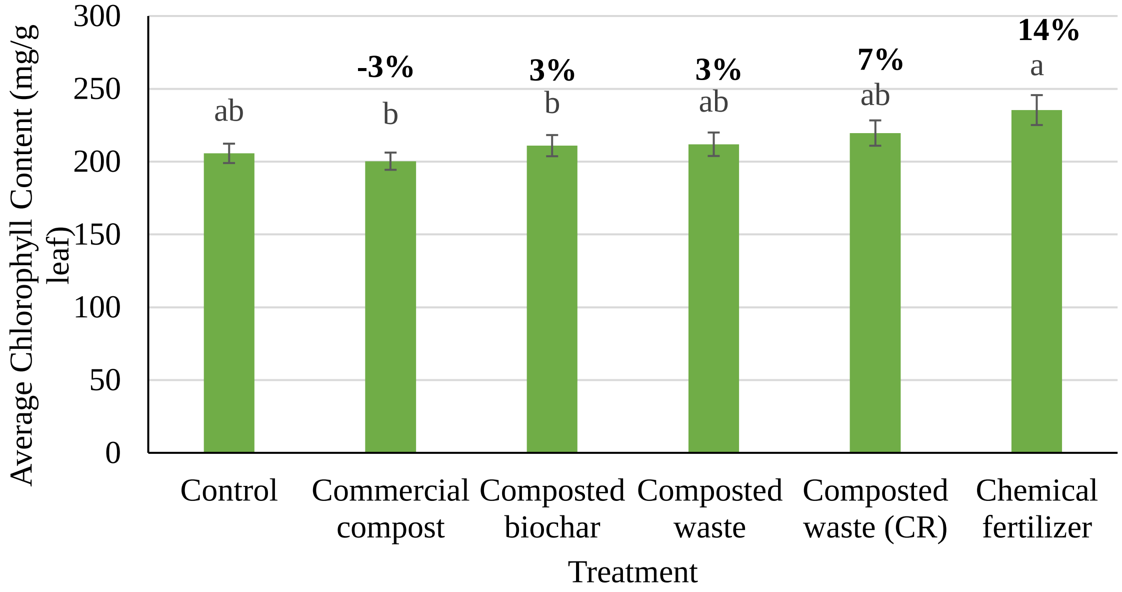

Figure 3.19: Average chlorophyll content of broccoli leaves during the growing period. Statistical differences are represented by letters of significance tested using Tukey test at p< 0.05.

3.3.2.2.5.2 Crop Yields and Quality

The chemical fertilizer produced significantly higher ($p < 0.05$) yields of 34 t/ha relative to organic amendments and control, while composted waste produced second highest yields of 22 t/ha (Figure 3.20). There were no statistical significant differences between the broccoli yields of treatments C, CB, CC, and CWCR (Figure 3.20). Additionally, average fresh weight of broccoli heads harvested from plots amended with CW, CWCR and CF were significantly higher ($p < 0.05$) than the control and CB treated plots, while the average head weight obtained from CC treated plots was intermediate (Figure 3.21). However, the number of plants that survived to harvest did not significantly differ between the control and organic amendment treatments (Figure 3.22). Hence, analysis of variance showed that number of plants did not affect yields. The soil amendments increased crop yields relative to the control with broccoli head weight yields harvested from CC, CB, CW and CWCR being 23%, 13%, 62%, 33% and 136% more than the control yields, respectively.

Broccoli fresh head weight yields are generally consistent with N mineralisation observed in the various treatments (Figure 3.17), except for CWCR which caused elevated immobilization of N when compared to N mineralisation in the control plot, but produced 33% more fresh head weight relative to the control. However, there was a statistical positive correlation (R^2= 69%) between broccoli yields and cumulative total soil N which confirms the hypothesis that mineral soil N would be one of the most yield limiting factors in organic farming systems as the treatment with the highest total mineral N increased yields significantly ($p < 0.05$). It is possible that the high assimilated Ca and S content measured in broccoli heads harvested from CWCR treated plots (Table 3.14) could have enhanced yields because Ca functions to activate certain enzymes that could also be activated by N while S aids in chlorophyll formation and N is the major constituent of chlorophyll molecule (Silva and Uchida 2000). Broccoli fresh head weight yields are consistent with those observed by Ouda and Mahadeen (2008) as their study showed highest yield in plots amended with 80 t/ha organic material blended with 60 kg/ha chemical fertilizers while plots amended with 40 t/ha organic material only performed the worst. However, effects of mineral N availability were also evident in the field as broccoli heads did not mature at the same time (Table 3.13). Therefore, broccoli heads were harvested over a period of five weeks with broccoli heads grown on chemical fertilizer amended plots maturing first followed by organically amended plots.

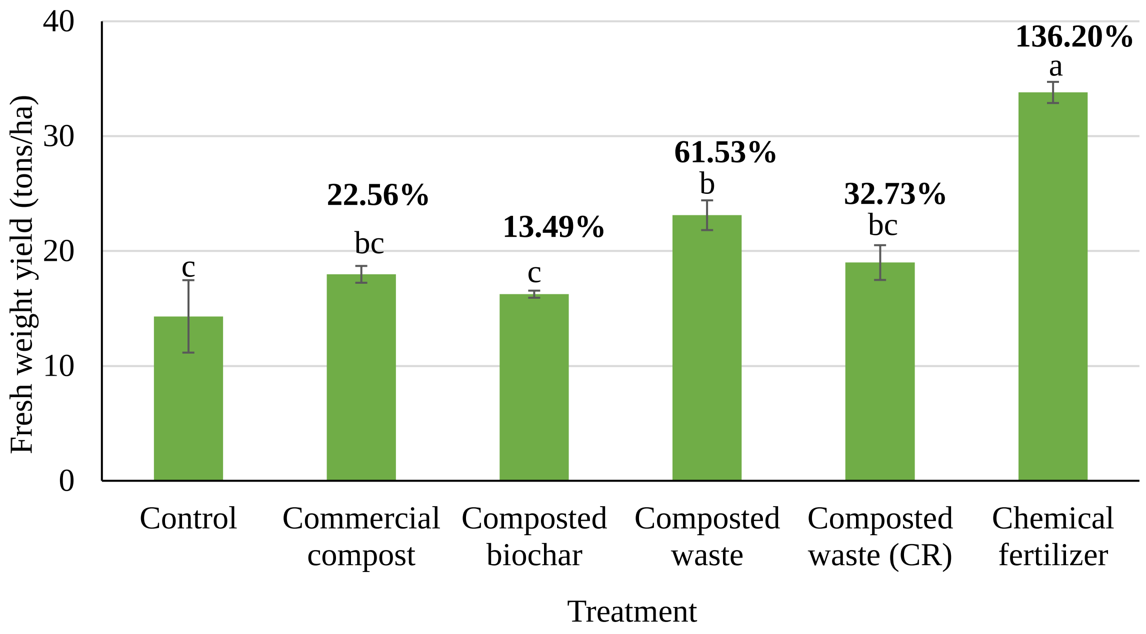

Figure 3.20: Fresh broccoli head yields from the amended treatments compared to the control. Letters of significance shows statistical differences tested using Tukey test.

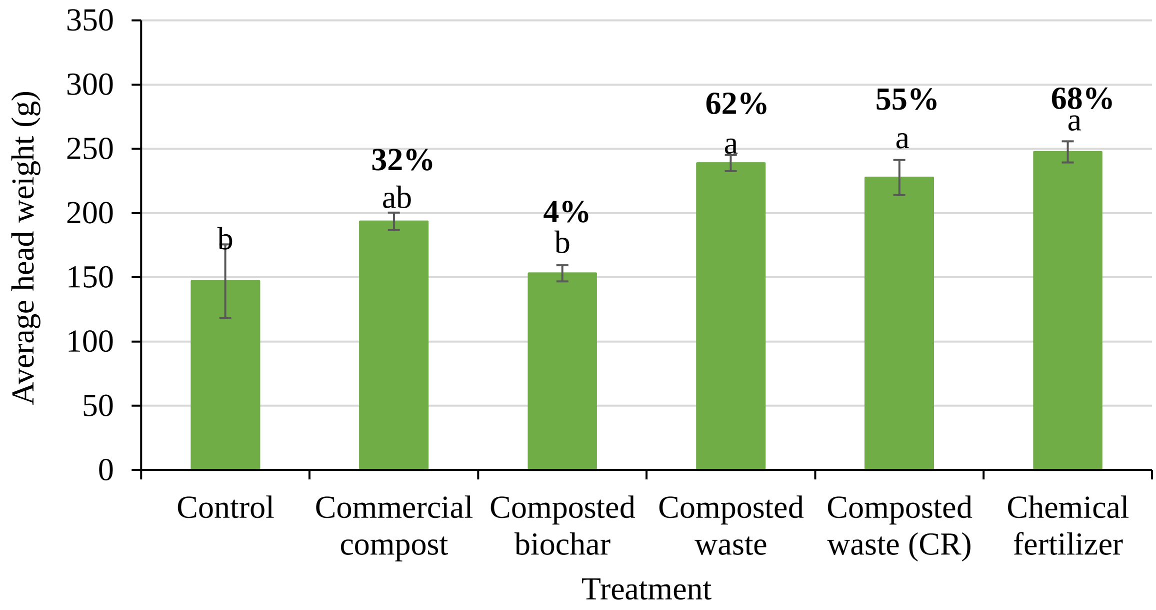

Figure 3.21: Average broccoli head weight harvested from organic and chemical amended plots compared to the control. Letters of significance shows statistical differences tested using Tukey test and % change relative to the control is written in bold.

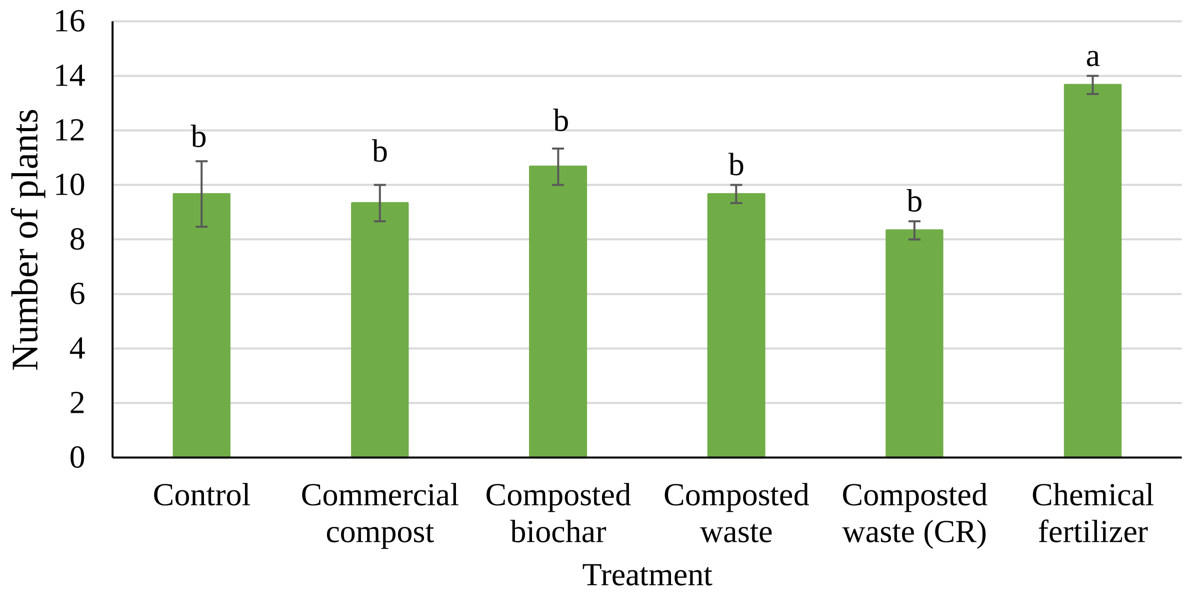

Figure 3.22: Number of plants that yielded broccoli heads at harvest. Letters of significance show statistical differences tested using Tukey test.

The insignificant differences in average sizes of broccoli heads harvested from CW and CWCR compared to heads obtained from CF can be easily attributed to the fact that plants grown on organically amended plots were more susceptible to pests hence some of the plants died due to pest manifestation which then reduced competition between plants enhancing production of large broccoli heads (Figure 3.22)Broccoli heads harvested from CF amended plots were generally large due to readily available nutrients supplied by the chemical fertilizer (Figure 3.22). Additionally, phosphorus and potassium are responsible for broccoli head development as suggested by Silva and Uchida (2000) hence broccoli heads treated with CF, CW and CWCR did not significantly differ in size as there no significant differences in soil P while organically bound K was higher on CWCR (Table 3.3 and Table 3.9).

It is evident that 60% of broccoli yields from plots amended with CF were harvested at week 14 after planting while nothing was harvested from organic amended plots and from the control (Table 3.13). Broccoli heads started to mature from week 15 in organic amended plots and most yields were obtained at week 16 from all amended plots, and from the control. This has financial implications on farm labour as crop that should stay longer in the field requires water supply, pest and weed control which essentially means more labour costs will be incurred.

Duration of the growing season and availability of nutrients for plant uptake would influence crop quality.

Table 3.13: Broccoli fresh head weight weekly and total yields from various treatments

Treatment	Weekly Fresh head weight yields (tons/ha)					Total yield
	Week 14	Week 15	Week 16	Week 17	Week 18	(tons/ha)
Control	0	0	7.56	2.25	4.7	**14.51**
Commercial compost	0	0	8.78	5.61	3.25	**17.64**
Composted biochar	0	0	9.45	2.11	4.68	**16.24**
Composted waste	0	0	14.89	2.33	6.09	**23.31**
Composted waste (CR)	0	7.5	5.55	1.81	4.04	**14.51**
Chemical fertilizer	20.94	1.26	3.04	1.05	7.3	**33.59**

Determining nutrient content of an economic yield obtained from both organic and inorganic fertilizer amended soil is crucial as there is a growing belief that organically produced crops are more nutritious compared with chemical fertilizer produced crops. There were no statistical significant differences in broccoli head nutrient contents between treatments (Table 3.14). However, there was a positive correlation (R^2=69%) between plant available phosphorus in soil as influenced by the amendments and P assimilated in broccoli heads. This positive correlation can be associated with the substantial differences in plant available P measured at planting and the fact that P is relatively mobile in plants, so it would move more easily from plants roots to broccoli florets or heads. Nitrogen content of the broccoli heads was highest in heads harvested from plots amended with CWCR and CF with 4.38% and 4.37% N (Table 3.14), respectively. It was not expected that N content in broccoli heads obtained from CWCR amended plots would be higher compared to other organic amendments as application of CWCR resulted in net N immobilization which was more pronounced relative to CB (Figure 3.17). Broccoli plants grown on plots amended with CWCR could have been more efficient in absorbing N since other essential nutrients (P and K) were abundant because nutrients are required in certain ratios in plant tissues such that there was less N in soil. Broccoli heads grown on the control plots had the lowest N content amounting to 3.68%. These results are consistence with observations of Ouda and Mahadeen (2008) on broccoli, and Wamba et al. (2012) on groundnut. Phosphorus content was higher in broccoli heads that were obtained from

CF treated plots, while K content was higher in broccoli heads that were obtained from CC treated plot (Table 3.14). Phosphorus and potassium content results are in line with observations of Ouda and Mahadeen (2008) when they found that P and K contents to be lower in broccoli leaves and postulated that it would have been higher in broccoli heads since both nutrients are responsible for grain and head development in crops (Silva and Uchida 2000).

Calcium and Mg content results were inconsistent as broccoli heads harvested from control plots had generally higher Ca and Mg contents compared to the amendments. However, the differences were statistically insignificant. Sulphur is an important constituent of chlorophyll molecule, broccoli heads harvested from plots amended with CWCR and CF had higher S content of 1.16% and 1.08%, respectively. Broccoli head S content results are consistent with broccoli head N content results as heads produced from plots amended with CWCR and CF were also high in N content relative to those produced from other plots. Schonhof et al. (2007) pointed out N and S contents, and their ratio in broccoli heads is very essential since they have an influence on production of glucosinolate compounds which are known for their health benefits associated with their anticarcinogenic properties. A study conducted by Omirou et al. (2009) which evaluated effect of N and S supply on broccoli florets yields and glucosinolates content in florets showed that S supply did not have a significant effect on yields but its highest application had a significant ($p < 0.05$) effect on glucosinolates concentration in florets while N supply had a significant effect ($p < 0.05$) on both yields and glucosinolates concentration. Since this study focused on N supply from the amendments its results are in agreement with those observed by Omirou et al. (2009) as CF and CWCR had the highest N application levels (Table 3.3) and these amendments resulted in higher N and S contents in broccoli heads relative to other amendments.

Concentration of the following micro nutrients: iron, manganese, boron and zinc are very critical to evaluate in crops, as human deficiencies may cause anaemia, osteoporosis, arthritis and eczema; respectively. Concentration of Fe, Mn, B and Zn were all higher in broccoli heads harvested from plots amended with CF while CB treated plots resulted in second best in Fe content whereas CWCR plot was second best in Zn.

Table 3.14: Broccoli head nutrient content from plots amended with organic and inorganic soil amendments, and from the control

Treatment	Broccoli heads mineral content											
	N	P	K	Ca	Mg	S	Na	Fe	Cu	Zn	Mn	B
	← (%) →						← (mg/kg) →					
Control	3.68	0.50	2.75	1.32	0.26	0.94	429.67	112.69	5.39	37.81	11.20	49.04
Commercial compost	3.93	0.49	2.87	0.95	0.24	1.01	477.67	111.79	4.62	38.13	9.16	51.43
Commercial fertilizer	4.37	0.59	2.78	0.90	0.24	1.08	485.33	201.71	4.41	43.67	13.45	60.67
Composted biochar	3.93	0.57	2.73	1.06	0.25	1.06	484.00	142.97	5.69	42.65	9.75	50.60
Composted waste	3.88	0.54	2.64	0.84	0.23	1.04	426.67	82.31	6.39	41.42	10.48	52.36
Composted waste (Commercial Rate)	4.38	0.58	2.83	0.87	0.29	1.16	513.33	142.07	4.62	43.47	3.68	53.56

3.3.2.3 Marginal analysis of the treatments

To make recommendations that farmers will use, researchers must be aware of the human element in farming, as well the scientific and economic aspect of the research. Researchers should consider farmers' goals and the constraints on achieving those goals. Smallholder farmers are primarily concerned about producing enough to sustain their households and secondly farmers are concerned about the economic returns from the portion of their yield that they would sell. Farmers will consider the costs of changing from one practise to another and the economic benefits resulting from the change. They will consider the risks involved in changing their practices and they will attempt to protect themselves from risks involved.

For the purposes of this study, marginal analysis was performed on soil amendments used considering opportunity cost from the organic amendments as some of the composts used were produced by the researchers and the farmer. Since all the treatments were managed the same way in the field, costs varied due to the treatment used and without any external factors that were due to management practices. Crawford and Kamuanga (1988) suggested that marginal rate of returns is the most reliable method to use when evaluating economic feasibility of treatments used in agronomic studies as it considers economic yield from each treatment and total costs of that treatment. However, marginal analysis outcome would differ from one farm to another as one would have to consider costs of transportation especially with studies that involve soil amendments such as compost, fertilizers and lime. Cost of transport would have to be considered when dealing with yields as well as that would depend on how far the farmer is from his/her market.

Marginal rate of returns (MRR) depicted that CF and CW are the most profitable and economically feasible treatments with MRR of ~450% and ~150%, respectively (Figure 3.23). Growing broccoli without any soil amendment proved to significantly decrease farmers profit by 36% while CB and CWCR decreased profits by 9% and 11%, respectively (Figure 3.23). All soil amendment expenditures and income generated by the smallholder farmer on broccoli heads sales were compared with those of the commercial compost as it is the farmer's normal practice to use commercial compost in the field.

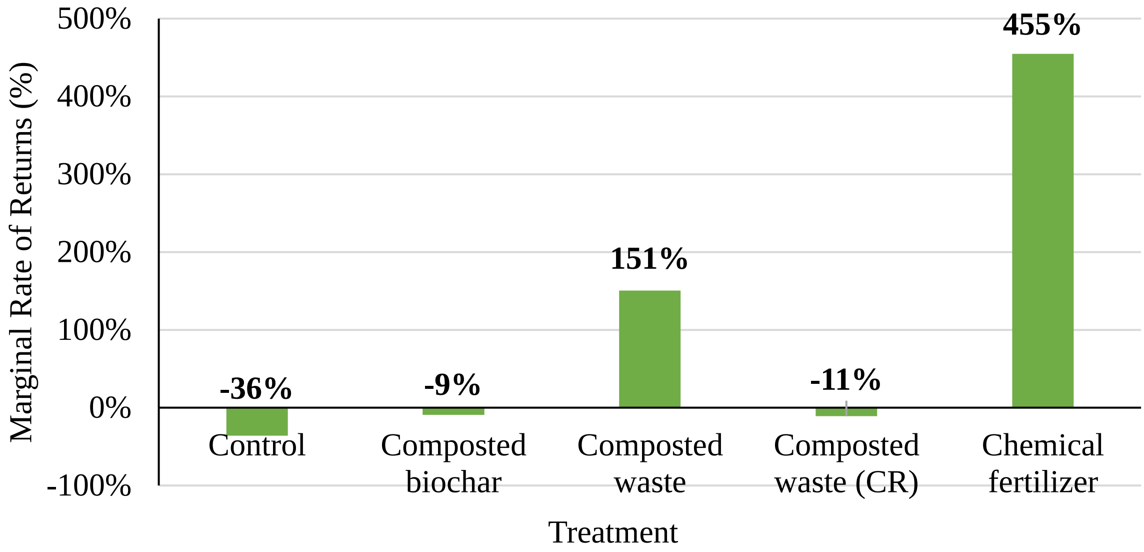

Figure 3.23: Marginal Rate of Returns from the expenditures and income of yields from each soil amendments compared to the farmers normal practice (i.e. commercial compost).

3.4 CONCLUSIONS

This study aimed to evaluate the effect of current and viable alternative soil amendments used by the organic smallholder farmer on soil quality, broccoli growth, yield and quality and economic profitability.

Application of all organic amendments and the chemical fertilizer resulted in non-significant changes in soil fertility parameters at planting, including: soil pH, EC, ECEC, total N, macro and micro-nutrients, except for CWCR which significantly increased soil K and CB which significantly increased soil C. Only the application of CWCR significantly ($p< 0.05$) increased water holding capacity of both sandy (5.6% increase) and sandy loam (11.8% increase) soils relative to the control. The on-farm produced compost applications (CB, CW and CWCR) significantly ($p< 0.05$) increased SOM at planting while CC had the least contribution to SOM among organic amendments due to its highest ash content (88.83%) which indicates a high content of mineral matter (likely sand). Only the CF treatment significantly increased soil mineral N (150-160%) during the first 11 weeks of growth, which was found to be the main driver of broccoli yields. The addition of C in the organic treatments did not increase microbial activity as soil respiration was significantly lower than in the control treatment. This was attributed to the inefficiency of the microbes to decompose the materials, likely due to the high C and low N content of the substrates and winter weather. The CF treatment broccoli heads matured 2 weeks earlier than the organic and control treatments and gave the significantly highest yields compared to the control (136% higher) and farmer's routine practice (CC) (88% higher). Among the organic amendments, CW at 10 t/ha resulted in significantly higher yields than the control (61%) or CC (28%) treatments. Furthermore, the CF resulted in greater number of plant survival, as plants were more vigorous and showed greater resistance to pest damage (aphids, caterpillars and snails).

There were no significant differences in broccoli mineral nutrient content between the treatments, although N and S contents tended to be higher in CF and CWCR treatments. The CF and CW treatments were the most profitable treatments relative to the farmer's routine amendment practice (CC), resulting in 433% and 151%, increase in marginal rate of returns, respectively. Composted biochar and CWCR performed the worst in terms of yields and economic profitability, which is attributed mainly to lack of N mineralisation.

It is evident from the winter broccoli field trial results that amending soil with 10 t/ha of compost that is produced on farm is far better than using a commercial compost in terms of soil quality measures, crop response and economic benefits. However, the use of a well-designed chemical fertilizer programme proves to have both greater economical yield and similar crop quality relative to composted waste. The main limiting factor in using composted waste for crop production is the low rate of N mineralisation, especially in winter months.

CHAPTER 4

SUMMER FIELD TRIAL: COMPARISON OF ORGANIC AND CHEMICAL AMENDMENTS ON GREEN BEAN PRODUCTION AND SOIL QUALITY

4.1 INTRODUCTION

Peri-urban smallholder farmers around Cape Town are likely to experience a decline in food production due to constant intensive use of marginal land, lack of agronomic/technical support and threat posed by climate change as it is seen that the sea level is on a steady rise which is expected to lead to erratic rainfall events of high intensity and short duration with an increase in atmospheric temperature (Western Cape Government, 2016). This poses a threat to fresh vegetable production for the city as it estimated that annual produce of 100 000 tons of fresh vegetables for the Cape Town market is supplied by peri-urban farmers who are mostly farming on marginal land consisting of sandy soils that are freely drained and have low storage capacity for water and nutrients. The report released by the Western Cape Government (2016) the suggests that peri urban smallholder farmers must practice conservation agricultural practices such as maintaining permanent organic soil cover and incorporation of organic amendments to sustainably supply crops with nutrients and save water.

Production and application of organic amendments to soil such as compost can function to mitigate climate change, reduce natural resource pollution and increase SOM (Wamba et al. 2012; Bationo 2003). However, nutrient release from organic amendments is still a major constraint in crop production as it depends on environmental factors that smallholder farmers cannot control (Mnkeni and Austin 2009). Since organically bound nutrients in organic amendments depend on microbial activity for mineralisation, it is essential to understand the factors that affect efficiency of microbial activity as the latter indicates nutrient (particularly N) mineralisation in soil. Warm moist conditions are ideal for microbial activity as most microbes prefer average temperature of 25°C and moisture content less than 60% for optimum growth (Diaz et al. 2007).

Subsequently, there is a need for evaluation of nutrient release from soils amended with various organic amendments as influenced by microbial activity and inherent soil properties. This could help in planning and managing cropping systems in organic and smallholding farms. Additionally, it is ideal to compare nutrient release (particularly N) from organic amendments with chemical fertilizers as that would help farmers and researchers to decide which form of fertilization is efficient and economically feasible for crop production.

This chapter focuses on data collected during the summer field trial which was planned and developed based on main findings of the winter field trial. The composts utilized during the broccoli winter field trial generally mineralised very little N, whereas N was found to be the main driving factor for broccoli yields. Thus, it was decided that commercial organic fertilizers will be included during the summer field trial to evaluate whether the organic fertilizers will mineralise more N, thus increasing crop yields. Two commercial organic fertilizers were chosen based on their mineral nutrient composition, potential degradability of the material and the fact that there are easily accessible on the market to the farmer. One of the organic fertilizers mainly consisted of bone meal and blood while the other was composed of chicken manure, both materials are known to be highly mineralisable (Brady and Weil 2008). Additionally; the organic smallholder farmer had adjusted his soil amendment practices by producing his own compost since the commercial compost he was using during the broccoli winter field trial was proven to be poor in terms of quality and was economically infeasible to use because it did not markedly increase crop yields. The farmer's compost together with four commercial composts were sent to a commercial laboratory to determine their mineral nutrient composition which was used as a criterion to select the two composts that were to be used for the summer field trial. The results indicated that the compost produced by Stellenbosch University was the most fertile among the commercial composts and farmer's compost had to be used as it was his current soil amendment practice. The farmer selected green bush beans (*Phaseolus vulgaris L.*) a model crop since there was a strong demand from his regular clients at the time. Similar to the first field trial, the organic amendments were compared with a commercial chemical fertilizer programme for green bean production. Green beans have been shown to increase smallholder farmers economic turnover in most developing countries thus improving smallholder farmers livelihoods (Getachew et al. 2014).

This chapter aims to evaluate the effect of the smallholder farmer made compost, a commercial compost, two commercial organic fertilizers and a chemical fertilizer programme on green bean (*Phaseolus vulgaris L.*) growth, yield and quality; soil quality and economic profitability.

4.2 MATERIALS AND METHODS

4.2.1 Effect of soil amendments on green bean growth, yield and quality

4.2.1.1 Site description

See section 3.2.2.1 for site description, however, it should be mentioned that a different previously fallow experimental plot was selected at the smallholding farm to limit bias from using the broccoli field trial experimental plot as it was treated with different soil amendments.

4.2.1.2 Experimental design and treatments

Green bush bean (*Phaseolus vulgaris L.*) was selected as a model crop for the summer field trial conducted from February-May 2017, as there was a strong demand for green beans from the smallholder farmer's existing market. The farmer had adjusted his soil amendment practices by producing his own compost with chicken manure and crop residues he had on farm since it was recommended to him that he should use his own compost as the commercial compost was proved to be off poor quality during the broccoli winter field trial. The effect of the smallholder farmer's current soil amendment practice (farmer's compost-FC) was compared with the application of university compost (UC), two organic fertilizers (OF1 and OF2) and a chemical fertilizer (CF) programme on soil quality and green bean production. The university compost was selected since based on the initial nutrient content screening it contained the highest nutrient levels, and it was available for the farmer to buy. The commercial organic fertilizers were selected on the basis that they are more nutritious than composts (Table 4.1) and certified organic. Organic fertilizer 1 (OF1) was composed of bone meal and blood (known to be highly mineralisable) while OF2 was mainly chicken manure pellets (known to be off medium-high quality). All the organic amendments application rates were calculated to supply N application rate of 158 kg N/ha which is recommended for green beans (ARC 2013). However, the two composts were applied at incorrect rates due to an incorrect compost elemental analysis supplied by Bem Lab (Pty) Ltd., Somerset

West, prior to the start of the field trial. The compost samples were sent for total C, N and S analysis using the Stellenbosch University, Central Analytical Facility's (CAF) new elemental CNSH analyser directly after the field trial was completed (Table 4.1). After repeated analysis, it was found that Bem Lab must have swapped two compost samples provided, which lead to incorrect application rates based on N content that they provided (Table 4.2). This was also confirmed by the soil fertility results of the field trial.

Table 4.1: Chemical characteristics of the organic amendments used during the green bean field trial.

Organic amendment	pH (H_2O)	EC (mS/m)	Total C (%)	Macro nutrients (%) N	P	K	Ca	Mg	S	Micro nutrients (mg/kg) Na	Mn	Fe	Cu	Zn	B	C:N Ratio
FC°	6.57	58.70	18.63	1.76	0.14	1.03	4.32	0.49	0.12	1341	238	8616	25	188	37	10.59
UC°	8.14	176.10	8.02	0.89	0.65	0.14	2.14	0.16	0.09	356	38	18229	17	21	34	9.01
OF1*	7.40	-	29.00	7.40	3.70	4.90	9.20	0.30	2.30	3	51	735	20	112	30	3.92
OF2*	7.00	-	11.50	2.60	1.80	3.30	3.60	0.70	1.00	-	610	5000	60	540	50	4.42

° Determined by Bem Lab and CAF, Stellenbosch University

* Determined by the supplier

The treatments of the field trial were laid out in a randomized completely blocked design and there were three blocks with each block having six plots which were 5 m^2 in size. Composts (FC and UC) were applied two weeks prior to planting of green bean seeds, since it is the smallholder farmer's normal practice. The two commercial organic fertilizers (OF1 and OF2) were applied at planting, while the first increment of the commercial chemical fertilizer (CF) programme was applied a week before planting of green bean seeds as recommended by the manufacturers of the organic fertilizers and chemical fertilizer company (Yara Fertilizers), respectively. The chemical fertilizer was applied in split applications on weekly basis for a period of 10 weeks according to the programme designed by Yara for green beans (Table 4.3). A randomized completely blocked design was used to block the fertilizer from interfering or contaminating the organic amendment treatments and the control (Figure 4.1). Chemical fertilizer was applied on three experimental plots that were on the bottom edge of the whole experimental site, as the experimental plot was slightly sloping to avoid contamination of the adjacent organic plots (Figure 4.2).

A pathway of 1 m between blocks and on the edges of the blocks was left fallow to limit interactions between blocks and edge-effect from weeds or farmers production (Figure 4.1). Even though the plot sizes were 2.5 m × 2 m, only 2 m × 1.8 m was planted with row and inter row spacing of 0.15 m, and amended 2 m × 0.7 m buffer strip was left fallow to measure soil respiration. Microjet sprinkler irrigation system was used to irrigate the experimental plots, each plot had a micro jet sprinkler that irrigated 2-2.5 m surface in diameter (Figure 4.2). The irrigation system was automated to irrigate from 06:30-07:30 in the morning on daily basis as it tends to be windy during the day on site since it is close to the coast. Irrigation scheduling was decided upon determining the time it takes for waterfront to reach vegetable rooting depth of 30 cm. No pest control was required during the field trial besides manual weeding.

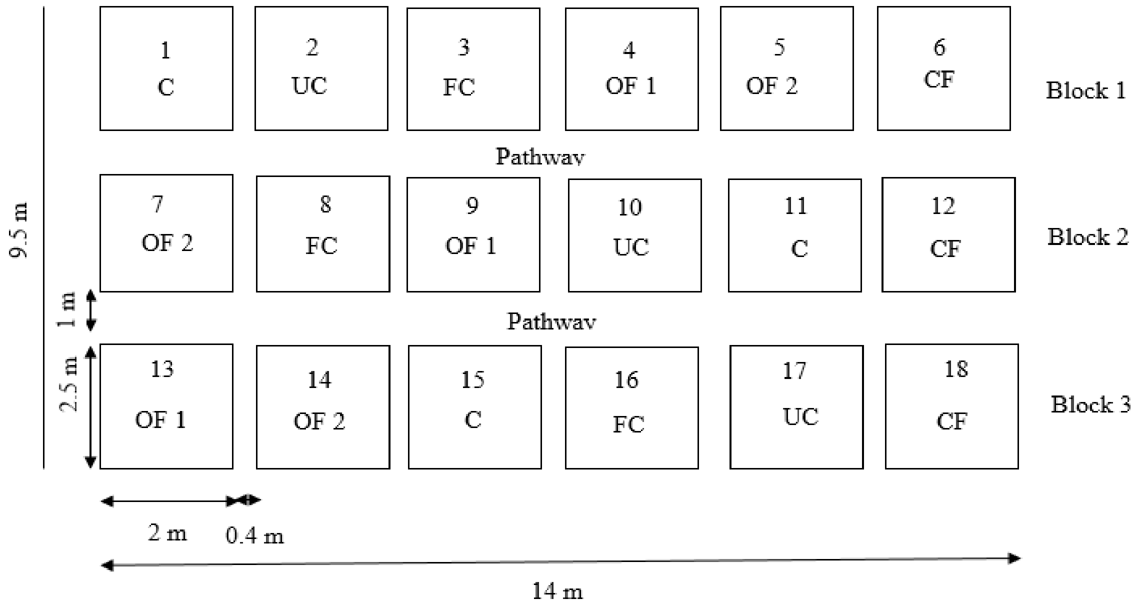

Figure 4.1: Plan of the experimental layout with six triplicated treatments.

Figure 4.2: Actual digital image of the experimental plot three weeks after planting.

Table 4.2: Experimental treatments, their application rates and macro nutrients input.

Treatment name:	Treatment abbreviation	Application rate (t/ha)	Amount of macro nutrients applied (kg/ha)					
			N	P	K	Ca	Mg	S
Control	C	0	0	0	0	0	0	0
Farmers Compost	FC	17.76	181	13	183	767	87	21
University Compost	UC	8.98	49	75	13	192	14	47
Organic Fertilizer 1	OF1	1.76	158	65	86	162	5	40
Organic Fertilizer 2	OF2	5.46	158	98	180	197	38	55
Chemical Fertilizer	CF	1.35	158	60	122	115	8	53

Table 4.3: Weekly applications of chemical fertilizer products and the amount of macro nutrients supplied by each application.

Time	Product name	Application rate (kg/ha)	Macro nutrients supplied (kg/ha)					
			N	P	K	Ca	Mg	S
Before planting	Superstart	300	23.1	23.1	23.1	30	2.4	20.7
Week 1	Turbo 30	75	16.1	1.6	4.8	0.0	0.0	3.8
Week 2	Turbo 30	75	16.1	1.6	4.8	0.0	0.0	3.8
Week 3	Nitrabor	100	15.4	0.0	0.0	18.3	0.0	0.0
Week 4	Superstart	300	23.1	23.1	23.1	30	2.4	20.7
Week 5	Nitrabor	100	15.4	0.0	0.0	18.3	0.0	0.0
Week 6	TopUp	100	11.1	3.7	22.0	0.0	0.9	1.3
Week 7	Nitrabor	100	15.4	0.0	0.0	18.3	0.0	0.0
Week 8	TopUp	100	11.1	3.7	22.0	0.0	0.9	1.3
Week 9	TopUp	100	11.1	3.7	22.0	0.0	0.9	1.3

4.2.1.3 Methods used to measure the effect of soil amendments on soil fertility and crop response

A composite soil sample was collected from each experimental plot at planting and harvest to determine soil fertility status. The following parameters were measured on the samples: soil pH (water and 1 M KCl), electrical conductivity, plant available P, exchangeable basic cations and acidity, micro nutrients content, total C and N, and soil organic matter content. Mineral N and dehydrogenase enzyme activity was determined on samples collected at planting and on weekly basis until harvest according to methods developed by Mulvaney (1996) and Casida et al. (1964), respectively. Soil respiration was measured on two weeks intervals to monitor microbial decomposition according to a method explained by Keith and Wong (2006). All the soil analytical methods are described on section 3.2.2.3.

Crop vigour was monitored by measuring leaf chlorophyll content index (CCI) on weekly basis using a chlorophyll meter as described in section 3.2.2.4. Despite the varying experimental treatments, green beans were treated the same throughout the growing period to limit bias and no pest control was required as pest infestation was not observed until harvest. Green bean pods were harvested at week twelve after planting of green bean seeds. At harvest, the number of plants per plot were calculated and the mass of pods harvested per plot was recorded to estimate yields on per hectare basis and the average mass of pods per plant. Green bean pods from each experimental plot were analysed for nutritional quality at harvest to evaluate the effect of the soil amendment treatments on crop quality, as explained in Section 3.2.2.4.

In the laboratory, a soil water holding capacity study was conducted on the two composts used during the field trial to evaluate their effect on soil water holding capacity, similar to the previous chapter as described in Section 3.2.2.5. The two composts were applied at 10 t/ha as the normal farmer's practice and at field application rates (Table 4.2) on the sandy loam soil from the field trial site and the sandy soil from the Cape Flats.

The data obtained was statistically analysed using analysis of variance (ANOVA) for repeated measures which is a two-way ANOVA and where necessary a one-way ANOVA was used to analyse the results for statistical differences. Analysis of covariate (ANCOVA) was used for green bean yields as crops did not grow uniformly in the field, number of plants that green bean pods were harvest from were used as a covariate in the analysis. The treatment means were compared using the Least Significant Difference range test at 95% confidence level. All statistical analyses were performed using R statistical software package (version 3.2.3, University of Auckland, New Zealand).

Marginal analysis was performed by determining marginal rate of returns (MRR) of each experimental treatment relative to the smallholder farmer's current soil amendment practice (i.e. application of farmer's compost at N crop requirement) as described by (Louis 2011). Marginal rate of returns was calculated by determining marginal net benefit of using a certain amendment relative to use of farmer's compost and dividing marginal benefit by marginal cost, which is essentially comparison of variable costs of a certain soil amendment with farmer's compost cost. Field price was used for each treatment and cost of labour was considered when costs were determined on per hectare basis. The equation for determining marginal rate of returns is provided on section 3.2.3.

4.3 RESULTS AND DISCUSSION

4.3.1 Effect of soil amendments on soil properties and crop response

4.3.1.1 Laboratory Study: Soil Water Holding Capacity

Only the application of FC at the field trial application rate of 17.76 t/ha significantly ($p < 0.01$) increased soil water holding capacity of the sandy loam soil compared to the other treatments (Figure 4.3). Field application rates (Table 4.2) of UC and FC respectively increased soil water holding capacity of the sandy loam soil by 1% and 14% while the smallholder farmers typical application rate (10 t/ha) of UC and FC individually increased soil water holding capacity by 2%.

There were no statistical significant differences in soil water holding capacity of sandy soil that were due to the soil amendments (Figure 4.3). The statistical insignificance of the differences obtained can be associated with the dominance of macro pores in sandy soils and the fact that sand particles do not aggregate strongly with each other nor with added organic matter. This means that it is likely that considerably more organic material must be added to the sandy soil for a significant increase in water retention to be observed, which has economic and possibly nutrient mineralisation implications.

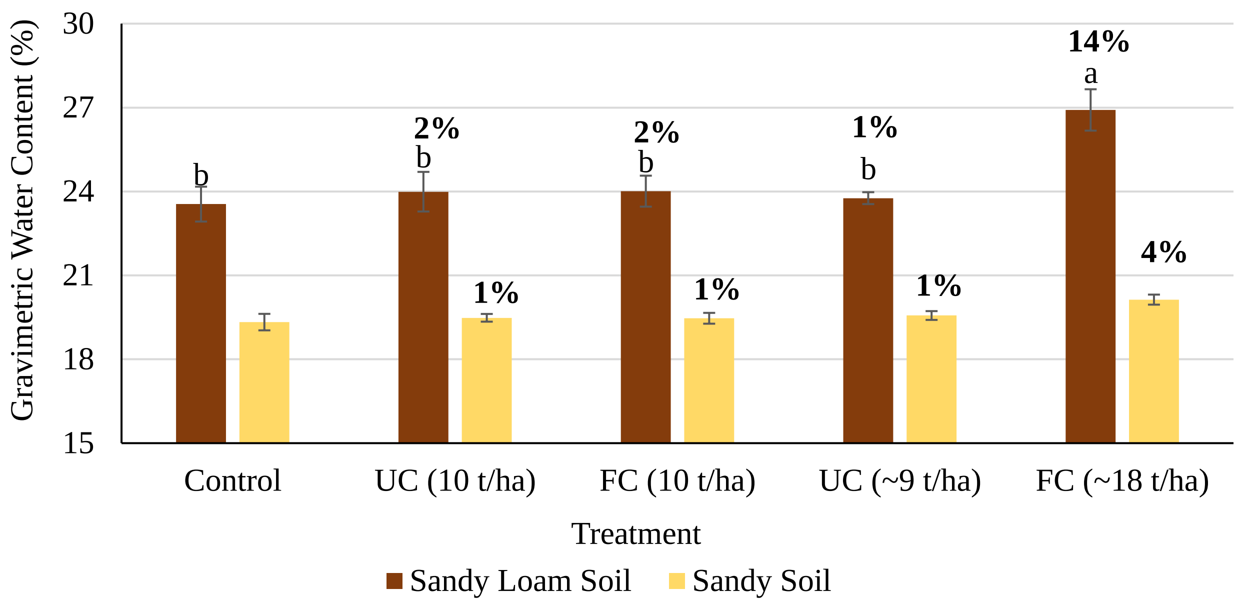

Figure 4.3: Effect of compost amendments on soil water holding capacity of a sandy and a sandy loam soil. Statistical significant differences are illustrated by letters of significances at p< 0.05.

4.3.1.2 Green Bean Field Trial

4.3.1.2.1 Soil pH, electrical conductivity and nutrient content

At planting, only application of the chemical fertilizer (CF) significantly ($p < 0.05$) reduced soil pH in water to pH 6.94 compared to the control (pH 7.38) or organic treatments (pH 7.10-7.34), while there were no statistically significant differences in exchangeable pH (KCl) between treatments (Table 4.4). Soil pH measured in water of CF amended plots was within accepted level of 5.5-7.0 for common bean (*Phaseolus vulgaris L.*) production as recommended by Singh (2005), however, the soil pH of the control and the organically amended plots was above neutral pH (7) but within the maximum threshold of 7.5 for manganese deficiency as suggested by Borchgrevink (2012). The significant ($p < 0.05$) decline of soil pH of about 0.44 units in plots amended with CF relative to the control can be attributed to the acidifying ability of ammonium-based fertilizers (Mnkeni and Austin 2009) and the lower C content of the CF treatment, which meant it was less buffered. On the contrary, reduction of soil pH in plots treated with organic amendments was not significantly different from the untreated plots and this can be attributed to relatively low nitrogen content which is representative of organic N molecules such as amines and amides that would attract H^+ from solution forming ammonia, thereby reducing soil pH. Soil pH measured in 1 M KCl did not show significant response to any of the amendments, whether organic or inorganic, and this indicates that the soil has an adequate buffering capacity since soil pH in KCl represents exchangeable acidity. Soil pH decreased in all treatments from planting to harvest and that was expected as irrigation leaches nutrients and nitrification of ammonium N lowers soil pH (Table 4.5). Soil pH measured in water was significantly ($p < 0.05$) lower (0.65 pH units) in CF treatment. Constant use of ammonium-based fertilizers would require the soil to be limed and it would also be advisable to incorporate more organic residues to help buffer the soil pH in CF treated soil.

At planting, only the application of OF2 significantly ($p < 0.05$) increased electrical conductivity of the soil threefold to 0.91 $mS.m^{-1}$ compared to the control soil (0.30 $mS.m^{-1}$) (Table 4.4). The application of the commercial organic fertilizers increased soil EC by the greatest extent, which indicates that these fertilizers contained higher concentrations of soluble ions, as indicated by the higher levels of exchangeable K, Mg and Ca in these treatments (Table 4.4). According to Brady and Weil (2008) beans are among the most sensitive crops to salinity where a 10% loss in yields can be expected if the EC of the saturated paste extract of the soil exceeds 200 $mS.m^{-1}$. However, the EC of a 1:2.5 soil to water ratio extract (measured in the study) was within the maximum threshold of ~50 $mS.m^{-1}$ for a 10% loss in yields for all the treatments. The conversion from EC of a saturated paste extract to that of a 1:2.5 soil to water ratio was performed using linear equations developed by Sonmez et al. (2008). There were no significant differences in soil EC at harvest among treatments and EC decreased significantly ($p < 0.05$) from planting to harvest in all the experimental plots (Table 4.5). This can be attributed to the number of bases that were dissolved in soil water and absorbed by the plants or leached down the soil profile to below the rooting depth of vegetables. It is beneficial that the EC declined over time in all the treatments as accumulation of salts would encourage the formation of salt-affected soils with EC of greater than 4 dS/m (McBride 1994; Brady and Weil, 2008).

Application of UC, OF1, OF2 and CF significantly ($p < 0.05$) increased plant available P content at planting of green bean seeds (Table 4.4). Plant available P results are in accordance with calculated P application rates of the amendments as indicated on Table 4.2, as FC supplied the least amount of P compared to other amendments. According to FSSA (2007) the plant available P content in the control (16.02 mg/kg) and FC (16.87 mg/kg) treatments was deficient for green bean growth as it was lower than 25 mg/kg (threshold amount for vegetables). This has implications on green bean yields as P is responsible for development of seeds in grain crops such as common beans and P deficiency in grain fields is a common occurrence in Sub Saharan Africa (Namugwanya et al. 2014). Application of UC, OF1, OF2 and CF respectively supplied 2.20, 1.90, 13.32 and 7.29 mg/kg more plant available P relative to the threshold amount while FC amended plots and the control were deficient by 8.13 and 8.93 mg/kg, respectively. Since leguminous crops such as green beans form symbiotic relationships with arbuscular mycorrhizal fungi, this would also facilitate P uptake by the roots provided that the symbiotic relationship exists (Grant et al. 2005) and that would help to limit the reduction in yield on FC amended plots and the control. Plant available P content significantly ($p < 0.05$) decreased from planting to harvest in all the experimental plots and this decline can be attributed to plant uptake and organic P leaching due to irrigation and rainfall.

Application of organic and chemical amendments significantly ($p < 0.05$) reduced soil exchangeable acidity (EA) at planting of green bean seeds (Table 4.4). Application of UC, FC, OF1, OF2 and CF respectively reduced exchangeable acidity by 0.06, 0.11, 0.21, 0.24 and 0.11 $cmol_c$/kg. The greatest significant ($p < 0.01$) reduction of EA due to application of organic fertilizers (OF1 and OF2) can be attributed to relative high number of basic cations added by the application of organic fertilizers (Table 4.2) which essentially would have displaced exchangeable acidity (H^+) due to the preference of colloidal surfaces to adsorb divalent cations more than monovalent cations. This is in accordance with electrical conductivity results which indicate that application of both organic fertilizers increased the amount of salts (bases) in soil solution (Table 4.4). Additionally, the less pronounced reduction of EA ty associated with application of both composts can be attributed to added pH dependent charges that would adsorb more ions dissolved in solution which would also be expected from organic fertilizers, however, the application of organic fertilizers was relatively lower than that of composts meaning that the organic substrate content was higher in compost amended plots. The less pronounced reduction of EA due to application of CF can be attributed to low application of CF at planting due to split applications set out by the fertilizer producing company. The exchangeable acid saturation was within the accepted level of less than 10% (FSSA, 2007) in all the amended plots and the control. Experimental plots amended with UC, FC, OF1, OF2 and CF respectively had an acid saturation of 2.04%, 1.50%, 0.53%, 0.34% and 1.43% while the untreated plots had an acid saturation of 2.86%. Exchangeable acidity significantly ($p < 0.05$) declined from planting to harvest in all the experimental plots and this can be attributed to adsorption of cations with stronger ionic strength than that of H^+ on colloidal surfaces (Table 4.5).

There were no statistically significant differences in basic cation contents of amended plots and the control at planting of green bean seeds (Table 4.4) and at harvest of green bean pods (Table 4.5). According to FSSA (2007) the control soil initially had adequate amount of Ca, Mg and K for the growth of vegetables; and the amendments added Ca, Mg and K content that falls within the respective accepted ranges of 200-3000, 50-300 and 40-250 mg/kg except for OF2 which added 163.4 mg/kg of K more than the accepted level. Exchangeable Ca and K generally decreased from planting to harvest of green beans while exchangeable Mg and Na increased from planting to harvest. The decline of Ca and K content can be attributed to uptake by plants and the antagonistic relationship between Ca and Mg which could have led to more absorption of Ca by plants while compromising Mg thereby causing an increase in Mg content in the soil as it would be released from organic chelates over time.

There were no statistically significant differences in micro nutrient contents of experimental treatments at planting of green bean seeds (Table 4.4) and harvest of green bean pods (Table 4.5). Zinc content was deficient in all the treated and control plots as the element was lower than the recommended minimum threshold value of 2 mg/kg (FSSA 2007). Application of organic amendments (UC, FC, OF1 and OF2) respectively increased extractable Zn by 0.67, 0.26, 0.72 and 0.82 mg/kg relative to the control which was deficient in plant available Zn by 1.93 mg/kg while application of CF did not add any significant amount of Zn at planting. Manganese and copper contents of all the experimental plots were within respective critical ranges of 1-5 mg/kg and 0.1-2.5 mg/kg while Fe content of all the experimental plot was higher than the critical range of 2.5-5 mg/kg (Pais and Benton, 1997). Even though Fe content was higher than the critical range for crop production, it was lower than the toxic range of 125-300 mg/kg which is considered unsuitable for crop production since it would render soil P unavailable for plant uptake (Suresh 2005).

Table 4.4: Soil fertility status at green bean seeds planting in the compost, organic and chemical fertilizer treatments compared to the control. Statistical differences due to the treatments are presented by letters of significance at $p < 0.05$.

Treatment	pH (H_2O)	pH (KCl)	EC (mS/m)	P (mg/kg)	Exch. Acid ($cmol_c$/kg)	Total elemental composition: Basic cations ($cmol_c$/kg)				Micro nutrients (mg/kg)				ECEC ($cmol_c$/kg)
						Ca	Mg	K	Na	Cu	Zn	Mn	Fe	
Control	7.38 a	7.06	0.30 b	16.02 b	0.28 a	8.57	0.47	0.30	0.17	0.69	1.07	1.37	14.57	9.79
University Compost	7.18 a	6.91	0.42 b	27.20 a	0.22 b	8.90	0.80	0.63	0.19	0.59	1.74	2.11	19.81	10.74
Farmers Compost	7.27 a	7.15	0.39 b	16.87 b	0.17 bc	10.23	0.53	0.25	0.16	0.58	1.33	1.58	14.28	11.34
Organic Fertilizer 1	7.34 a	7.12	0.76 ab	25.90 a	0.07 c	11.37	0.83	0.62	0.22	0.58	1.79	1.83	16.81	13.11
Organic Fertilizer 2	7.10 a	6.92	0.91a	38.32 a	0.04 c	9.50	1.00	1.06	0.25	0.47	1.89	1.95	16.04	11.85
Chemical Fertilizer	6.94 b	6.92	0.49 ab	32.29 a	0.17 bc	10.67	0.50	0.35	0.13	0.64	1.06	1.36	17.78	11.82

Table 4.5: Soil fertility status at green bean pods harvest in the compost, organic and chemical fertilizer treatments compared to the control. Statistical differences due to the treatments are presented by letters of significance at $p< 0.05$.

Treatment	pH (H_2O)	pH (KCl)	EC (mS/m)	P (mg/kg)	Exch. Acid ($cmol_c/kg$)	Total elemental composition: Basic cations ($cmol_c/kg$)				Micro nutrients (mg/kg)				ECEC ($cmol_c/kg$)
						Ca	Mg	K	Na	Cu	Zn	Mn	Fe	
Control	7.14 a	6.58	0.01	11.43 b	0.09 a	9.00	1.47	0.09	0.68	1.04	3.03	3.55	27.27	11.38
University Compost	7.33 a	6.79	0.04	14.62 ab	0.03 b	9.00	1.37	0.12	1.65	1.10	3.32	4.14	33.51	12.17
Farmers Compost	7.46 a	6.93	0.04	16.02 ab	0.01 c	8.77	0.83	0.09	0.55	0.85	1.97	2.60	25.28	10.25
Organic Fertilizer 1	7.45 a	6.93	0.03	22.11 a	0.01 c	10.50	1.07	0.10	1.01	1.09	3.07	3.20	29.17	12.69
Organic Fertilizer 2	7.43 a	6.88	0.04	14.37 ab	0.06 a	8.87	1.53	0.10	1.49	0.87	3.78	4.17	32.62	11.70
Chemical Fertilizer	6.73 b	6.13	0.03	13.82 ab	0.03 b	10.70	1.50	0.13	0.74	1.14	1.62	2.52	29.02	13.10

4.3.1.2.2 Total C and N at planting of green bean seeds and changes in soil organic matter

There were no significant differences in the C and N contents of the control and treated plots at planting of green bean seeds (Table 4.6). Even though the differences were insignificant, application of organic amendments tended to increase C and N content of the soil relative to the control or CF treatment. Application of UC, FC, OF1, and OF2 respectively increased total C content by 26%, 27%, 44%, and 54% while total N content correspondingly increased by 24%, 13%, 43%, and 52%. Both organic fertilizers (OF1 and OF2) resulted in highest increment in C and N content, and this can be attributed to that OF1 was mainly composed of bone meal mixed with blood while OF2 was mainly chicken manure.

There were also no significant differences in the SOM content of the control and treated plots at planting and harvest of green beans (Table 4.7). Similar to total C results, application of organic amendments tended to increase SOM at planting relative to the control; application of UC, FC, OF1 and OF2 increased SOM by 16%, 24%, 22% and 24%, respectively. There was a relative decline in SOM content from planting to harvest in all organically amended treatments, ranging between -5.2 % to -15.6 % (Table 4.7), while there was little or no change in the control treatment, whereas, there was a relative increase (+11.5%) in the CF treatment. The relative decline in organically treated plots can be attributed to enhanced microbial activity due to added labile C substrates, while the relative increase in CF amended plots can be associated with increased root biomass and relatively lower microbial activity (Vanlauwe and Giller 2006). It is likely that little or no change observed in the control treatment can also be due to lower microbial decomposition, but also lower inputs of root biomass compared to the fertilized treatment.

Table 4.6: Soil total C and N content at green bean seeds planting in the compost, organic and chemical fertilizer treatments compared to the control.

Treatment	C (%)	N (%)	C: N
Control	1.74	0.13	13.71
University Compost	2.34	0.17	13.52
Farmers Compost	2.36	0.15	15.76
Organic Fertilizer 1	3.13	0.23	13.79
Organic Fertilizer 2	3.78	0.27	13.84
Chemical Fertilizer	1.84	0.16	11.74

Table 4.7: Total SOM in plots treated with compost, organic and chemical fertilizer compared to the untreated plots at green bean seeds planting and after harvest.

Treatment	SOM (%)		Relative change in SOM (%)
	At Planting	At Harvest	
Control	6.29	6.31	0.32
University Compost	7.32	6.44	-12.02
Farmers Compost	7.81	6.59	-15.62
Organic Fertilizer 1	7.68	7.22	-5.99
Organic Fertilizer 2	7.82	7.41	-5.24
Chemical Fertilizer	5.91	6.59	11.51

4.3.1.2.3 Soil Respiration

There were no significant differences in soil respiration that were due to the application of soil amendments (Figure 4.4 and Figure 4.6), however, there were significant differences ($p< 0.01$) in soil respiration due to time of measurement (Figure 4.4). There was a spike increase in soil respiration from week 2 after the application of soil amendments to week 4 in the control and plots treated with FC and OF1, with latter being significantly ($p< 0.05$) higher than all other treatments at week 2 (Figure 4.4). However, plots treated with CF, UC and OF2 showed decline in soil respiration from week 2 to week 6 after the application of the organic amendments. This decline can be attributed to relatively low C added in UC and CF treatments (Scherer et al. 2011) while it can be associated with the greatest increase in soil EC on OF2 amended plot which would render microbes in efficient in breaking down the material (Table 4.4). Soil respiration increased from week 6 to week 10 in treated plots and the control, signifying that microbes adjusted to the changes brought by the application of organic amendments. Additionally, an increase in soil temperatures could have contributed to an increase in soil respiration since weekly average air temperature increased from 21°C in week 6 to 22°C in week 10 (Figure 4.5). Evolution of CO_2 declined again in all the experimental plots from week 10 to harvest, indicative of stability of the organic matter in soils amended with organic amendments and exhaustion of easily degradable matter in control soil and CF treated soil. The line graph (Figure 4.4) does not clearly depict the treatment effect on soil respiration as the lines constantly overlap.

Cumulative soil respiration data was computed from the line graph and normalized to soil C content at planting to compare the relative degradability of the amendments (Figure 4.6). The application of all the amendments resulted in lower normalized cumulative respiration (10-41% lower) compared to the control treatment (Figure 4.6). The lowest normalized soil respiration was measured in OF2 treatment (-41%), which can be partially attributed to the fact that OF2 added the highest amount of salts at planting (Table 4.4) which could have suppressed microbial activity thereby reducing microbial respiration. It also indicates the C in the OF2 (chicken manure based) was less decomposable than the other amendments. The application of CF also resulted in lower respiration than the control, which indicates that chemical fertilizer inhibited microbial activity, as no additional organic matter was added to these two treatments. The composts, FC and UC were more degradable than the as indicated by the cumulative normalized respiration (Figure 4.6) and LOI results (SOM) (Table 4.7).

Cumulative soil respiration (Figure 4.6) and relative change in SOM (Table 4.7) both measure degradability of organic substrates from planting to harvest of green beans. Therefore, a correlation relationship was tested between the two parameters and the relationship was not significant even though the methods measure the same parameter. This inconsistency between the two methods can be associated with the fact LOI for determination of SOM includes root biomass while soil respiration was measured on a buffer strip where there were no plants. This can easily be seen in relative change of SOM (Table 4.7) for CF treatment since it was positive due vigorous root development (Table 4.8) while CF resulted to second least cumulative soil respiration (Figure 4.6). However, the two methods showed consistency for the two composts (UC and FC) as both methods indicated that the two composts were most degradable relative to other amendments.

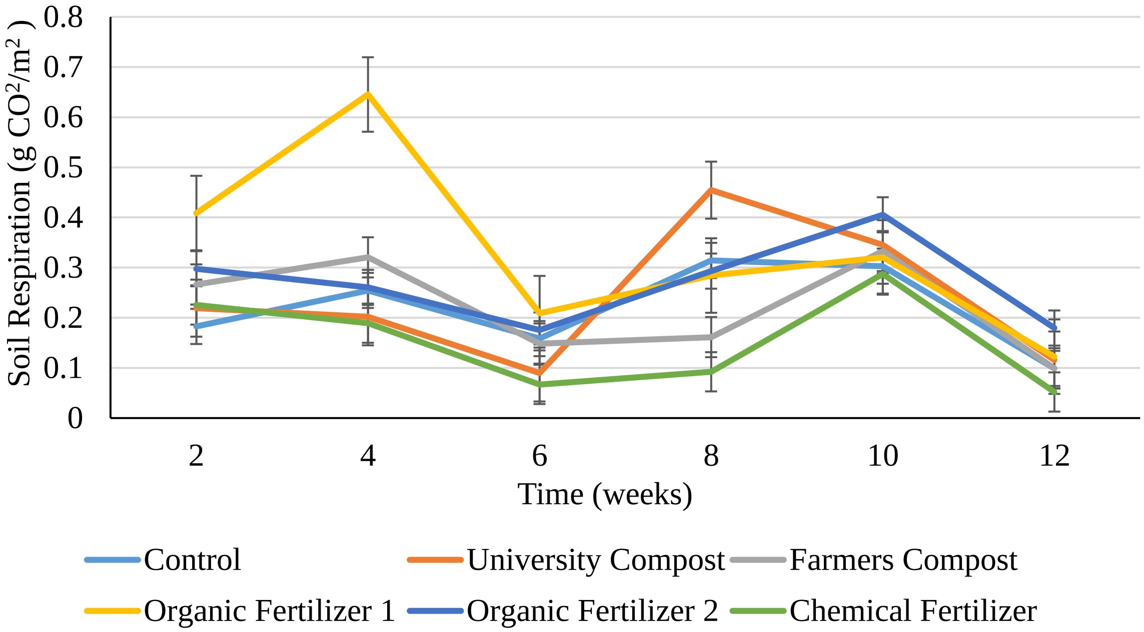

Figure 4.4: Effect of soil amendments on soil respiration during the growing period of green beans.

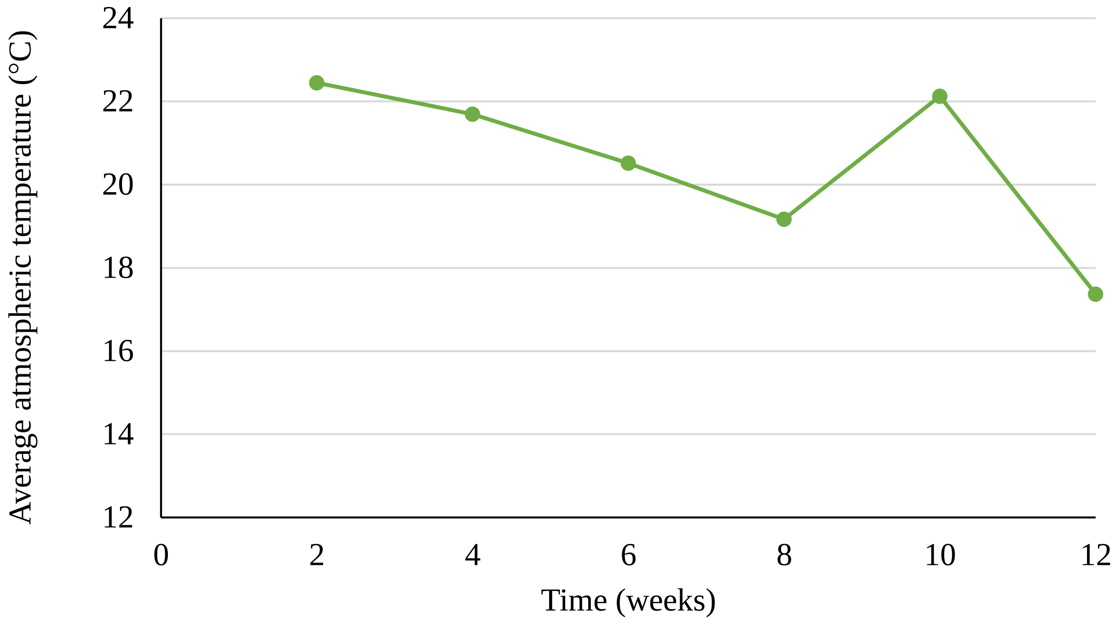

Figure 4.5: Average weekly temperatures during the green bean field trial.

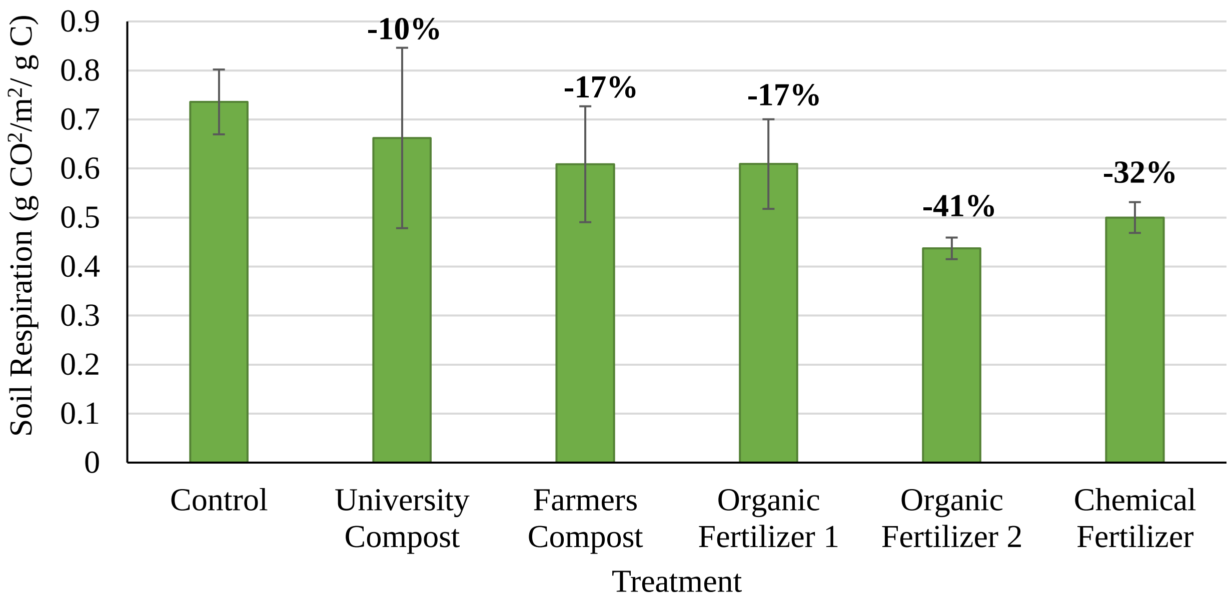

Figure 4.6: Effect of soil amendments on cumulative soil respiration relative to total soil C content at planting during the bean field trial.

4.3.1.2.4 Dehydrogenase Activity (DHA)

Weekly evolution of dehydrogenase activity (DHA) measured in the control and treated plots during the growing period of green beans is shown on Figure 4.7. Application of soil amendments had a significant ($p < 0.01$) effect on DHA and weekly measurements were significantly ($p < 0.05$) different from each other with DHA measured at planting (week 1) being significantly ($p < 0.01$) higher than at other weeks on most plots. Dehydrogenase activity decreased from week 1 to week 3 in all the plots and the activity stabilized from week 4 to week 8 as the line graph shows that there was a net increase in DHA from week 3 to week 8 in all the plots (Figure 4.7). Enzyme activity decreased from week 9 to harvest (week 12) and that indicates the inefficiency of microbes to decompose highly stable organic matter that would be present in soil after the easily degradable matter is depleted. The differences in DHA over time can easily be seen on Figure 4.7, however, the treatment effect is not clearly depicted as the lines constantly overlap.

Consequently, a bar graph of weekly average DHA was constructed to clearly indicate the differences in soil DHA that were due to the treatments (Figure 4.8). Average DHA was significantly ($p < 0.01$) higher in the control with UC amended plots having second highest DHA while application of FC, CF, and OF 1 significantly ($p < 0.05$) reduced dehydrogenase activity. Application of UC insignificantly reduced DHA by 4% while application of FC, OF1, OF2, and CF significantly ($p < 0.05$) reduced DHA by 23%, 21%, 14%, and 23% respectively. There appears to be a trend between soil respiration data and soil enzyme activity (DHA) except for the OF2 treatment. Suresh (2005) pointed out that soil enzymes are generally associated with soil organic matter since they are functions of soil microbial activity while Brady and Weil (2008) suggested that added SOM and its characteristics affect the environmental conditions at which microbes function and that determines changes in enzyme activity released by the microbes. The latter suggests that an increase in SOM can either enhance or inhibit enzyme activity depending on the stability and composition of organic compounds present in the added matter. Cumulative soil respiration (Figure 4.6) and average soil DHA (Figure 4.8) indicate that application of both organic and chemical amendments inhibited microbial activity while the lines graphs of both respective measures show similar trends attributed to weekly average air temperatures.

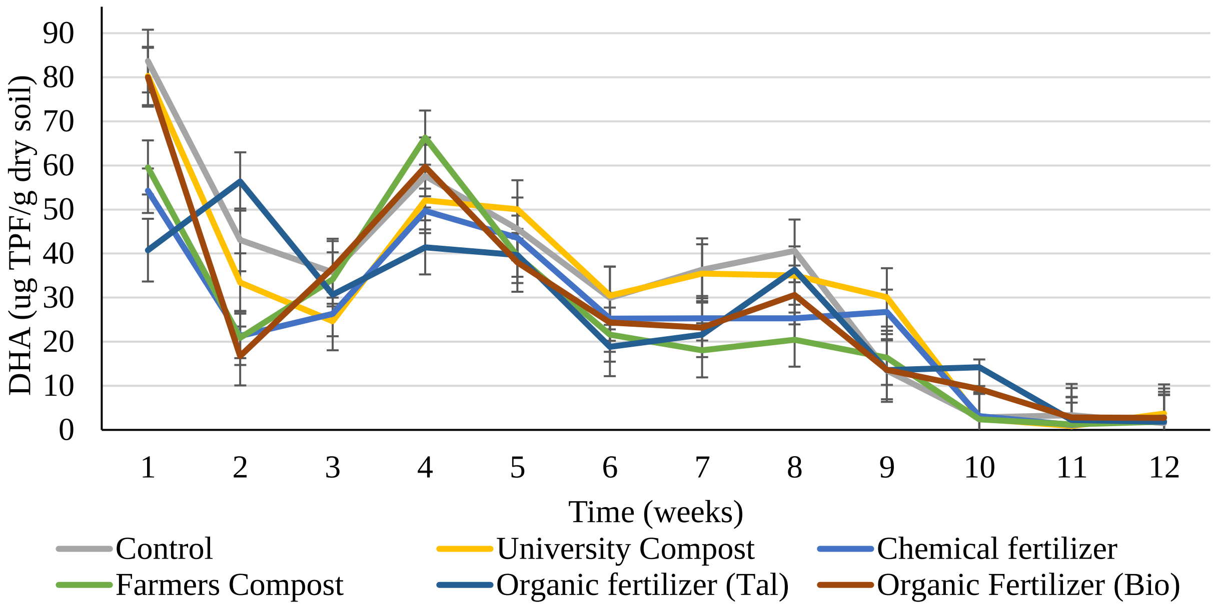

Figure 4.7: Effect of soil amendments on dehydrogenase activity during the growing period of green beans.

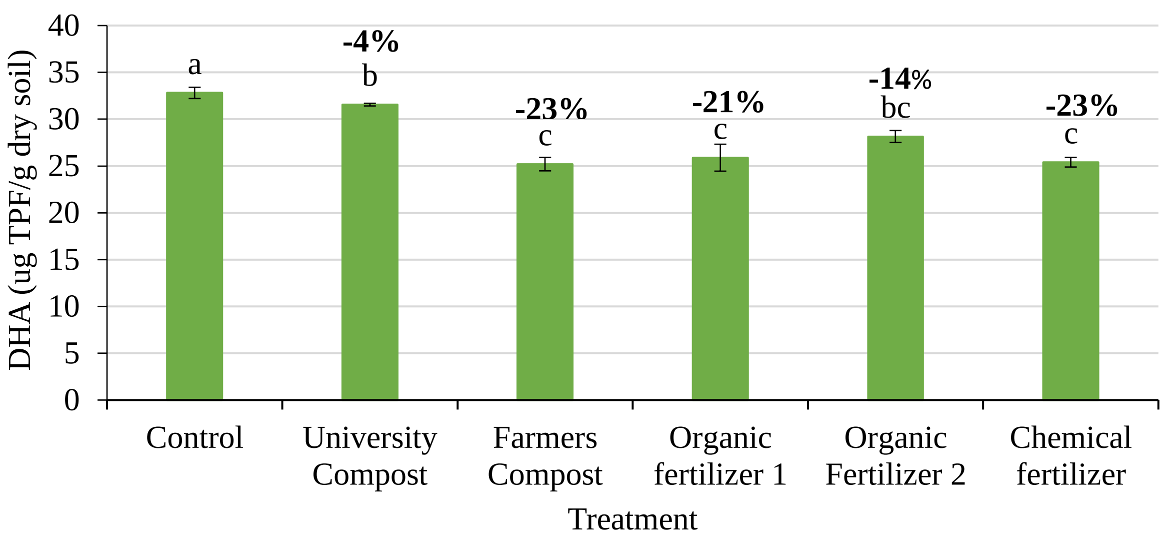

Figure 4.8: Effect of soil amendments on average soil DHA during the growing season of green beans. Statistical significant differences are illustrated by letters of significance at p< 0.05.

4.3.1.2.5 Nitrogen mineralisation

The soil mineral N content measured during the growing period of green beans is shown on Figure 4.9 (NH_4-N) and Figure 4.10 (NO_3-N). The application of chemical fertilizer had a significant ($p< 0.05$) effect on exchangeable ammonium content of the soil (Figure 4.9) while there were statistical significant differences in exchangeable nitrate content (Figure 4.10) of the control and amendments. The time of sampling had significant ($p< 0.05$) effect on both exchangeable mineral forms of nitrogen (NH_4-N and NO_3-N) with exchangeable ammonium significantly ($p< 0.05$) higher at week 4 and 9 while exchangeable nitrate was significantly ($p< 0.05$) higher at week 6-8. The organic amendments mineralised most soil NH_4-N from week 1-3 and there was a decline until week 10 (Figure 4.9), while soil NO_3-N showed substantial nitrification from week 5-8 comparable to that on CF amended plots especially for the organic fertilizer that contained chicken manure (OF2) (Figure 4.10). According to Tisdale and Nelson (1958) uptake of NH_4-N by plants proceeds well at neutral soil pH while the rate of uptake of NO_3-N is generally high and is favoured by low soil pH. Thus, the highest soil NH_4-N at week 4 and 7 in CF treatment could increase yields since the soil pH was between the accepted range of 5.5-7.0 (Table 4.4) for crop production which essentially promotes uptake of NH_4-N by plants since the soil pH is close to neutral.

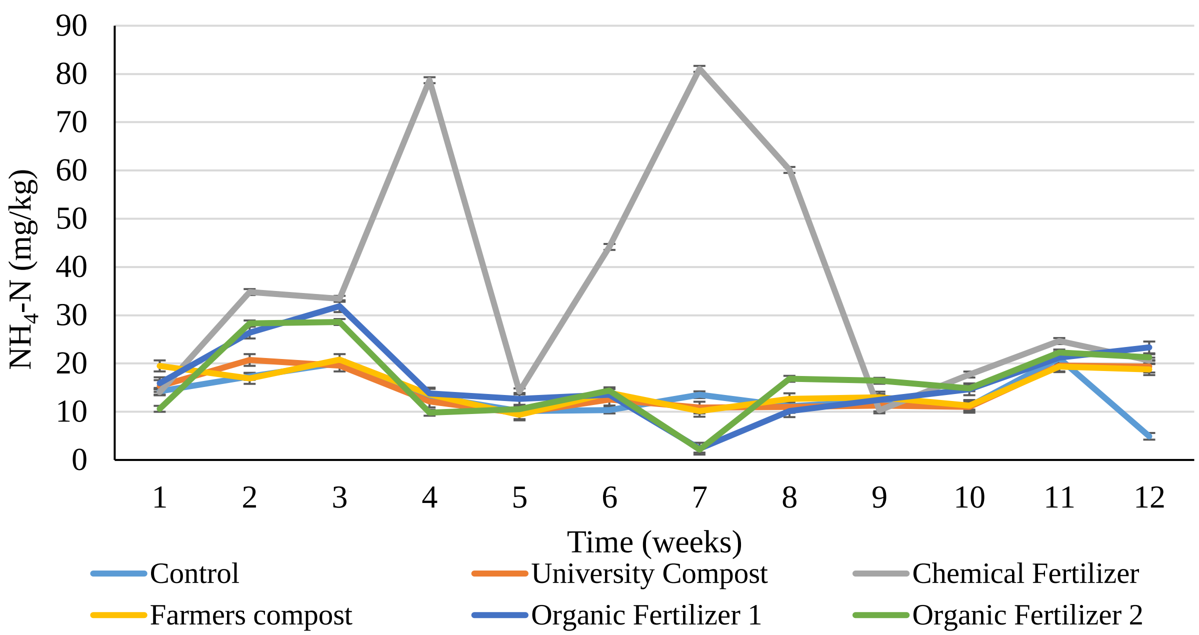

Figure 4.9: Effect of soil amendments on soil mineral N in ammonium form during the growing period of green beans.

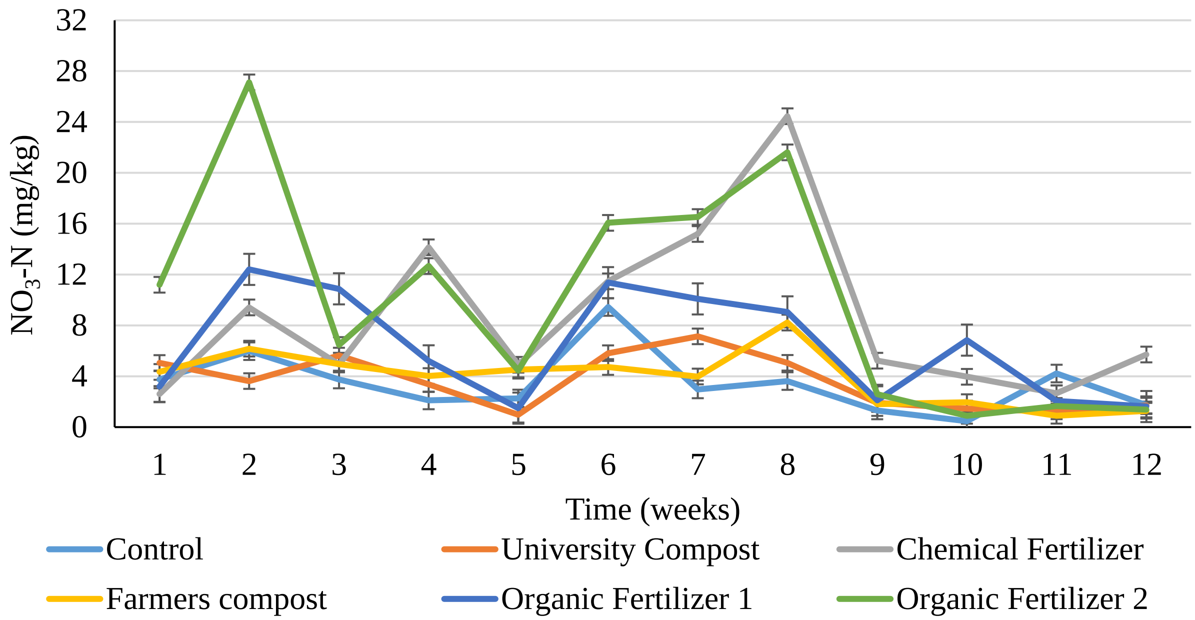

Figure 4.10: Effect of soil amendments on soil mineral N in nitrate form during the growing period of green beans.

Total soil mineral N was calculated from ammonium and nitrate contents of the soil measured on weekly basis during the growing period of green beans (Figure 4.11). There were significant ($p < 0.05$) differences in soil mineral N due to the application of the amendments and there were also significant ($p < 0.05$) differences in soil mineral N content that were due to time of measurement. The chemical fertilizer programme was designed to meet crop nutrient requirements at critical growth stages and supplied most N from weeks 2-4 and 6-8 (Figure 4.11) during flowering and seed filling stages as explained by Chandhla (2001). However, the commercial organic fertilizers released the most N during weeks 2-4, thus it did not synchronize with when the beans required N the most during seed filling stage. The pattern and extent of N mineralization of the composts was very similar to that of the control soil, whereby peak N mineralisation occurred in weeks 2-4 (Figure 4.11). The N mineralisation patterns of the organic amendments also correlate with DHA activity results (Figure 4.7), which indicate peak activity at week 4, and then general decline afterwards.

Application of UC, OF1, OF2 and CF resulted in a net positive change in soil mineral N from planting to harvest by 3%, 58%, 31%, and 4% respectively, while there was a net negative change in mineral N in the control and FC amended plots of 63% and 16%, respectively (Figure 4.11). The elevated N mineralisation due to application of organic fertilizers compared to application of compost can be attributed to mineral composition and lower C:N ratio (Table 4.1) of the organic fertilizers as Masunga et al. (2016) suggested that organic amendments that contain high N content which results to lower C:N ratio are known to be highly mineralisable. Organic fertilizer 1 mainly consisted of bone meal and blood while OF2 was made from chicken manure, which are more easily mineralisable than composts (Brady and Weil, 2008). The elevated net negative change in soil mineral N in control treatment can be associated with the fact that no N source was added, while the negative change in the FC treatment can be associated with reduced efficiency of microbes to decompose organic amendments when more than 10 t/ha is supplied, as previously seen during the broccoli field trial (Chapter 3). The net positive change in soil mineral N from planting to harvest on CF amended plots can be associated with the weekly applications of CF (Table 4.3).

The cumulative amount of mineral N extracted over the whole growing season is shown in Figure 4.12. All the amendments significantly (p< 0.05) increased cumulative mineral N relative to the control treatment (Figure 4.12). Chemical fertilizer significantly (p< 0.01) increased mineral N by 168% relative to the control, while application of OF2 which mainly consisted of chicken manure pellets resulted in the second highest cumulative mineral N, which was 59% higher than in the control. Application of UC, FC and OF1 significantly (p< 0.05) increased total mineral N relative to the control by 7%, 13% and 37% respectively. The smallest total mineral N increment due to application of UC can be attributed to the fact that UC supplied the lowest N content (Table 4.2) while the second lowest increment due to application of FC can be attributed to the stability of FC as compost is generally more stable and contains less nutrients compared to organic fertilizers (Brady and Weil, 2008).

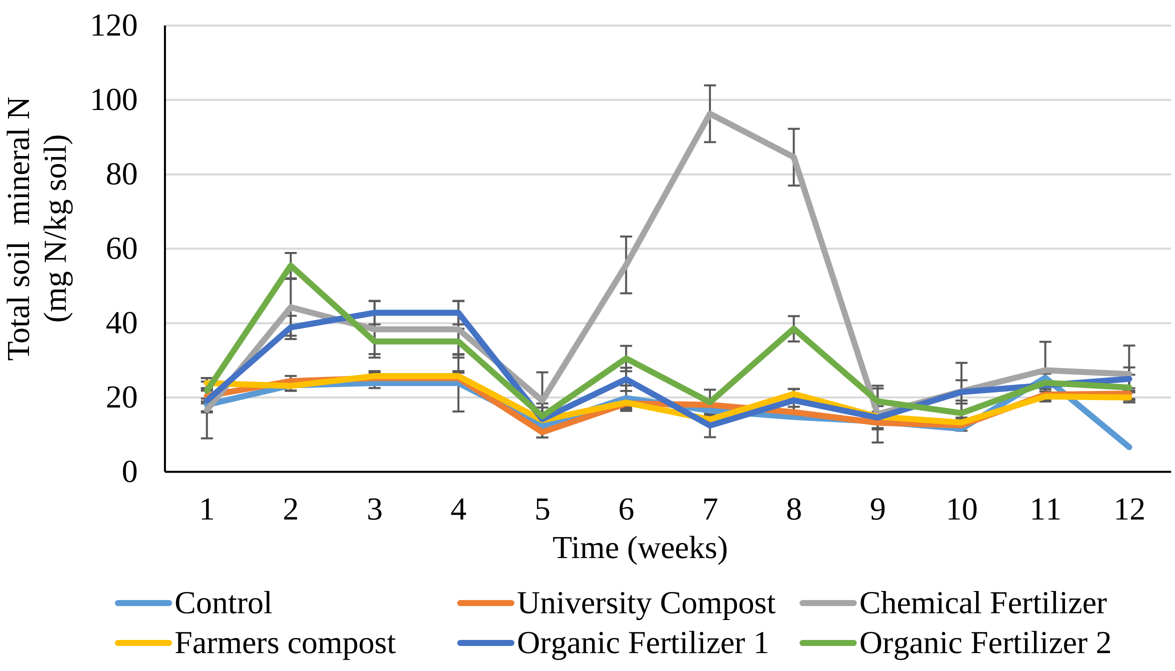

Figure 4.11:Effect of soil amendments on soil mineral N during the growing period of green beans.

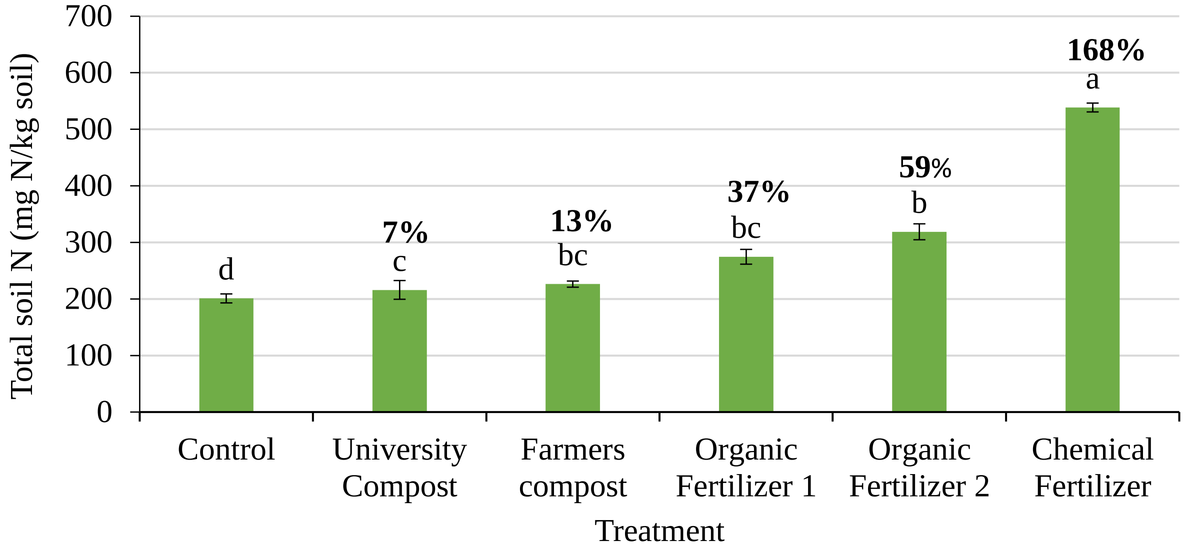

Figure 4.12: Cumulative mineral N extracted from control and amended treatments during the growing period of green beans. Statistical significant differences are illustrated by letters of significances at p< 0.05.

4.3.1.3 Crop response to soil amendments

4.3.1.3.1 Green bean growth

Chlorophyll content of the green bean leaves measured on weekly basis is shown on Figure 4.13. The weekly leaf chlorophyll content of green beans grown on chemical fertilizer treated plots was significantly ($p < 0.05$) higher than the one of green beans grown on organically treated and the control plots. This higher leaf chlorophyll content on green beans grown on CF plots is in accordance with soil N mineralisation (Figure 4.11) during the green bean growing period as N was higher on CF amended plots. Nitrogen content in plants is very important as N is a constituent of enzymes that synthesize chlorophyll molecules, therefore, leaf chlorophyll content is associated with soil mineral N and crop yield since improved chlorophyll content enhances photosynthetic efficiency of crops (Argaw et al. 2015). Correlations were tested between soil fertility parameters and crop response parameters to evaluate which soil fertility parameters have the greatest influence on crop productivity. There was only a positive significant ($p < 0.01$) correlation between cumulative soil N and average leaf chlorophyll content, however, macro and micro nutrients were relatively higher on organically amended plots than in the control (Table 4.4) and that could have an influence on crop vigour since N is not the only constituent of the chlorophyll molecule.

Average leaf chlorophyll content graph was computed to clearly depict the effect that was due to the amendments during the growing period of green beans (Figure 4.14). The chemical fertilizer significantly ($p<0.01$) increased leaf chlorophyll content of beans while there were no significant differences between organic amendments and the control. The leaf chlorophyll content on beans grown in CF amended plots was 20% higher than for those grown in the control while UC, FC, OF1 and OF2 reduced leaf chlorophyll content by 4%, 3%, 1% and 6% respectively. Statistical analysis indicated that cumulative total soil exchangeable N (Figure 4.12) had a significant ($p< 0.05$) effect on average leaf chlorophyll content (Figure 4.14), however, there was a weak correlation (R^2=0.40) between the two factors. This weak correlation can be associated with the fact that soil mineral N was higher on all organically amended plots than in the control while leaf chlorophyll content was lower on green beans grown on organically amended plots which can be associated early mineralisation of N followed negative change in during flowering stage.

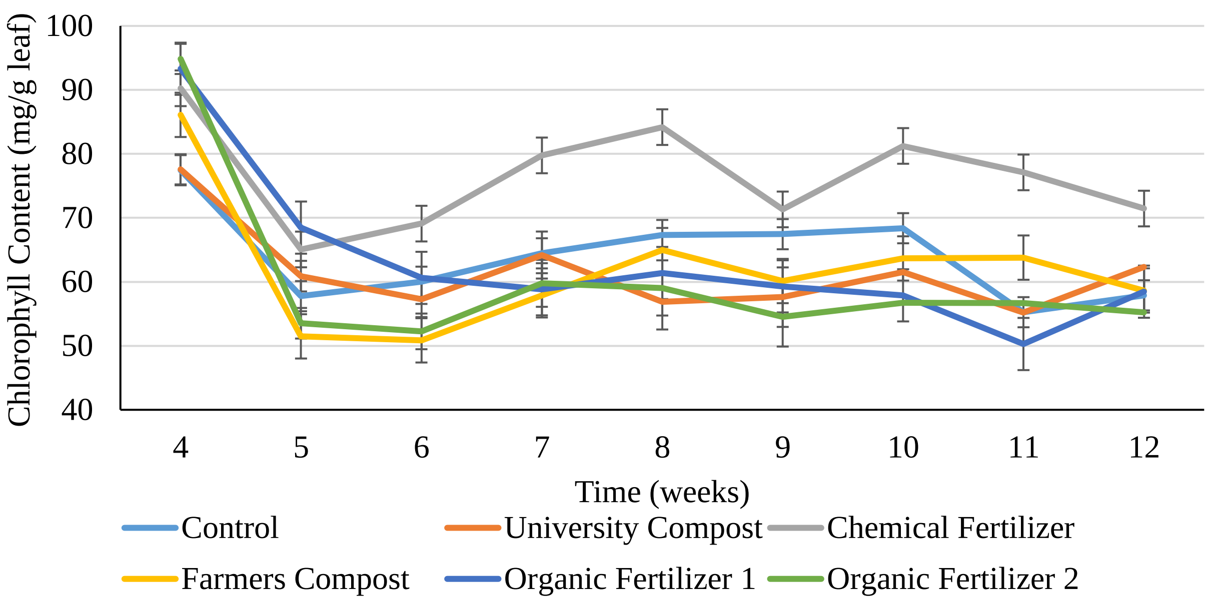

Figure 4.13: Effect of soil amendments on green bean leaf chlorophyll content during the bean field trial.

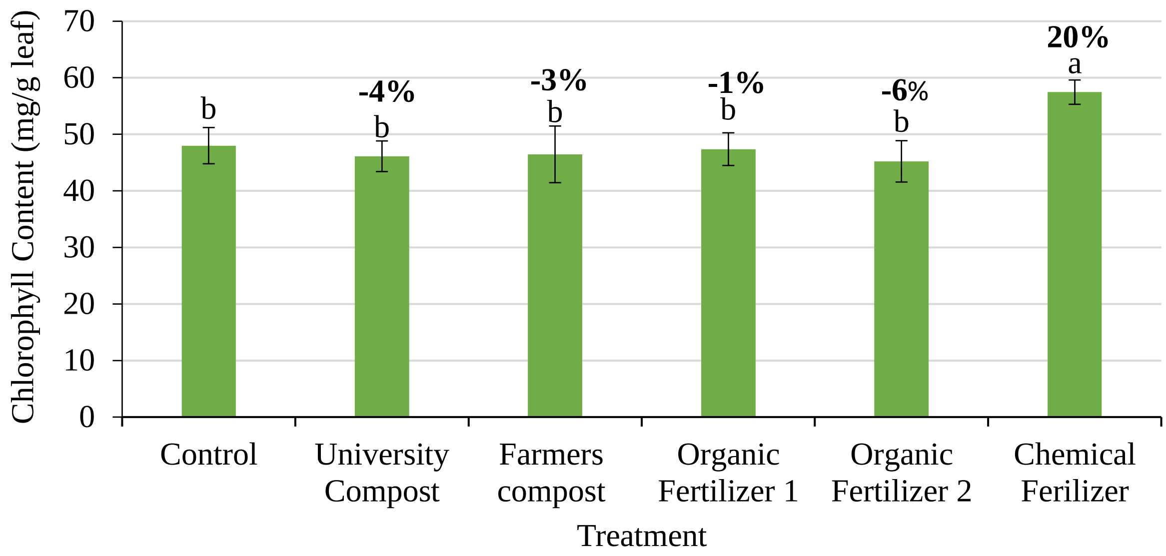

Figure 4.14: Effect of soil amendments on average leaf chlorophyll content during the green bean growing period. Statistical significant differences are illustrated by letters of significances at p< 0.05.

Since leaf chlorophyll content is associated with the intensity of chlorophyll pigment which is responsible for capturing light energy that facilitates photosynthesis, it is important to evaluate the sizes of varying photosynthesizing plant shoots as it is an indicator of the photosynthetic efficiency. However, it would be injudicious to measure the size of plant shoots without measuring plant roots as plant roots function to intercept and absorb nutrients from the soil to various parts of the plant through a tissue called xylem, and it is the absorbed nutrients assimilated in plants that are transformed by plants in their photosynthetic parts through photosynthesis to form carbohydrates, proteins, fats and lipids that are then transported to various parts of the plant through a tissue called phloem. Thus, root-shoot ratio was measured at harvest to evaluate the effect of absorption of nutrients by plant roots and transformation of nutrients by the photosynthesising plant shoots on green bean growth, yields and quality (Table 4.8).

There were no significant differences in root and shoot mass of green beans harvested from organically and chemically treated plots compared to the control (Table 4.8). However, there were significant ($p < 0.05$) differences in root to shoot ratio due to soil amendments since there was a trend in root and shoot mass obtained from the treatments. Application of FC, OF1, OF2 and CF respectively increased root mass of green beans relative to the control by 17%, 22%, 1% and 1% while application of UC inhibited root development by 1% relative to the control. Additionally, both composts applications (UC and FC) inhibited shoot growth relative to the control by 20% and 6% respectively while the application of OF1, OF2 and CF increased shoot growth by 37%, 21% and 17% compared to the control. These results are in accordance with cumulative total soil exchangeable N results, however, no positive correlation was obtained for the two parameters primarily because the organic amendments supplied more N before the critical time for N requirement by the green beans hence shoot growth was vigorous on green beans grown on organic fertilizer treated plots. Harris (1992) pointed out that an increase in root-shoot ratio indicates more root development than above ground plant growth, whereas a decrease indicates vigorous above ground plant growth relative to slight root development. This statement confirms the results that were obtained in this study as the root-shoot ratio was lower for beans that had vigorous above ground plant growth while the plants that had more root development had higher root-shoot ratio.

Table 4.8: Root and shoot mass of green beans harvested from chemically and organically amended plots compared to the control. Statistical significant differences are illustrated by letters of significances at $p < 0.05$.

Treatment	**Morphological properties**		**Root: Shoot**
	Root mass (g)	**Shoot mass (g)**	
Control	0.69	7.24	0.10 ab
University Compost	0.68	5.78	0.12 a
Farmers Compost	0.81	6.84	0.13 ab
Organic Fertilizer 1	0.84	9.89	0.09 ab
Organic Fertilizer 2	0.70	8.79	0.08 b
Chemical Fertilizer	0.76	8.44	0.09 ab

4.3.1.3.2 Green bean yields

The application of chemical fertilizer significantly ($p<0.05$) increased mass of pods harvested per plant relative to the control while the application of organic fertilizers (OF1 and OF2) and the farmer's compost had an intermediate effect on mass of pods carried by each plant (Figure 4.15). The mass of pods per green bean plant grown on UC amended plots did not significantly differ from the control. These results confirm that the commercial chemical fertilizer programme was designed to meet the green bean economical yield (pods) requirements because even though green beans grown on plots amended with organic fertilizers (OF1 and OF2) had greater above ground growth (Table 4.8), the economical yield (pods) was greater on CF amended plots.

The application of chemical fertilizer significantly ($p<0.05$) increased green bean yields compared to the control and UC amended plots, however, there were no significant differences in green bean yields between FC, OF1, OF2 and CF (Figure 4.16). This significant increase of green bean yields from FC, OF1 and OF2 could be attributed to the amendments nutrients contents, particularly N, as Table 4.2 clearly indicate that the above-mentioned three organic amendments supplied more N than UC. Additionally, higher yields in chemical fertilizer amended plots could be attributed to readily available nutrients from the chemical fertilizer and CF's N content as Table 4.2 clearly indicates that nitrogen content from CF was the same as N content supplied by OF 1 and OF 2. The results of green bean yields show similar trend with cumulative N mineralisation results on Figure 4.12 as plots amended with CF, FC, OF1 and OF2 had significantly ($p<0.05$) higher soil mineral N than UC amended plots and the control. Literature has shown that readily available nutrients supplied through the application of chemical fertilizer increases crop yields while organically bound nutrients supplied through the application of organic amendments are not as effective as readily available nutrients from chemical fertilizers (Barnard and du Preez 2004; Amujoyegbe et al. 2007; Mnkeni and Austin 2009; Kayser et al. 2010; Roberts 2009; Roy et al. 2010) and green bean yield results obtained from this experiment are in accordance with existing scientific knowledge. As mentioned previously, analysis of covariate was used when yield results were subjected to statistical analysis with number of plants treated as covariate since plant growth was not uniform and the results indicated that the number of plants did not have a significant effect on yields. However, application of organic fertilizers significantly ($p< 0.05$) reduced the number of seeds that germinated after planting which latter produced pods that were harvested from the treatments (Figure 4.17). Even though EC was within accepted levels at planting in all the experimental treatments, the higher EC on plots amended with organic fertilizers (OF1 and OF2) clearly inhibited seed germination since bean seeds are sensitive to salinity (Figure 4.18). Number of plants that were on FC amended plots at harvest were 5% more than the green bean plants in control while UC, OF1, OF2 and CF amended plots respectively had 1%, 21%, 23%, and 21% less green bean plants than the control. This in turn would influence yields per plant rather than per hectare.

Furthermore, a simple linear regression was performed on N mineralisation (Figure 4.12) results and green bean yields (Figure 4.16) obtained from various amended plots and the untreated plots. Simple linear regression results indicated that cumulative total soil N content has a highly significant ($p< 0.01$) influence on green bean yields, however, the relationship between cumulative total soil N content and green beans was not strongly correlated as the correlation coefficient (R^2) was 60%. This moderate correlation between total soil N and green bean yields could be attributed to the fact mineralization of N in the organic fertilizers (OF1 and OF2) was rapid at week 2-4, which was earlier than required as beans need most N at week 6-8 during seed filling stage (Figure 4.11). It is thus advisable that the commercial organic fertilizers rather be applied in split applications every 4 weeks in order to improve N mineralisation synchronisation with crop demand and also reduce soil salinity at planting.

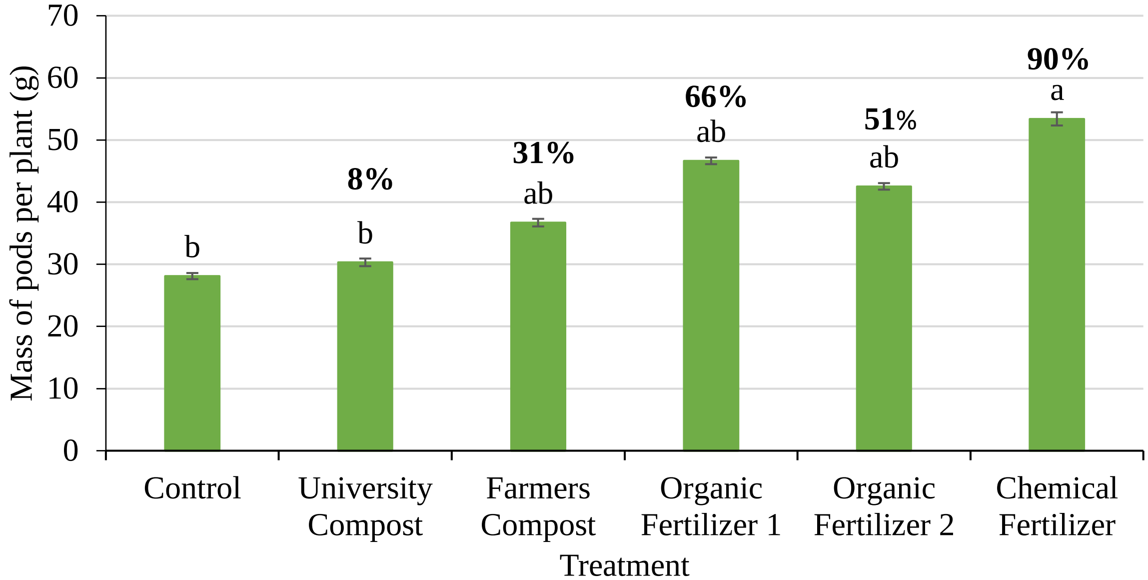

Figure 4.15: Effect of soil amendments on average mass of pods per plant at harvest. Statistical significant differences are illustrated by letters of significances at p< 0.05.

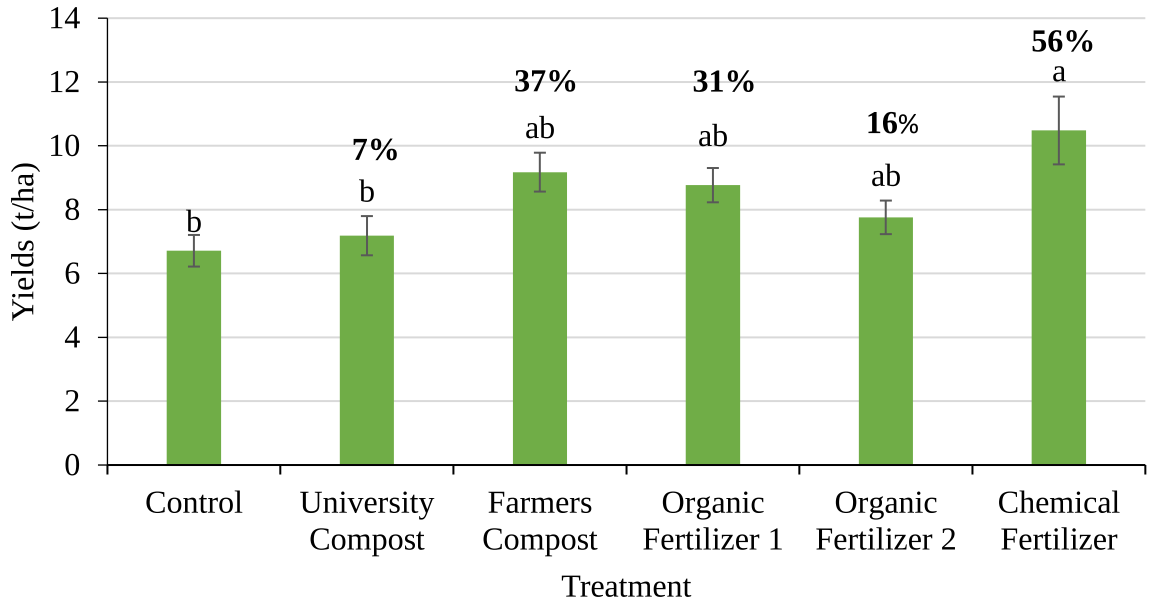

Figure 4.16: Effect of soil amendments on green bean yields at harvest. Statistical significant differences are illustrated by letters of significances at p< 0.05.

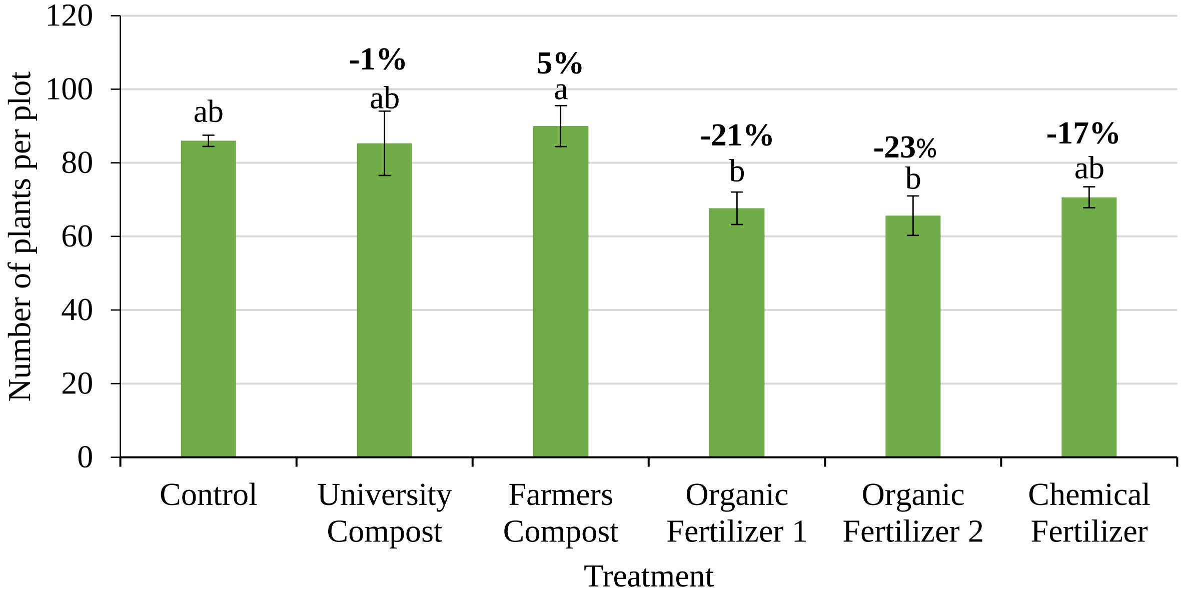

Figure 4.17: Effect of soil amendments on number of green bean plants at harvest. Statistical significant differences are illustrated by letters of significances at p< 0.05.

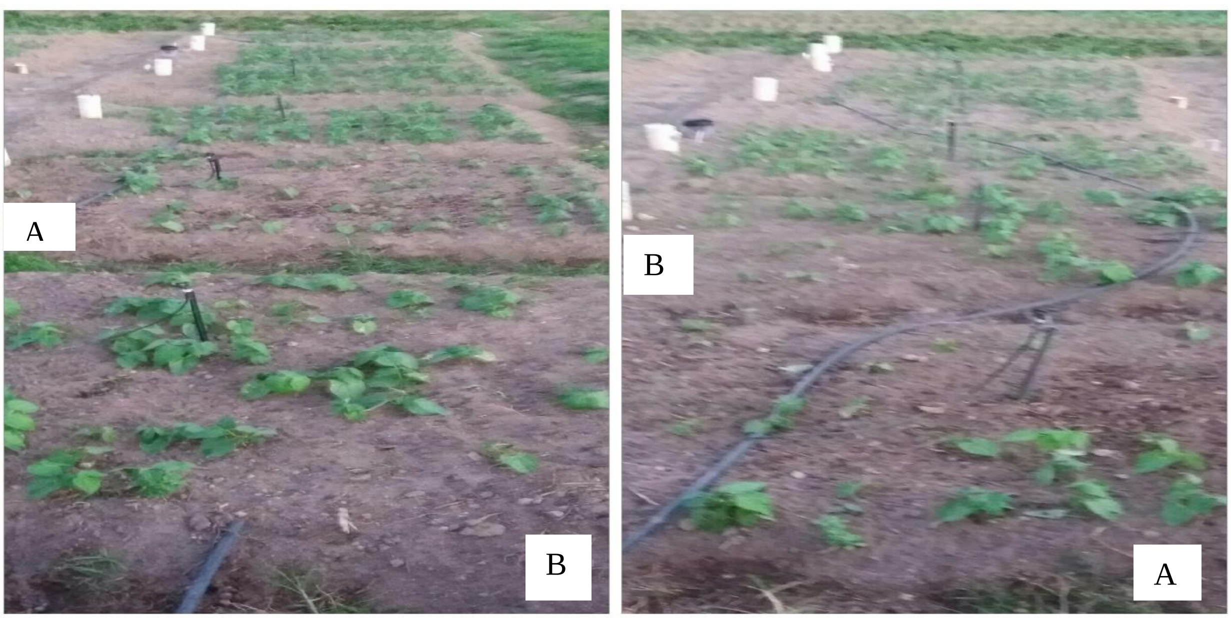

Figure 4.18: Number of germinated seedlings after planting on organic fertilizer (OF1-A and OF2-B) amended plots.

4.3.1.3.3 Green bean pods nutritional quality

There is a growing belief that organically produced crops are more nutritious than chemically produced ones and this belief can be associated with more dilution of assimilated nutrients in plants grown on chemical fertilized growing mediums as crops tend to be bigger in size compared to organically produced ones. However, it is not always the case that organically produced crops would have higher concentration of nutrients as the amount of nutrients supplied by soil amendments, inherent soil fertility status, soil properties that affect the mobility and solubility of nutrients in soils, and physiological characteristics of plants play a crucial role in availability of nutrients and mineral uptake by plant roots. There were no statistically significant differences in macronutrient (N, P, K, and Ca) contents of green bean pods between treatments, except Mg (Table 4.9). The significantly ($p< 0.05$) lower Mg content in green pods harvested from OF1 treated plots compared to the control could be associated with low level of Mg and high amount of Ca supplied by OF1 (Table 4.2), as Ca and Mg are antagonistic. Additionally, plots amended with OF1 had the highest amount of Ca at planting (Table 4.4) among experimental treatments and that could have resulted to more uptake and assimilation of Ca while compromising Mg in the plant tissues. The soil P and Mg content at planting (Table 4.4) had a significant ($p<0.05$) influence on P and Mg assimilated on green bean pods (Table 4.9), however, the correlation coefficient was very weak.

Even though primary nutrient contents of harvested pods from various treatments did not show significant differences, there were noteworthy slight increases in assimilated primary nutrient tested in pods because of the soil amendments used in the study. Nitrogen content was higher in pods harvested from OF1 and UC amended plots while P and K contents were higher in pods harvest from CF treated plots. Nitrogen content of green beans is very essential as N is the major constituent of proteins and it is estimated that common beans supply 50% of dietary proteins in Sub-Saharan Africa (Namugwanya et al. 2014). Nitrogen content of green pods from all the experimental treatments was within accepted critical values of 1.83-3.80% for legumes as reported by Mitova and Stabcheva (2013). The protein content of green beans is very essential as it is associated with prevention of metabolic diseases such as diabetes and cancer (Borchgrevink 2012).

Furthermore, green bean pods K content had a significant ($p<0.05$) effect on mass of pods produced per plant with both, mass of pods per plant and pod K content higher on CF amended plots, however, the correlation between the two factors was weak. This significant effect of K content on mass of pods per plant is in accordance with existing literature as K is known to be responsible for fruit or seed development (Silva and Uchida 2000). Potassium content is very important also during the synthesis of proteins as it is known to activate some of the essential enzymes. Calcium content of green bean pods increased due to both organic and chemical amendments. Among the micro nutrients, only Mn content was significantly ($p< 0.05$) higher on pods of green beans grown in the control while UC and OF1 significantly ($p< 0.05$) reduced amount of Mn on green bean pods. This higher Mn content on beans grown in the control can be ascribed to the fact that the control had higher exchangeable soil Mn at planting while organic amendments could have chelated Mn throughout the growing period even though it was higher on organically amended plots at planting (Table 4.4). These results are on the contrary with the belief that organically produced crops are more nutritious than chemically treated crops and some scientific studies have proven that there are no differences in mineral nutrient composition of organically treated plants and chemically fertilized plants (Hargreaves et al. 2008; Mitova and Stabcheva 2013;Bridige et al. 2014).

Table 4.9: Mineral nutrient content of green bean pods harvested from treated and untreated plots. Statistical significant differences are illustrated by letters of significances at p< 0.05.

	Green bean pods mineral content										
Treatment	**N**	**P**	**K**	**Ca**	**Mg**	**Na**	**Fe**	**Cu**	**Zn**	**Mn**	**B**
	← (%) →					← (mg/kg) →					
Control	3.74	0.43	2.81	0.66	0.36 a	86.67	84.65	8.84	30.33	7.71 a	20.18
University Compost	4.12	0.44	3.67	1.07	0.32 ab	92.33	80.74	9.76	30.88	5.06 b	23.74
Farmers Compost	3.60	0.41	2.67	0.62	0.30 ab	104.33	82.09	8.74	29.12	5.74 ab	21.59
Organic Fertilizer 1	4.12	0.46	6.73	0.67	0.28 b	73.67	66.02	7.49	32.66	5.02 b	23.91
Organic Fertilizer 2	4.00	0.49	5.74	0.74	0.33 ab	91.67	77.60	8.88	34.81	6.24 ab	22.63
Chemical Fertilizer	4.10	0.50	6.95	0.71	0.32 ab	102.67	82.84	8.67	33.57	5.80 ab	23.89

4.3.1.4 Marginal Rate of Returns

Marginal rate of returns from experimental treatments including the control was determined by comparing the ratio of variable income and variable costs from treatments compared to the farmer's normal practice. The farmer's compost applied at 17.76 t/ha was used as a reference treatment since the farmer adjusted his practices from winter to use his own compost in summer. All the organic amendments and the control resulted in net loss of income for the farmer while application of chemical fertilizer increased the net income of the farmer by 27% (Figure 4.19). The highest loss of income due to application of OF1 and OF2 which amounted to 120% and 146% can be attributed to high costs of organic fertilizers relative to the farmer's compost and chemical fertilizer costs since the organic materials (chicken manure and bone meal with blood) that were used to produce organic fertilizers had to be treated to prevent pathogens. Therefore, the organic fertilizer producing companies would have to charge higher prices to cover the production costs of the organic fertilizers. The highest income obtained due to application of chemical fertilizer can be attributed to highest green bean yields (Figure 4.16) obtained from CF treatment which can be linked with highest cumulative soil mineral N (Figure 4.12). The second highest income due to application of the farmer's compost can be attributed to its second highest green bean yields (Figure 4.16) and FC relatively cheaper cost of production compared to other organic amendments since it was produced on farm.

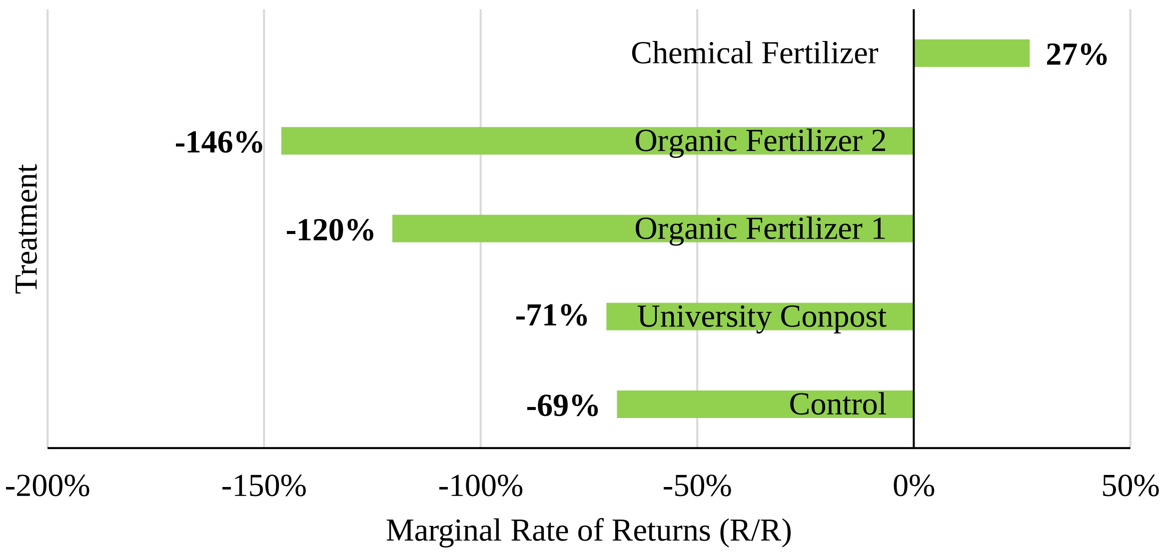

Figure 4.19: Marginal Rate of Returns from the expenditures and income of yields from each soil amendment compared to the farmers normal practice (i.e. farmer's compost).

4.4 CONCLUSIONS

This study aimed to evaluate the effect of a commercial compost, two commercial organic fertilizers and a chemical fertilizer programme relative to the control and adjusted smallholder farmer soil amendment practice on green bean production.

Some of the soil fertility parameters were significantly affected by the soil amendments, with all the amendments significantly ($p < 0.05$) reducing exchangeable acidity at planting while only the control and FC treatment had significantly ($p < 0.05$) lower plant available P than the minimum threshold value of 25 mg/kg at planting compared to other soil amendments. Additionally, application of CF significantly ($p < 0.05$) reduced soil pH measured in water while application of OF2 significantly ($p < 0.05$) increased soil EC threefold more than the control soil. There were no significant differences in ECEC, basic cations and micro nutrient contents of all the treatments including the control at planting. There were no significant differences obtained between treatments in soil quality parameters, including: total C and N, SOM and soil respiration, except for soil enzyme activity (DHA), which was significantly ($p < 0.05$) higher in the control treatment, and soil water-holding capacity which was significantly increased (14%) in the FC treatment only. Unlike the winter broccoli trial, all of the organic and chemical amendments significantly ($p < 0.05$) increased cumulative soil mineral N during the bean growing period relative to the control. The commercial amendments increased cumulative soil mineral N by much greater amounts (CF = 168%, OF2 = 59% and OF1 =37%) compared to the composts (FC =13% and UC = 7%). However, in contrast to the organic amendments, the CF highest applications of mineral N were synchronized with critical flowering (weeks 2-4) and seed formation and filling (weeks 6-8), whereas, the organic amendments mineralised highest N during the first 2-4 weeks only. It is thus advisable that the commercial organic fertilizers rather be applied in split applications every 4 weeks in order to improve N mineralisation synchronisation with crop demand and also reduce soil salinity at planting.

Consequently, the CF treatment produced significantly ($p < 0.05$) higher yields (56%) relative to the control and organic amendments while FC produced second highest yields (37% more). The greatest yield increment due to FC treatment among the organic amendments can be associated with significantly ($p < 0.05$) higher number of plants at harvest in FC. However, when comparing the two variables (i.e. yields and number of plants) using an analysis of covariance, it indicates that the number of plants did not significantly affect yields between treatments.

There were no significant differences in green bean nutritional quality observed between treatments, except OF1 which contained significantly lower Mg compared to control treatment. The CF treatment was the most economically profitable amendment (27% income increase) compared with farmer's current practice of applying on-farm produced compost, while all other amendments were economically infeasible compared to FC. It is important to consider that the CF treatment would require more frequent liming than the organic treatments, which would increase production costs over the longer term.

The results of the summer bean field trial indicate that it is more economically feasible for the farmer to produce his own compost using easily accessible material rather than purchasing organic amendments, or rather to make use a chemical fertilizer programme.

CHAPTER 5

5.1 GENERAL DISCUSSION AND CONCLUSIONS

The main aim of this study was to evaluate the smallholder farmer's soil amendment practices on soil quality, crop response and economic profitability compared with alternative organic and chemical fertilization methods.

In Chapter 3, the effect of the farmer's routine soil amendment practice of adding 10 t/ha of commercial compost was compared with alternative farm-produced compost amendment practices and a commercial chemical fertilizer programme on broccoli production during late winter. There were no significant differences in soil fertility parameters such as pH, EC, plant available nutrients or broccoli nutrient content between the different treatments. Only CF treatment significantly increased cumulative soil mineral N (155.9%) relative to the control, and mineral N was found to be the main driver of broccoli yields in this trial. The CF treatment resulted in significantly higher number of plants that survived pest attacks to reach maturity which is attributed to greater vigour as also indicated by significantly higher average chlorophyll content. The organic amendments mineralized little N, especially CB and CWCR, which resulted in 2.0 and 3.2% less cumulative mineral N compared to the control, indicating that these treatments enhanced immobilization. All of the compost applications suppressed microbial activity as absolute and relative soil respiration was highest in the control treatment, which was attributed to the relatively low amount of N in the amendments, and also the winter weather, which likely led to greater microbial inefficiency. Application of CF significantly increased broccoli yields (88% increase compared to CC), followed by CW (28% increase compared to CC). Application of CC, CB and CWCR resulted in non-significant changes in yield compared to the control. Compared to the farmer's routine amendment practice (CC), the CF resulted in the greatest income increase (455%) followed by CW at 10 t/ha (151%). Thus, it was concluded that farmer should rather produce his own compost which was of higher quality and cheaper to produce than purchasing CC. However, the use of a chemical fertilizer programme was significantly more profitable for broccoli production.

In Chapter 4, the effect of the farmer's compost (FC), university compost (UC), two commercial organic fertilizers (OF1and OF2) and a chemical fertilizer (CF) programme was evaluated on green bean production in summer. The soil amendments did not significantly affect most soil quality parameters, including: total C and N, SOM and soil respiration, except for soil enzyme activity (DHA) which was significantly reduced by the application of the amendments. The application of CF significantly reduced soil pH measured in water by 0.6 pH units in contrast to the winter trial, likely due to enhanced nitrification in summer, even though relatively less ammonium was applied. The application of the commercial organic fertilizers OF1 and OF2 increased soil EC 2-3 times relative to the control, correspondingly decreasing the germination of green beans. Unlike the winter broccoli field trial, all organic amendments significantly increased cumulative soil mineral N in the bean field trial. The commercial amendments increased cumulative soil mineral N by much greater amounts (CF = 168%, OF2 = 59% and OF1 =37%) compared to the composts (FC =13% and UC = 7%). Synchronization of the N supply by commercial organic fertilizers could have been improved if added in split applications every 4 weeks, which would have also reduced negative impact on soil EC. In contrast to the broccoli field trial, it was found that N mineralization was not the main driver of crop yields in this trial, likely due to sensitivity of the legumes to soil salinity. Only the application of CF significantly increased yields compared to control treatment (56% increase), which was 14% higher than FC. The smaller differences in yields between treatments as compared to the broccoli field trial can be attributed to the fact that N mineralisation of organic materials was higher in summer, there were fewer pest problems and that a legume was cultivated. Furthermore, CF was the only treatment to increase profitability (27%) compared to application of farmer's own compost (FC). There were no significant differences in bean nutrient content between treatments, except for OF1 which contained significantly lower Mg content.

The effect of the composts was also evaluated on soil water holding content (WHC) of the loamy sand from the field trial site and sandy soil from the Cape Flats. In the case of the sandy loam soils, only the CW applied at 22 t/ha and FC applied at 17.8 t/ha significantly increased the loamy sand water holding capacity by 11 and 14% respectively compared to the control. Whereas, the application of the composts resulted in much lower relative increases in WHC in the sandy soil, and only the application of CW at 10 and 22 t/ha resulted in significant increases of 1.73 and 5.60

% increases relative to the control. This indicates that the composts had a greater effect on the WHC of sandy loam soil than sandy soils, and that large quantities of compost are needed to achieve significant changes.

Among the all the organic amendments evaluated, the compost produced by the farmer and applied at 17.76 t/ha (bean N requirement) was shown to be more economically feasible than other organic amendments. However, compost applications should not exceed 10 t/ha in winter as the winter field trial results indicated that the application of compost at 22 t/ha suppressed microbial activity and promoted N immobilization. The results from this study highlight the importance of compost quality and application rates for optimal organic vegetable production by smallholder farmers. Furthermore, chemical fertilizers proved to be less expensive and more reliable in terms of nutrient availability especially N delivery to crops which would help smallholder farmers to farm more profitably. This study also demonstrated that there were no significant differences between mineral nutrient content of organic and chemically fertilized crops. In the short-term there were also no major differences in terms of soil quality, however, soil pH management is important in routine use of chemical fertilizers.

5.2 RECCOMENDATIONS FOR FUTURE RESEARCH

The limited number of agronomic studies performed in smallholding farms in the Western Cape indicate that on farm field trials need to be conducted in smallholding farms to transfer current ideas between science and the small-scale farming communities. This will help the researchers to incorporate indigenous farming methods of the smallholder famers while providing agronomic support to the farmers and that will make scientific research applicable to the small-scale farming society. Furthermore, mathematical models need to be estimated and validated for nutrient release in agroecosystems to help farmers who use organic amendments for fertilization to know when to apply organic amendments before organic nutrients can become available for plant uptake. The mathematical models should consider the application rates of organic amendments and the environmental conditions that prevail during a cropping season as high application tends to inhibit microbial decomposition of soil organic matter during cold-wet winter season of the Western

Cape. This will require use of numerous soil organic amendments available on the market and farm produced amendments as nutrient mineralisation is dependent on biochemical characteristics of organic amendments and biogeochemical properties of the amended soil.

In view of the water problems faced by the Western Cape Government and the national government of South Africa due to drought, it is advisable to incorporate organic amendments in soils to improve water holding capacity to help retain more water as that reduces water use through irrigation. Scientific irrigation studies should also consider incorporation of organic amendments to determine significant application rates that help retain substantial amounts of water for crop production.

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