Examining links between soil fertility and various nutrient management regimes on yield and quality of sweet potato (*Ipomoea batatas*)

by

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Declaration

I confirm that this Master's thesis is my own original work and I have documented all sources and material used. I declare that I am the authorship owner (unless to the extent explicitly stated). This thesis in its entirety or in part has not been previously submitted for obtaining any qualification.

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SUMMARY

Food producers are faced with the task of meeting growing global food demands that follow a surging and increasingly wealthy population. This pressure is compounded by a global movement towards sustainability that necessitates agriculturists, specifically, crop growers, to ensure that intensive food production does not strain the essential resources that future generations will need in order to feed themselves. In other words, crop production must be done in such a way that crop yields are either maintained over time or enhanced through good management practices that prioritise two essential resources: the soil and the environment. Maintaining or enhancing soil fertility is the single most important way to help ensure sustainable crop yields. One of the ways to accomplish the maintenance of soil fertility and minimize damage to the environment, without compromising crop yields is to replace or reduce inorganic fertilisers use through the inclusion of organic and more sustainable soil conditioners like compost and co-applications of organic and inorganic fertilisers. There are few comparative studies that assess the impact of chemical fertilisers and numerous sustainable and organic soil nutrient management systems within the African context. The African context is characterised by a dire need for nutritious crops like sweet potato (*Ipomoea batatas (*L.*)* Lam) and small-scale farming operations. In keeping with this, a study was conducted to determine and compare the effects of inorganic NPK fertiliser and four alternative soil nutrient management regimes on soil fertility. The study also investigated the effects of these different soil nutrient management regimes on sweet potato growth, yield and nutrition. Experiments took place at the Welgavellen Experimental Farm in Stellenbosch between December 2016 and May 2017. A randomised complete block design was used where each treatment was represented in each block to give four replicates. The treatments were an inorganic fertiliser applied at the recommended rate of 100 $kgN.ha^{-1}$ in an NPK formulation (100% CM); a co-application of biochar applied at a rate of 2% and inorganic fertiliser applied at 50 $kgN.ha^{-1}$, half the recommended rate (2% BC + 50% CM); a compost comprised of 30% food waste and 70% dairy cow manure applied as a 5 cm layer (FWC); a commercial organic fertiliser applied in the same formulation as the inorganic fertiliser and also applied at 100 kgN.ha-1 (COF) and manure-derived anaerobic digestate (MAD) applied as a liquid fertiliser at a rate of 17 L per plant. The control was unfertilised soil. Both the organic and inorganic fertilisers were applied in a split fashion with half applied at planting and the rest 6 weeks after transplanting. ANOVA

and the Tukey HSD were used to analyse the data. Canopy coverage was recorded 6 weeks after transplanting and was observed to be most extensive in the integrated 2% BC + 50% CM treatment, followed by the FWC treatment (73.67 % and 65%, respectively). These were significantly higher (P < 0.05) than the 100% CM, COF and MAD treatments, which only produced 41.08%, 39.92% and 39.2% canopy coverage, respectively. Although, the FWC and 2% BC + 50% CM treatments also resulted in the high fresh and dry shoot biomass at harvest (16 weeks after transplanting), it was not significantly different to the rest of the treatments. The integrated treatment produced the significantly higher fresh tuber yields (26.41 t.ha-1), followed by the 100% CM treatment 19.02 t.ha-1 and FWC 14.55 t.ha-1. Yields were lowest in the COF and MAD treatments. The same trend was observed for marketable yields. The longest tubers were observed under the 2% BC + 50% CM treatment. Tuber diameter, harvest index were unaffected. Sweet potato moisture, crude fiber and starch content were unaffected and did not differ significantly (P > 0.05). However, protein was significantly different (P < 0.05) from the unfertilised control and the MAD treatment. The inorganic treatment resulted in a 2.12% protein content in tubers. Biochar trailed behind by a relatively large margin and resulted in tubers with a 1.45% protein content. Soil cation exchange capacity, pH and acidity were most improved under the 2% BC + 50% CM and FWC treatments, while the highest acidity and lowest pHs and CEC's were observed under the remaining regimes. Mineral content was richest in soils amended with FWC, however, the highest NH_4^+ and NO_3^- levels were observed under the control. Soil fungal and aerobic microbe populations were unaffected by fertiliser regime. COF and MAD performed very poorly as soil conditioners and crop yield enhancers and proved to be inadequate organic alternatives to inorganic soil nutrient management systems. In contrast, 2% BC + 50% CM produced higher yields than the inorganic fertiliser despite the 50% reduction in NPK. Soil FWC enhanced yield satisfactorily, albeit to a slightly lower extent than 100% CM. Both alternative regimes are viable sustainable alternatives to completely inorganic soil nutrient management regimes. However, the high nutrient content and imbalance in FWC may result in yield penalties if certain cations like Na+ compete with cations like K^+ and Ca^{2+}.

OPSOMMING

Voedselprodusente word gekonfronteer met die taak om groeiende globale voedselbehoeftes te ontmoet wat gepaard gaan met 'n groeiende en toenemend ryk bevolking. Hierdie druk word vererger deur 'n wêreldwye beweging na volhoubaarheid wat landbouers, spesifiek gewasprodusente, noodsaak om te verseker dat intensiewe voedselproduksie nie die noodsaaklike hulpbronne wat toekomstige geslagte benodig om hulself te voed, benadeel nie. Met ander woorde, oesproduksie moet so gedoen word dat oesopbrengste oor die jare gehandhaaf word of verbeter word deur goeie bestuurspraktyke wat twee noodsaaklike hulpbronne prioritiriseer: die grond en die omgewing. Bevordering of verbetering van grondvrugbaarheid is die enkele belangrikste manier om volhoubare gewasopbrengste te verseker. Een van die maniere om die vrugbaarheid van grond te bewerkstellig, sonder om opbrengste nadelig te beïnvloed is om anorganiese bemestingstowwe te vervang of te verlaag deur die insluiting van organiese en volhoubare grondverbeterings soos kompos en mede-toedienings van organiese en anorganiese bemestingstowwe. Daar is min wye vergelykende studies wat die impak van chemiese bemestingstowwe en volhoubare en organiese grond nutriëntbestuurstelsels binne die Afrika-konteks assesseer. Die Afrika-scenario word gekenmerk deur 'n ernstige behoefte aan voedsame gewasse soos patats (*Ipomoea batatas* (L.) Lam) en kleinskaalse boerderybedrywighede. In ooreenstemming hiermee is 'n studie gedoen om die effekte van anorganiese NPK-kunsmis en vier alternatiewe grondvoedingsbestuursregimes op grondvrugbaarheid, soetpatat-groei, opbrengs en voeding te bepaal en te vergelyk. Die studie het op die Welgavellen-proefplaas in Stellenbosch plaasgevind tussen die Desember 2016 en Mei 2017. 'n Gekontroleerde volledige blokontwerp is gebruik waar elke behandeling in elke blok verteenwoordig was om vier replikate te gee. Die behandelings was 'n anorganiese bemesting toegedien teen die aanbevole dosis van 100 kg N.ha^{-1} in 'n NPK-formulering (100% CM); 'n mede-toepassing van 'biochar' toegedien teen 'n koers van 2% en anorganiese bemesting toegedien teen 50 kg N.ha^{-1}, die helfte van die aanbevole dosis (2% BC + 50% CM); Kos afval kompos toegepas as 'n 5 cm laag (FWC); 'n kommersiële organiese bemesting wat in dieselfde formulering as die anorganiese kunsmis toegepas word, is ook toegedien teen 100 kg N.ha^{-1} (COF) en mis-afkomstige anaërobiese verteer (MAD) wat as 'n vloeibare kunsmis toegedien word teen 'n koers van 17 L per plant. Die beheer was onbevrugte grond. Beide

organiese en anorganiese bemestingstowwe is op 'n gesplete wyse toegedien. ANOVA en die Tukey HSD is gebruik om die data te analiseer. Die plantbedekking is 6 weke na uitplant aangeteken en is waargeneem as die mees omvattende in die geïntegreerde 2% BC + 50% CM behandeling, gevolg deur die FWC behandeling (onderskeidelik 73,67% en 65%). Dit was aansienlik hoër (P <0,05) as die 100% CM, COF en MAD behandelings, wat onderskeidelik slegs 41.08%, 39.92% en 39.2% canopy dekking behaal het. Alhoewel die FWC en 2% BC + 50% CM behandelings ook op die oes (16 weke na uitplanting) hoë vars en droë loot biomassa tot gevolg gehad het, was dit nie beduidend teenoor die res van die behandelings nie. Die geïntegreerde behandeling het die grootste vars knol opbrengs (26.41 t.ha^{-1}) opgelewer, gevolg deur die 100% CM behandeling 19.02 t.ha^{-1} en FWC 14.55 t.ha^{-1}. Opbrengs was laagste in die COF en MAD behandelings. Dieselfde tendens is waargeneem vir bemarkbare opbrengs. Die langste knolle is waargeneem onder die 2% BC + 50% CM behandeling. Tuber deursnee, oes-indeks was onveranders. Soet aartappel vog, ruwe vesel en stysel inhoud was nie beïnvloed nie en het nie beduidend verskil nie (P> 0.05). Proteïene was egter aansienlik anders (P <0.05) van die onbevrugte beheer en die MAD-behandeling. Die anorganiese behandeling het gelei tot 'n 2,12% proteïeninhoud in knolle. Biochar het agtergebly met 'n relatief groot marge en het tot knolle met 'n 1,45% proteïeninhoud gelei. Grond kationuitruilingskapasiteit (KUK), pH en suurheid was optimaal onder die 2% BC + 50% CM en FWC behandelings, terwyl die hoogste suur en laagste pH en KUK onder die oorblywende regimes waargeneem word. Minerale inhoud was die rykste in gronde wat met FWC gewysig is, maar die hoogste NH4^{+} en NO3^{-} vlakke is onder die beheer waargeneem. Grondskimmel- en aërobiese mikrobe bevolkings is nie beïnvloed deur kunsmisbeheer nie. COF en MAD het baie swak gedoen as grond 'opkikkers' en gewasopbrengsverbeteraars en blyk onvoldoende organiese alternatiewe vir anorganiese grondvoedingsbestuurstelsels te wees. In teenstelling hiermee het 2% BC + 50% CM hoër opbrengste as die anorganiese kunsmis geproduseer ten spyte van die 50% -verlaging in NPK. Grond FWC het opbrengste bevredigend verbeter, al is dit ietwat minder as die 100% CM behandeling. Beide alternatiewe regimes is lewensvatbare volhoubare alternatiewe vir volledige anorganiese grondvoedingsbestuursregimes. Die hoë nutriëntinhoud en wanbalans in FWC kan egter opbrengsstraf tot gevolg hê indien sekere katione soos Na^{+} kompeteer met katione soos K^{+} en Ca^{2+}.

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CHAPTER 1
Introduction

1.1   Background

The combination of a soaring global population and a growing proportion of affluent individuals have resulted in an ever-increasing demand for nutritious food. This greater demand is placing a tremendous amount of pressure on agriculture to increase crop yields. If food security is to be achieved and if the nutritional needs of both current and future populations are to be fully satisfied, agronomists and farmers alike need to ensure that crop production is not only at its most efficient, but also that it is sustainable in terms of soil fertility and subsequently, crop yield. Currently, much research is being conducted with the goal of establishing improved and innovative agronomic practices that will ensure that crop yields are maximal with as minimal damage as possible inflicted on the soil and the extended environment. The supposed necessity of the use of agrochemicals as observed in conventional crop production systems is under question. Agronomists are increasingly considering and re-introducing organic practices to improve soil fertility and increase crop yields substantially. One idea that most comparative studies have communicated is that, while agrochemicals are essential for achieving high crop yields, the quantities in which they are applied is not sustainable for the soil and environment and consequently, crop production. It is therefore, incumbent for researchers to establish practices that serve as an adequate alternative to agrochemical-centered management practices without compromising yields. One way to achieve this is to integrate the use of mineral fertilisers and organic-based fertilisation regimes. With this goal in mind, more alternative and inherently, sustainable nutrient management systems that are claimed to either maintain or improve soil fertility without compromising crop yields have surfaced.

Mineral fertilisers deliver important macroelements and microelements like nitrogen (N), phosphorus (P), potassium (K^+) and zinc (Zn^{2+}) to the soil and eventually, the plant. The availability of these elements is dependent on the organic matter (OM) content of the soils in which the particular crops of interest are cultivated. Inorganic fertilisers supply crops with nutrients more rapidly because they are in a soluble and more readily-available form. In contrast, the availability of nutrients from organic amendments generally depends on the state of decay (directly proportional to the source material) and often the enrichment of the soil does not happen immediately, but rather takes place over prolonged periods of time. Owing to their

inability to serve as a long-lasting nutrient source, mineral fertilisers need to be applied frequently and at high rates. This is a problem because amongst other drawbacks, mineral fertilisers, are a poor source of soil OM and N fertilization and imbalanced fertilization deplete soil organic carbon (C) (Yan et al. 2007, Kaur et al. 2008). Since SOM is in itself responsible for the various physicochemical properties that determine soil health and fertility, the depletion thereof has far reaching implications on crop growth, development and yield. Furthermore, chemical fertilisers are more readily transformed into other forms of compounds that leak into the soil and broader environment through various processes such as volatilisation, immobilisation and leaching. Mineral fertilisers are not a sustainable nutrient management system and some studies have shown a perceptible decrease in crop yield over time (Belay et al. 2002).

The adoption of organic fertilisers offers a more holistic approach to farming as it incorporates the current nutritional and physiological needs of the crops as well as those that will exist in the future. Moreover, it is able to maintain and improve soil fertility leading to higher and more stable yields in the future. Some studies reveal that excessively high rates of manure-based fertilisers may suppress germination and damage seedlings due to high salt levels (Domingo-Olive et al. 2016). Thus, it is essential that the application of organic amendments is carried out judiciously. Compost, whether plant-based or manure-based, enhances soil microbiological activities significantly, which affects N availability. Tejada and Benitez (2011) showed an increase in plant nutrition, crop growth and development, yield, enzyme activities as well as an increase in soil biomass, specifically in response to amendment with different types of compost. In addition, to enhancing soil health and fertility, compost is effective for the bioremediation of polluted and contaminated soil (Kastner and Miltner 2016). Various studies compare compost with other more industrialised and extensively processed and formulated organic amendments such as vermicompost. The latter tend to have a more balanced mineral composition and NPK ratio.

In recent times, biochar has emerged as a highly beneficial organic amendment. Biochar forms when organic material undergoes thermal degradation under anaerobic conditions (Lone et al. 2015). This process is known as pyrolysis. Although biochar is a relatively new term, it is a constituent of various soil types across the world. Biochar is associated with high soil fertility and subsequently, high crop yields as in the case of the *terra preta* soils in the Amazon (Parikh et al. 2014, Lone et al. 2015). The best crop yield responses to biochar amendment are

observed when it is applied in combination with chemical fertilisers and/or organic fertilisers. Crop yield dynamics are closely linked with the physiochemical properties of biochar, especially particle size, charge density and nutrient content (Lone et al. 2015). Crops cultivated on acidic soils will exhibit greater yield increases than crops grown on alkaline soil because most biochar has relatively high pHs. Soil plays a major role in how a fertiliser affects a crop and to what extent the effect is exerted. This is because fertilisers alter the soil environment by influencing soil properties that in turn influence the growth of a crop. Some important soil physiochemical properties that are affected by biochar amendment are bulk density, porosity, WHC, hydraulic conductivity, aggregation, aggregate stability, cation exchange capacity (CEC), pH and even electric conductivity (EC).

Anaerobic biodigestion, also widely referred to as biogas production, is the process in which organic material is decomposed by bacteria under anoxic conditions (Simon et al. 2015). The resultant biogas is high in methane (CH_4) and the by-product, digestate is composed of a liquid- and a solid phase. Anaerobic digestate may undergo further processing to separate the liquid fraction from the solid fraction. Studies conducted on the extent to which biodigestates positively influences crop yield, are scant. Literature reveals three major factors that determine the extent to which anaerobic digestate influences crop yield. These factors are the crop species, type of feedstock from which the digestate was derived and any further processing of the digestate. Xavier et al. (2015) found that the liquid portion of cow manure digestate leads to the greatest wheat yield when compared to compost, mineral, digestate- straw and cattle manure fertilisers. Liquid digestate may be a better fertiliser than digestate slurry because the liquid phase of digestate contains a much higher proportion of nutrients compared to the solid phase. Some studies have shown a definite improvement in soil aggregation and consequently drainage after digestate addition over a period of three years (Montemurro et al. 2010).

One very important aspect of soil fertility is the biological status of the soil, which is dependent on parameters like soil microbial biomass and enzymatic activity. Generally, any disturbance to the soil is known to cause a biological response, whether favourable or not. Organic fertilisation as opposed to agrochemical fertilisation is more-or-less associated with an increase in microbial biomass as well as speciation, which generally have positive effects on crop yields. For instance, both biochar and anaerobic digestate amendment have been shown to increase microbial biomass and result in a greater percentage composition of bacteria, which are essential in biogeochemical processes and that stimulate crop growth and yield (Rutigliano et al. 2013, Moller).

Although increased crop yields through adequate soil fertility is the main concern in crop production, nutritional quality is another important consideration and should not be neglected. Many studies that investigate both crop yield and quality often report a much more evident fertilisation effect on yield compared to nutritional quality. The effect mostly depends on the sort of nutritive parameter one is assessing. For instance, Mohammadi (2015) and Awad et al. (2014) both measured the oil quality of soybeans and sunflower, respectively, in response to a manure-based fertilisation system, an integrated fertiliser regime and a sole chemical fertiliser system. They found that the highest oil yield was observed when crops were grown on soil placed under a mixed-fertiliser system. Nitrogen uptake is negatively correlated to oil content because protein biosynthesis is intensified during carbohydrate metabolism, thus reducing fatty acid synthesis (Mohammadi 2015). Since manures release N at lower rates than chemical fertilisers, N-uptake is lower in crops grown on manure-supplemented soil and so accounts for the higher oil content. However, most studies fail to show any significant difference in the nutritive quality of crops grown organically, semi-organically and chemically. Baldatoni et al. (2016) observed lower concentrations of cadmium (Cd^{2+}), lead (Pb^{2+}) and N that are classified as toxic elements and elevated levels of soluble sugar in tomatoes grown on compost-amended soil when compared to tomatoes cultivated on soil treated with mineral fertilisers.

Comparative studies are extremely vital for establishing sustainable and high-yield generating nutrient management practices in crop production systems. This is true on both an industrial scale and smallholder scale. Globally, small-scale farming operations are acknowledged as having great potential to contribute substantially to the food system and subsequently, food security. About 92.3% of the world's farms are classified as small farms with 83% being less than 2 hectares in size (Von Loeper et al. 2016). Around 3 million farms in Africa are below 10 hectares. At this backdrop, it is vital that research is relevant to both industrial and small-scale farming operators. More comparative studies should be conducted on crops that are relevant to the African context. Two important factors that help define the 'African context' is (1) access to and availability of fertilisers (amongst other resources) to counteract the effects of degrading soil and (2) a poor nutrition. Economists and agronomists will often recommend technologies such as high-yielding seed varieties and chemical fertilisers that can drastically improve crop yield. However, African small-farmers can't afford these practices due to insufficient credit. In Ethiopia, 56% of fertilisers supplied to farmers is distributed by two big co-operations that sell on a credit- basis (Matsumoto and Yamano 2010). Researchers have found that crop yields are sub-optimal as a result of inadequate fertiliser application. The fertiliser packages are too often small in quantity so that even when farmers have bought several

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packages, the amounts are still too little to allow for sufficient mineral fertiliser rates. Ultimately, there is very little support for smallholders. Adjei-Nsiah and colleagues (2012) relate the same problem in Ghana. According to Mkahabela (2002), one of the biggest constraints to optimal crop production for small-scale farmers in South Africa, specifically, is declining SOM, soil nutrient content and consequently, declining soil fertility. This is in addition to the widespread problem of little financial and credit support for farmers. Experts in Ethiopia fully endorse reducing dependence on chemical fertilisers promoting agroecological practices and the use of organic amendments to smallholder farms (United Nation Economic Commission for Africa 2009, Mukasa 2017). Radebe (2014) reported that a document published by Fertiliser Society of South Africa (FSSA) (2003) state that South Africa was in possession of 3 million tons of manure that amounted to the R29.3 million worth of N, P and K. Furthermore, the publication stated that the organic waste material was able to meet 13.3%, 9.9% and 27.6% of the national needs for N, P and K, respectively. It appears that organic amendment is a highly viable solution for poorly-resourced African small-scale farmers who haveto farm on rapidly degrading land.

Statistics obtained from the SA National Health and Examination Survey (Department of Health, 2013) showed that 43.6% of the population of children below the age suffered from Vitamin A (Vit A) deficiencies, while the rate was 13.3% for adults. Almost eighteen percent of the population (aged above 15) suffered from iron (Fe^{2+}) deficiencies and anaemia. Stunting, which is closely linked to malnutrition is also a problem, with the Free- State showing the highest levels at 22.7% for girls aged below 15. The survey highlighted the dire need for some serious interventions. Nutrition should not just be the concern of government bodies and educators, but of agriculturists too. More programmes should be established to encourage farmers to cultivate highly nutritive crops. Agronomists should also research crops that hold high nutritional value, such as sweet potato.

Sweet potato (*Ipomoea batatas* (*L.*) Lam) is a prominent crop in smallholder cultivation systems. It outranks most staple crops in vitamins, minerals, dietary fibre and protein content (Lebot 2009, Agriculture, Forestry and Fisheries Department of South Africa 2011, Kareem 2013). It belongs to the second most important set of food crops, i.e. root crops, in developing countries. Sweet potato has a wide ecological adaptation, exhibits drought and salinity tolerance and has a relatively short maturation period of 3 to 5 months. It can also be harvested sequentially, thus ensuring continuous food availability and access, an important dimension of food security.

Orange-fleshed and yellow-fleshed cultivars are acknowledged as good sources of Vit A and are promoted across the developing world. Vit A deficiency in South Africa is still a severe health problem. Though the movement is towards orange-fleshed potatoes, the Western Cape and broader South African market still favour purple-skinned, cream-fleshed sweet potatoes. This variety is among the three that are popular in South Africa. The other two are the orange-skinned varieties and purple- skinned varieties. Although the Vit A levels in purple-fleshed sweet potatoes compare poorly to those contained in the biofortified orange-fleshed varieties, the former have notable nutritional benefits. Ji et al. (2015) conducted a comparative study on the nutritional quality and anti-oxidative activity of 4 different colour-skinned sweet potato varieties (purple, red, yellow and white). According to the study, purple-skinned sweet potatoes contain the highest levels of dietary fiber, phenols, protein, antioxidant capacity, and anthocyanin. Purple-skinned sweet potatoes are especially beneficial for people with diabetes, as they contain substantial levels of dietary fiber, which translates into a low glycaemic index. In general, sweet potatoes are low in fat, have notable Vit C and Vit B6 concentrations.

1.2   Research Rationale

1.2.1   *Problem statements*

There is a widespread consensus that conventional agrochemical nutrient management systems are not sustainable. Alternative nutrient management systems that are sustainable and don't compromise crop yields and quality need to be established. There are few studies that compare a broad spectrum of nutrient management systems in terms of their influence on crop yield, nutritional quality and soil fertility. This is especially the case in crops such as sweet potato that are (1) suited to small-scale farming operations, which are the largest contributors to total food production and (2) have high nutritional value.

1.2.2   Aim

The aim of this project is to assess the impact of 1) alternative nutrient management systems on soil fertility and sweet potato yield (Bosbok); as well as 2) the effects on nutritional quality of sweet potato.

1.2.3   Hypothesis

Alternative and organic nutrient management systems with a higher organic fraction will result in greater sweet potato yields. Soil fertility will perceptibly improve across the different organic amendments. Nutritional quality will differ between chemical and organic fertilisation regimes, but will remain similar across the different organic fertilisers.

1.2.4   Objectives

a.   Investigate the impact of the six nutrient management systems; i.e., (i) control (without any additions), (ii) chemical fertiliser, (iii) commercial organic fertiliser, (iv) compost, (v) biochar with half of the recommended chemical fertiliser rate, and (vi) anaerobic digestate on sweet potato growth parameters and yield.

b.   Assess soil fertility in terms of microbial biomass, WHC (as an indirect estimation of the relative abundance of SOM) under the aforementioned nutrient management systems.

c.   Assess sweet potato nutritional quality in terms of starch content, crude fibre and protein content in response to the six nutrient management systems.

1.3   Impact of study

Nutrient management systems are one of the key determinants of crop yield. Their role is rendered all the more important and complex within the context of yield and soil sustainability in vegetable production. The good news is that these alternative strategies are not only beneficial for soil and environmental health, but also have extremely positive impacts on crop yield. This project will contribute significantly to food security by exploring a broad spectrum of these alternative and sustainable fertilisation regimes.

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CHAPTER 2

Literature Review

2.1   Introduction

Achieving food security on a global scale is arguably the most daunting task facing modern-day agriculturalists/scientists. According to the most recent annual hunger report by the Food and Agriculture Organisation's (FAO 2015), the number of undernourished people in the world has decreased by 216 million since 1990. However, the UN is also predicting that the global population will reach 9.7 billion in 2050, which will require the agriculture sector to increase food production by at least 70%. The best approach for crop producers to adopt in order to meet rapidly increasing food demands both currently and in the future is to cater specifically to the needs of the environment and the crop first. It has been proposed that there should be a shift in emphasis from "nourish the masses" to "nourish the crop".

Crop productivity and yield depend on a number of factors including edaphic factors. Land workers, researchers and professionals, must endeavour to influence the soil's amenable properties positively. For years and especially since the Green Revolution, humanity has over-fertilised soils with chemical fertilisers to maximise crop yields. This has resulted in adverse effects on the soil's long-term mineral and organic matter (OM) content as well as on a number of other properties that negatively affect the fertility and consequently crop growth, yield and nutrition. On the other hand, agricultural workers and experts cannot completely dismiss chemical fertilisers as they still have a definite role to play in sustainable soil nutrient management systems. Inorganic fertilisers are detrimental only when applied in excess or in an imbalanced fashion. Unfortunately, the excessive and unchecked use of inorganic fertilisers is still a common occurrence.

Organic amendments are a powerful tool; however, they carry their own level of risks. These include surface crusting, increased vulnerability to splash erosion and reduced hydraulic conductivity due to structural degradation. High concentration of potassium (K^+) and sodium (Na^+) anions as well as ammonium (NH_4^+) can accumulate and compete with other anions like calcium (Ca^{2+}) for adsorption (Haynes and Naidu 1998). This has a negative impact on crop growth. In addition, microbial populations, especially in compost and anaerobic digestate application, can secrete substances that repel water, thereby hindering water transportation through unfavourable infiltration rates and hydraulic conductivity (Voelkner et al. 2015).

Another risk is nutrient immobilisation due to an innately suboptimal C:N ratio, which determines the decomposition rate of organic material. High microbial activities can also lead to N immobilisation, which hinders crop growth and development (Esmaeilzadeh and Ahangar 2014).

Soil nutrient management can no longer simply be about transient increases of soil nutrient content. It must consider the soils continued capacity to sustain crop productivity throughout time. Farmers must maintain and enhance soil fertility and crop productivity through the implementation of regenerative organic practices like the application of organic soil amendments to reduce or even eliminate, where possible, the use of mineral fertilisers. Organic amendments like compost, biochar, anaerobic digestate and even industrially manufactured organic fertilisers are amongst the most effective and/or novel alternative soil nutrient management systems.

2.2   Chemical fertilisers

Historical evidence shows that fertilisers are mostly a by-product of warfare. In his highly informative book. By the dawn of the 1700's people had already recognised the dual purpose of potassium nitrate (KNO_3) as a primary component of gunpowder, but alternatively as a good fertiliser source (Leigh 2004). During this period, KNO_3 was commonly referred to as saltpetre and was derived from camel manure. Other fertiliser sources included chalk, common salt ($NaCl$) and ammonium chloride (NH_4Cl). It was not until the late 1700s and early 1800s (when the Western World started fearing that the booming population would soon lead to a situation where food demand outweighed food supply) that countries started importing and exporting vast amounts of fertiliser. By then fertilisers were widely recognised "to be productive of the most luxuriant effects, and to retain an advantageous influence upon the soil for at least two years". Soon after the possibility of food shortage emerged, Western powers took an interest in guano (bird droppings) collected and processed in Peru. A German explorer analysed the organic material and discovered its inherent abundance in phosphorus (P) and nitrogen (N). Half a century later, Britain was importing 300 000 tons of the organic fertiliser annually. Political disputes and the progressively popular inorganic alternative of NO_3^- soon collapsed Peru's lucrative trade of guano.

Thereafter, two major events occurred simultaneously: World War 1 and researchers'

appreciation of the importance of fixed N in crop production (Leigh, 2004). At the time of these events, three nitric acid (HNO_3) reactions were widely known: the Norwegian Arc process that converts dinitrogen (N_2), dioxygen (O_2) and water (H_2O) into HNO_3; the cyanimide process that coverts calcium carbonate ($CaCO_3$), N_2, carbon (C) and barium (Ba) into NH_4^+ and $BaCO_3$ and lastly, the most applied of the three, the Haber-Bosch process that converts N_2 and hydrogen (H) into NH_4^+. The British countries who were involved in the war decided to engage in chemical and gun warfare. Britain needed NO_3^- for fire power, while Germany pursued chemical methods. Its chosen gas of destruction was HNO_3 that could either be formed directly or from NH_4^+. WW1 was instrumental in accelerating the advancement of the technology needed to produce NO_3^- and NH_4^+. When the war ended, the globe sought to use all the knowledge acquired for the ill intention of warfare towards a more noble cause: fertiliser use to boost crop production.

Mineral fertilisers became progressively popular leading up to the 1920's. Forty years later, extensive research yielded astounding results that helped foster an age of intensive, industrial agriculture. This era, deemed the Green Revolution, which saw a surge in agrochemical use, therefore had its foundation in the events that occurred in the 1900s including WW1. One interesting notion had arisen from this narrative. The violent and contentious foundations of the Green Revolution, which included agrochemical technology advancement, almost make it seem that chemical fertilisers were fated to play the part of the 'Big Bad Villain' right from the beginning.

Crop production boomed during this era, with high-yielding varieties requiring high pesticide and inorganic fertiliser input. In the end, the high inputs, despite increased production, which Patel (2013) claims was more related to the increased area of land under cultivation and the expansion of the market rather than technology, proved too costly for farmers' pockets. Conservationists claim that the Green Revolution also proved too costly for the environment, particularly the soil. Organic agriculture proponents like the renowned anti-GMO activist, Shiva Vendana, bemoan chemical fertilisers' so-called potency in destroying the soil and environment (Specter 2014), but researchers must distinguish between popularised misconceptions and absolute truths in order to establish viable and sustainable practices.

This requires the scrutiny of data relating the effects of both organic and inorganic fertilisers on crop yield, nutrition and soil fertility from a completely objective point of view.

One of the most controversial consequences of the Green revolution is the excessive nutrient loading in water, soil acidification, eutrophication, soil structure disintegration, salinization, and excessive consumption of fossil fuel, the production of ammonia and nitrous oxide and consequent poisoning of the environment. In the 1980s, Indonesia was losing 50 metric tons of topsoil annually (Patel 2013), while many regions recorded severe nutrient depletion that subsequently led to diminished soil fertility. Growing dependency on fertilisers caused farmers to abandon practices that promoted OM accumulation in the soil. Ultimately, mineral fertilisers are an ideal source of nutrients as they are an immediate and readily accessible reservoir of essential minerals for plants.

2.2.1   Soil fertility

Chemical fertilisers affect one major component of soil health that determines various physicochemical and biological properties. This overarching component is soil organic matter. The common misconception is that mineral fertilisers lead to the depletion of soil organic matter (SOM). However, various studies reveal that the depleting effect that inorganic fertilisers have on SOM is over-stated. Organic soil amendments like manure augment SOM in the soil as do mineral fertilisers; however, organic matter increases SOM more substantially than inorganic fertilisers. Zhang et al. (2016) compared the impact of organic amendments to mineral fertilisers on SOM. The control contained no fertiliser or amendment. The SOM content in the control diminished over time, while the organic treatments increased it substantially. Chemical fertiliser also increased SOM, albeit to a lesser extent. The same trend is observable for soil organic C. Organic C content was 17% higher and 48% higher than the content in untreated vertisol soil after the application of NPK and NPK supplemented with farmyard manure, respectively (Hati et al. 2005). Xin et al. (2016) reported similar results on fluvo-aquic soil. The highest SOC content was found in sole organic compost at 9.08 g.kg^{-1} (138% higher than in unfertilised soil) and the second highest content was found in soil treated with equal amounts of organic compost and chemical fertiliser at 7.03 g.kg^{-1} (85% greater than in unfertilised soil). Sole fertiliser applications of the other treatments, namely, NP, NK, PK and NPK, all contained SOC that was 41%, 1.6%, 23% and 46% higher than in unfertilised soil, respectively. What was particularly intriguing about the results was the positive correlation

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between SOC and P, suggesting that P may have been the limiting factor. NK gave rise to the least SOC when compared to the other treatments. Soil organic C seemed to respond less to K than the other elements. In fact, the authors found no significant difference between the NP and NPK treatments. In another study, fertilization with just N decreased or maintained SOC, while the converse was true for fertilization with K and P (Yan et al. 2007). This emphasizes the relevance and central role of soil type and mineral composition. The authors cited lack of nutrient balance in the fertiliser formulation as the cause for decreased C. Inorganic fertilisers do confer some benefits to the soil, but application rates must account for soil mineral composition and must be applied in a balanced manner. In addition, Pernes- Debuseyer and Tesser (2004) make an important distinction between types of mineral fertilisers and emphasize that ammoniacal fertilisers, specifically, lower soil pH, while basic form of fertilisers that contain hydroxide and carbonate functional groups enhance the pH. Basic fertilisers also improve the soil's cation exchange capacity (CEC). This has important implications as a low soil pH favours aluminium (Al^{3+}) exchangeability, while a high pH favours Ca^{2+} exchangeability. Cation exchange capacity and pH affect soil-water relations, especially when SOM content is low.

Water-related properties like water-holding capacity (WHC), hydraulic conductivity, bulk density (BD) and water-stable aggregate formation rely heavily on SOM (Hati et al. 2005). Table 2.1 shows water-related soil properties after treatment with NPK and NPK with farmyard manure. The control was unfertilised soil. Bulk density decreased in both treatments, albeit to different extents with the largest and most favourable reduction was observed in the NPK + FYM (farm yard manure) treatment. Hydraulic conductivity and the percentage composition of water-stable aggregates, i.e. particles with a diameter greater than 0.25 mm increased for both treatments. Once again, the manure-supplemented treatment showed the most favourable results.

Zhang et al. (2016) investigated the effect of NPK and NPK with farmyard manure on SOC, bulk density, hydraulic conductivity, and particle mean weight diameter and water stable aggregates. Both treatments had a favourable effect compare to the untreated control soil. A combination of FYM and NPK produce the most favourable effects. While chemical fertilisers do not always lead to poor soil fertility, they are an inferior catalyst for soil organic carbon and organic matter accumulation to organic amendments. Injudicious application in terms of amount and formulation increases mineral fertilisers' potential to harm the soil.

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2.2.2   *Crop yields*

Mineral fertiliser opponents claim that fertilisers diminish yields over time (especially when compared to organic amendments) and fail to produce stable yields. Zhang et al. (2016) found that the same is true for organic fertilisers. Yields can drop even in soils amended with organic material. Furthermore, sole mineral fertiliser applications, over both a short and long term, can produce greater yield than sole organic fertiliser applications. If in some cases, chemical fertilisers tend to increase yields more than organic amendments, what is the issue? Data collected from North China Plains reports favourable yields under conventional systems compared to other organic and integrated fertiliser regimes (Celik et al. 2010, Gou et al. 2016, Xin et al. 2016, Zhang et al. 2016). Farmers in these regions apply excessive, unsustainable amounts of fertilisers, leading to the degradation of environmental health, specifically the soil, air and water. These studies have shown that combining mineral fertilisers with organic material not only improves soil fertility and the state of the environment, but also produces comparable, but slightly lower, yields relative to sole chemical fertiliser applications (Table 2.1). The combination of chemical and organic fertilisers allow for immediate nutrient availability and long-term nutrient availability that benefit the crop.

Table 2.1 Comparison of the effects of organic, inorganic, mixed and no fertiliser treatments on maize.

Source	Gou et al. 2016	Xin et al. 2016	Celik et al. 2010	Zhang et al. 2016
Crop	**Maize and wheat grain**	**Maize and wheat grain kg.ha^{-1}**	**Maize grain kg.ha^{-1}**	**Maize grain**
No. of years fertiliser of trial	5	23	12	3
Number of years averaged	5	1 (23rd year)	1 (12th year)	3
None	6 466	1 906	5 900	7 273
100% NPK	13 872	14 664	13 720	9 257
100% Org	11 551	13 860	10 500	N/A
Mixture 50 – 75 % NPK	14 274	14 460	N/A	9 303

Hundred percent organic treatments produced the least yield after no treatments consistently, while mixed fertilization produced the highest yields in two of the studies. This shows that mixed nutrient management systems are a viable and sustainable alternative to inorganic systems.

2.3   Compost

Compost is a widely researched and commonly used organic amendment across the world, especially in poor, rural communities that generate ample waste. Virtually any organic material is compostable and produces favourable yields.

2.3.1   *Soil fertility*

Like most organic amendments, compost enhances SOM and C well beyond the capacity of chemical fertilisers. Compost application is associated with a substantial increase in aggregation, WHC and BD (Celik et al. 2010, Babalola et al. 2012, Xin et al, 2016). The advantage of compost is that it is associated with an increase in soil microbes. The composting process is characterised by a proliferation of microbes that degrade organic material (Marinari et al. 2000). Thus, it adds living organisms and nutrients into the soil. Babalola et al. (2012) observed an increase in microbiological properties like the fungal population, total microbial population etc. with the addition of compost. Compost also enhances the nitrogen (ammonium and nitrate) content in the soil (Sánchez-García et al. 2015). Indeed many non-commercial farmers use only compost to treat their soils and obtain adequate yields. Other organic amendments like biochar lack sufficient N content to permit use as a sole fertiliser. The high N property comes from the feed source e.g. grass cuttings, fruit waste etc.

2.3.2   *Crop yield*

Compost increases yields by improving soil physicochemical properties. This means that compost has the ability to it moderate the effect of fluctuating water, air and heat conditions due to changing seasons (Amlinger et al. 2007) so that crops are not as vulnerable to changing climates. The effect that compost has on soil is not short-term, such as is the case for inorganic fertilisers (Astover et al. 2017). Potato yields were shown to increase by ~50% (compared to untreated soil) in response to the application of compost at planting. In the following year, a new potato crop was planted without the additional application of compost and the yield

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increased by ~ 30% and ~19% in the following year (Astover et al. 2017). This demonstrates the slow nutrient release effects of compost, which makes it ideal for sustainable low input cost farming operations.

Asagi et al. (2016) showed that the feedstock impacts the degree to which compost is able to increase yields, specifically in a potato crop. They found that poultry manure compost produced slightly higher yields than an inorganic fertiliser. The other composts, which were produced from food waste and cattle manure resulted in lower, but non-significantly, different yields compared to the same inorganic fertiliser. Moreover, cattle manure compost produced the lowest yields. A closer look at the chemical analyses results of the amendments and fertiliser revealed that the cattle manure compost not only had the lowest total and available N content, but also had the highest pH (9.2) compared to 8.3 and 8.5 in the food waste compost and poultry manure compost, respectively and the highest C:N ratio leading to greater nutrient immobilisation. Van Haute (2014) observed reduced pod numbers and seed weights per plant as well as a reduced yield in a bean crop cultivated on compost-amended soil. The yield reduction was in comparison to a bean crop grown on soil treated with mineral fertiliser. A likely reason for this may be that the slow nutrient release, which is ordinarily advantageous for crop production, resulted in nutrient deficiency at critical stages of the crop growth cycle.

A grievous concern is the nutrient composition of a particular compost. Compost formulations are often imbalanced, which can result in yield penalties. This is perhaps why vermicompost, an industrial organic fertiliser, outperforms compost (Tejada and Benitez, 2011, Doan 2015). In Guo et al.'s (2016) study, a combination of chemical fertiliser and compost produced greater yields than a sole compost application. The researchers attributed this to the balanced nature of the treatment.

2.4   Biochar

Biochar forms when organic material, mostly woody plant material undergoes thermal degradation under anaerobic conditions, through the process of pyrolysis (Lone et al. 2015, Vijayaraghavan 2016). In the conversion of woody material to charcoal, carbonaceous material is heated and dehydrated to form a material that is high in hydrocarbon content. Carbon dioxide and other gases like benzene, methane, carbon monoxide are formed as by-products (Vigoroux 2001). The temperature and rate of reaction may be adjusted to produce a product with a desired ratio of gas, liquid and solid particles. Significant rates of C sequestration coupled with the mitigation of greenhouse gas (GHG) emissions and substantial concentrations of SOC are biochar's two most highly recognised attributes (Lone et al. 2015, Laghari et al. 2015). Although biochar is a relatively new term and form of amendment, it is a constituent of various soil types across the world. Generally, biochar is associated with high soil fertility and subsequently, high crop yields as in the case of *terra preta* soils in the Amazon (Lone et al. 2015). Biochar's intrinsic properties make it a form of soil amendment that is rapidly gaining interest amongst agronomists and other scientists who are concerned about sustainability and conservation. The properties of different types of biochar are dependent on various factors. These factors are mainly the source of feedstock from which the biochar is derived (Zong et al. 2016) and the temperature and consequently, the rate at which pyrolysis occurs (Laghari et al. 2015, Li et al. 2017). The particle size and the chemical composition of biochar are key considerations in determining the type and extent of the effect that biochar amendment will exert on the crop. Furthermore, the interaction between the soil and biochar moderates the impact of biochar on the crop. A study done by Lim (2016) showed that biochar derived from four sources namely, pine chip, hardwood chip, oat husk and hardwood pellet had distinct bulk densities and C, N and O_2 concentrations. These distinct properties were responsible for the different effects that were observed when four different soil types were amended with four biochar treatments. The above listed properties have a major bearing on the productivity and yield of the crop. Before discussing the impact of biochar on crop yield, we will discuss the advantages and disadvantages that accompany the use of biochar.

2.4.1   *Feedstock and temperature*

Temperature has a major bearing on the intrinsic properties of biochar. These intrinsic properties alter soil conditions and characteristics, which in turn affect crop yields. For instance, pH increases with increasing pyrolysis temperature. Lagahari et al. (2015)

investigated sorghum yield responses to biochar processed at varying temperatures of 400°C, 500°C, 600°C, 700°C and 800°C. They observed the highest yields with biochar heated at 700°C, which also corresponded to the highest WHC, highest water-use efficiency (WUE) and most reduced hydraulic conductivity. Naeem et al. (2016) looked at pyrolysis at low temperatures (300°C, 400°C and 500°C) and found that the highest yields were obtained with 300°C and 400°C. This is more-or-less in agreement with Laghari et al. (2015) who also demonstrated comparatively higher yields obtained from 400°C biochar as oppose to yields obtained from 500°C biochar. Following both studies, one could argue that biochar processed around 400°C and 700°C produces good crop yields. Biochar processed at lower temperatures like 400°C has a higher content of easily degradable and thus assumable, compounds, while biochar processed at higher temperatures (around 700°C) have larger aromatic compounds (Jindo et al. 2014).

The type of feedstock from which biochar is also essential. For instance, manure-based biochar increases CEC more than woody biochar, which is more likely to contribute to properties related to WHC and hydraulic conductivity (Domingues et al. 2017). One has to consider the soil condition and crop requirements when selecting a type of biochar.

2.4.2   *Biochar rates*

Although biochar has been shown to increase yields, crop responses are not consistent. Xu et al. (2015) evaluated the ability of biochar to increase peanut yields when applied at a rate of 9.2 t.ha^{-1} under rain-fed and irrigated conditions. In this instance, biochar failed to boost yields because it was applied at an insufficient rate. Laghari et al. (2015) investigated sorghum growth in response to four application rates (0, 15, 22 and 45) of pine sawdust biochar. The best yields were obtained with the application rate of 15-22 t.ha^{-1}. Most studies record a positive biochar effect when the rate is above 10 t.ha^{-1}. Interestingly, Laghari and his colleagues (2015) recorded declining yields at a rate equal to and above 45 t.ha^{-1}. There are various reasons for compromised yields. They include the intrinsic biochar properties such as elevated C:N ratios, which lead to slow organic material decomposition rates and the rapid depletion of N during relatively early stages of the crop growth cycle. Al^{3+} concentrations also increase at high rates, leading to toxicity symptoms in the plant and suboptimal crop growth and yield (Laghari et al. 2015).

2.4.3   *Biochar and the soil*

Crop yield enhancement is seemingly more evident on acidic soils and therefore careful consideration has to be given to the type of biochar when amending soils, especially when alkaline (Abdullaeva 2014). This is because most biochar types increase soil pH. The application of alkaline biochar to soils with elevated pH levels reduces P, Fe^{2+} and manganese (Mn^{2+}) availability leading to plant 'malnutrition' and consequently yield reduction (Jeffrey, 2017).

Soil is a prominent factor in crop yield responses to biochar supplementation. When Manickam et al. (2015) applied biochar to two soil types (sandy and acid sulphate soils) and assessed corn yield over two seasons, they discovered that corn yield trends differed for each soil type. Moreover, the corn yields in the second season were drastically reduced on the sandy soil and either maintained at the same level or improved on the acid sulphate soils. The key reason for yield improvement in the first season in the sandy soils was that biochar increased plant available water. Yields declined in the second season as this effect faded, because the biochar moved to deeper soil profiles and the water was not as freely accessible to the crop. Yield increases in the acid sulphate soils were attributable to attenuated acidity following an increase in Ca:Al ratio conferred by the biochar.

Biochar affects soil physiochemical factors such as BD, porosity, WHC, hydraulic conductivity, aggregation, aggregate stability and CEC (Abdullaeva 2014). Biochar is able to reduce BD and therefore increase porosity and alter water retention through direct contribution from pores within the biochar and by creating pore space between biochar and surrounding soil aggregates. CEC increases with the addition of biochar because its surface area increases and the charge density on these large surfaces is directly correlated to pyrolysis temperature (Lede 2010). A high CEC, as well as a high pH, often lead to better nutrient availability. Biochar also increases SOM, which in turn improves nutrient availability and water retention.

Biochar has also been shown to alter soil microbial communities, which elicits changes in soil and health fertility (Dai et al. 2016). Biochar is pyrogenic; it can elevate pH and soil adsorption of basic cations. This typically enhances nutrient bioavailability, which promote microbial activities (Dai et al. 2016). Biochar also reduces the bioavailability of certain potentially hazardous elements in contaminated soils (Cui et al. 2016). Other factors that make biochar conducive to microbial growth is its ability to alter the physicochemical soil environment to better suit a specific (beneficial) microbial species, at the expense of more pathogenic microbes. It also provides C content with a high turnover rate and other nutrients to microorganisms and it serves as a protective shelter from predators and harsh conditions (Dai et al. 2016).

In a study conducted by Wang et al. (2015), the addition of biochar resulted in notable elevation in bacterial populations and other variable changes in the broader microbial community composition. Possible reasons are that an unfavourable C:N ratio prevented efficient nutrient availability and that biochar particle sizes may have been too large. Small organic amendment particles favour population growth (Sessitsch et al. 2001). Researcher propose that small pores exclude predators that prey on bacteria such as protozoa.

2.4.4   *Biochar's performance as a sole fertiliser*

The impact of biochar on rice yields was compared to the impact of four other organic amendments, specifically, rice husk, rice straw, rice husk ash and *Chromolaena odorata*, a type of bush plant. Results showed that biochar and *C. odorata* amendment of acid sulphate soils led to the greatest numbers of tillers and total dry biomass in cultivated rice. Thus, biochar compares favourably with other forms of plant organic amendments (Masulili 2010). Literature implies that biochar leads to appreciable and significantly higher crop yields when applied to acidic soils. Yao et al. (2016) reported a remarkable increase in pepper yields from biochar-amended soils compared to mineral fertiliser-amended soil owing to a higher Ca^{2+}, K^+, Mg^{2+}, Na^+ and S content in biochar. Clearly, biochar has several mechanisms by which it improves soil fertility, health and crop yield. It increases soil pH and consequently reduces Al toxicity (Qian et al. 2013). This facilitates the improvement of root growth and nutrient uptake.

Biochar does not only increase yields, it also favours the growth of specific parts of a crop over others. Akom et al. (2015) observed a observable decline in the number of grams of yam seeds per hectare with the application of biochar. The decline in seed yield corresponded to an increase in total marketable yam yield. In this case, biochar application resulted in the translocation of carbohydrates to yam production, rather than seed production. Olmo et al. (2015) showed a decrease in root density and diameter and an increase in root length in wheat in response to biochar addition. The roots were finer and facilitated improved P uptake, whereas Mn^{2+} and N uptake were reduced. The decrease in root density and tissue was attributed to attraction of water and nutrients to the biochar particles. Researchers are only just beginning to unlock biochar's potential and results so far, have been encouraging. Understanding biochar's effects fully can allow agronomists to manipulate crops for seed propagation, for cover crop biomass production and other uses other than fruiting yields.

2.4.4.1   Nitrogen-related yield

Nitrogen fixation contributes immensely to biomass accumulation and yield in leguminous crops. Biochar increases nodulation (Mete et al. 2015). Xu et al. (2015) hypothesise that biochar increases the bioavailability of micronutrients that are essential for nodulation and N-fixation. Perhaps An increase in nodules and therefore, an increase in biological nitrogen fixation and chlorophyll content in the leaves may ultimately lead to an increase in biomass accumulation and yield .

Mandal et al. (2016) evaluated the impact of biochar on N-related parameters that contribute to crop yield. They found that biochar amendment reduces NH_4^+ volatilisation from fertilisers. Ammonia volatilisation decreases yields by reducing the amount of available N that is essential for biomass accumulation. Furthermore, the reduction in NH_4^+ volatilisation corresponded to higher N-uptake. The added biochar was alkaline and subsequently increased the pH of the acidic soil to which it was applied. This increase in pH led to a greater NH_3 adsorption capacity in the soil, thereby increasing maize yields (Mandal et al. 2016).

Another way that biochar affects crop yields related to N parameters is that while it is not good source of N, it is a habitat for N-fixing microbes and other microorganisms (Deb et al. 2016). The activity of these N-fixing microbes may induce the immobilisation of N, which is ordinarily undesiarable. However, this leads to the storage of N in the soil that can be released over time thus facilitating improved N use efficiency (Mandal et al. 2016).

2.4.4.2   Phosphorus-related yield

One of the ways in which biochar enhances crop yield is by increasing P availability and uptake (Mete et al. 2015). When acidic biochar derived from sawdust was applied to alkaline soil (pH 8.8), the decrease in soil pH caused by biochar amendment resulted in greater P availability as well as better micronutrient availability (Mete et al. 2015). Kim et al. (2016) observed a similar trend when biochar increased the soil's water-soluble content and overall phosphorus concentration.

One of the indirect ways that porous and large surface area biochar particles contribute to crop productivity, is through providing a habitat for P-solubilising microbes (PSM) as well as for other microbes and facilitating higher PSM activity. These in turn lead to higher P uptake and higher crop yields. Deb et al. (2016) reported a remarkable increase in the yield of rice grown

on soil amended with biochar and PSM in relation to soil inoculated with PSM alone and soil amended with only biochar. The trend was the same for all grain and root crops, but yield enhancement by PSM and biochar amendment was not evident for leafy crops (Deb et al. 2016). Another limitation of this nutrient management strategy is that yield improvement mostly occurs when the soil is low in P content and not when P concentrations in the soil are sufficient.

2.4.5 *Biochar's synergy with other fertilisers*

Evidently, biochar is an efficient and valuable form of soil amendment. Despite its powerful remedial properties, it compares poorly to mineral and organic fertilisers like compost and manure, and is therefore, usually used in co-applications (Doan et al. 2015, Sanchez). Biochar does not allow the complete discontinued use of mineral fertilisers, but simply lowers the amount of external nutrient inputs required in crop management (Olmo et al.2015). Basri et al. (2013) conducted an elaborate study on the crop yield response of kenaf to 16 different nutrient management systems. Biochar, zeolite, chemical fertiliser and chicken manure were all applied as single treatments to soil and in various combinations of two, three and four per treatment. They found that the best yield response was observed with the combination of biochar, chemical fertiliser and zeolite. When biochar was applied alone, yields were comparable to the control i.e. unfertilised soil. Seemingly, biochar only lead to improved yields when combined with other fertilisers (Basri et al. 2013)

Similarly, biochar increased soybean yield by 67% compared to unfertilised soil (Mete et al. 2015). Sole mineral fertiliser applications can achieve a 201% increase, while a combination of biochar and mineral fertiliser leads to a 391% yield increase (Mete et al. 2015). Chemical fertilisers and biochar have a strong, positive interactive effect on crop yield (Doan et al. 2015). Zhang et al. (2016) presented a case in which farmers were using a conventional mineral fertilisation regime that was characterised by high N and low P application for a maize crop. They tested formulation with different ratios and supplemented the treated soils with biochar. Biochar managed to increase yields by 23% more in the second year when they applied NP at a suitable ratio of 3:5. Biochar works exceptionally well when combined with balanced mineral fertilisers.

2.4.6   Biochar's disadvantages

Kuppusamy et al. (2016) suggested four main risks to biochar application. The first is interference with agrochemicals through binding deactivation and the second is the discharge of harmful heavy metals and polycyclic aromatic hydrocarbons that may constitute part of the biochar, providing excessive concentrations of nutrients to the soil and microbial communities. The remaining two are its interference with soil biological processes and germination and the unfavourable increases in soil pH and electrical conductivity (EC).

One of the drawbacks of biochar is that its high C:N ratio may lead to the immobilisation of inorganic N and subsequently lead to deficient N amounts that are supplied to the plant (Ding et al. 2016). Thus, it is disadvantageous to apply biochar alone. In a case where N content was increased by the addition of biochar, Baker et al. (2015) found that this was a result of an increase in N availability, rather than a case of increased in the amount of N. This increase in N availability was in turn due to the decrease of C availability because of biochar's intrinsic C-retaining properties. The co-application of mineral fertilisers and biochar does not always enhance yields (Akom et al. 2015). Soil nutrient management is a complex system and factors like the age, type and rate of application of biochar as well as crop species can interfere with efficacy.

2.5   Anaerobic biodigestate

Anaerobic biodigestion, also widely referred to as biogas production, is the process in which bacteria decompose organic material under anoxic conditions (Nkoa, 2013) The main product, biogas is high in methane (CH_4) and the by-product, digestate is composed of a liquid and a solid phase (Ngesi, 2012). Digestate is composed mainly of low molecular- weight organic acids (Andruschkewitsch 2012, Fogassy et al. 2010, Voelkner 2015). The biogas serves as a source of renewable energy, while the digestate is a suitable fertiliser/soil conditioner (Andruschkewitsch 2012). Anaerobic digestate may undergo further processing to separate the liquid fraction from the solid fraction in which case the former is applied as a liquid fertiliser and the latter is applied as a solid soil conditioner (Fogassy et al. 2010). The large volumes of waste water that come from the food and beverage industries, the excessive amount of animal

waste due to intensive livestock farming as well as other forms of mass waste all form the substrate from which digestate is produced (Simon et al. 2015, Romero-Güiza et al. 2016, Thomas and Soren 2017). Thus, anaerobic digestion not only addresses energy and fertiliser issues, but also plays a vital role in the treatment of organic waste material in the form of manure, municipal sewerage sludge and solid waste, industrial waste water and energy crops ref. Studies with digestate affirm that it is an efficient and suitable soil supplement for crop production (Ngesi 2012; Nkoa 2014). Generally, many of the properties that characterise biodigestate depend on the source from which the product is derived (Andruschkewitsch 2012) However, this has always been an assumption based on the performance of the crop rather than data that measures qualities related to the chemical composition and physiochemical nature of biodigestate (Simon et al. 2015). Before reviewing anaerobic biodigestion as a nutrient source for plants, it is useful to consider what is held to be generally true of biodigestate.

2.5.1   *Anaerobic biodigestate properties*

Biodigestate has a high pH (between 7.3 and 9), and relatively high composition of the macroelements N, P and K^+ (Nkoa 2013). The ratio of NH_4^+ to total organic N is higher than that of other forms of organic fertilisers (Nkoa 2013). The microelements include heavy metals such as copper (Cu^{2+}), Zn^{2+}, mercury (Hg^{2+}) and even Ca^{2+} as these are not degraded during the decomposition process (Nkoa 2013). Digestate generally comprises of low levels of OM and the organic C and has a lower C:N ratio is smaller in comparison to that of manure (Simon et al. 2015, Thomas et al. 2017). Biodigestate is characterised by high EC, which interferes with soil physiochemical properties (Nkoa 2013). Digestate destroys most weed seeds allowing the wide use of the organic fertiliser with ensured minimal risk of weed dispersal (Nkoa 2013). This may reduce the required use of herbicides as well as other weed control measures.

2.5.2   *Biodigestate and the soil*

Various studies report different extents to which biodigestate impacts the soil microbial community, with some even claiming that no effect is exerted by the organic fertiliser (Andruschkewitsch et al. 2012, Kouřimská, et al. 2012, Nkoa 2013, Lošák et al. 2016). The number of studies that investigate the impact of biodigestate on soil properties other than those that are chemical in nature are limited. Thus, not much is known about soil aggregate and WHC

effects. However, the low content in OM is a major concern for agronomists and soil scientists who are concerned with soil conservation. Furthermore, the N mineralisation rate is still a concern. Organic amendments tend to have an imbalanced C:N ratio leading to nitrogen immobilisation i.e. the uptake of ammonium and nitrates by microbes that makes nitrogen unavailable to plants. Other concerns that are peripheral to the agronomic value of digestate are the high costs of production and the production of harmful effluents that may prove detrimental to the environment, humans and animals. Digestate is also characterised by a high microbial population that includes microbes that are not necessarily beneficial.
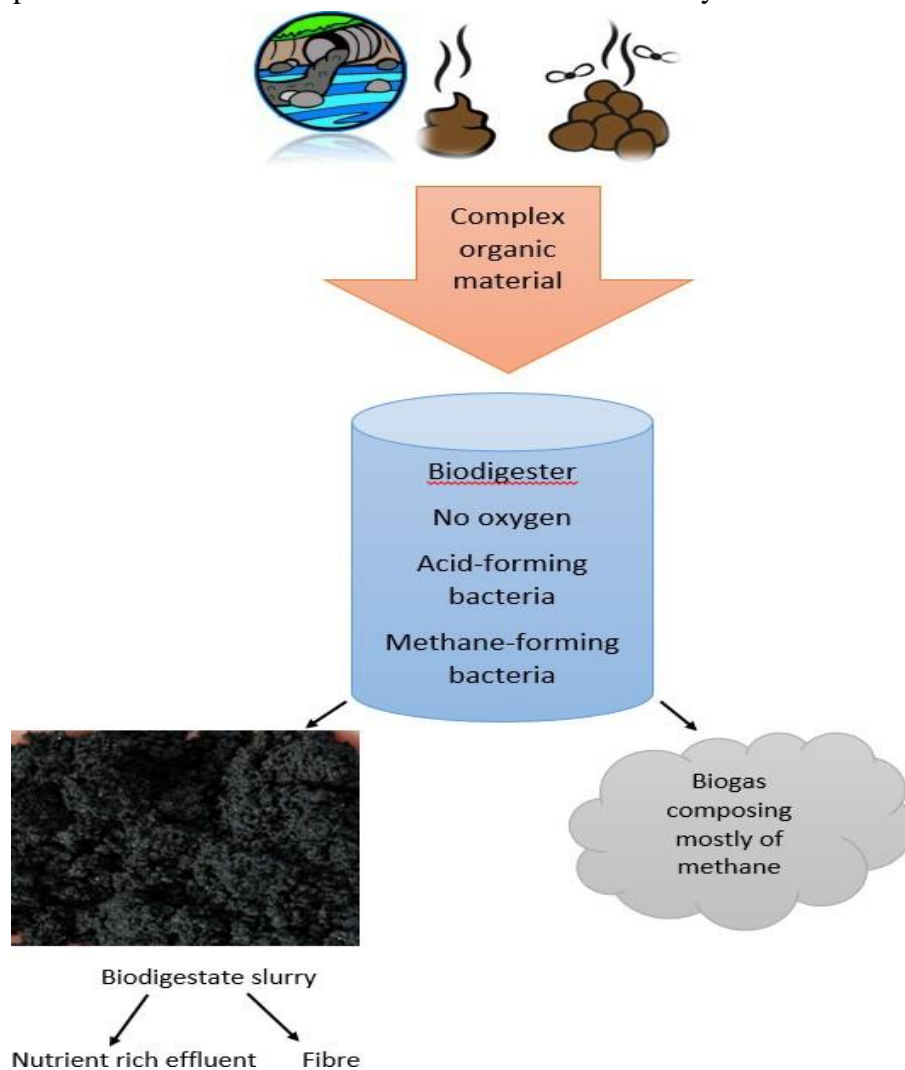
Figure 2.1. Simplified anaerobic biodigestion process. *Organic material is decomposed by methanogenic microbes in an anoxic tank. Biogas (mostly methane) is produced and the slurry is used to fertilise soil.*

2.5.3   Digestate effects on crop yield

Four major factors moderate biodigestate's influence on crop yield. These factors are the crop species, type of feedstock, any further processing of the digestate and the combination of the digestate with other forms of fertilisers.

2.5.3.1   Crop species

The most notable impact on the performance of any fertiliser is the crop species. Montemurro et al. (2015) looked at the effect of five different nutrient management systems (olive-pomace compost, organo-mineral, anaerobic digestate, mineral and no fertiliser) on the growth of three fodder crops, namely proteic peas, clover and Italian ryegrass. Different trends were observed across all the three crops (Montemurro et al. 2015). The digestate, which was produced from wine distillery wastewater, resulted in the highest production of dry matter (DM) and green forage in ryegrass. The high yields were attributed to slow N-release that suited the grass species. The compost and digestate fertilisers led to the two highest DM production levels in clover. Proteic pea yields were similar across all five fertilisers. The same was observed for melon when the same treatments were used (Lopedota et al. 2013). The uniformity in yields across the fertilisers was due to high temperatures and adequate soil moisture. These conditions facilitated high rates of N-mineralisation for all fertilisers allowing yield increases. Yield penalties in crops cultivated on anaerobic digestate soils are sometimes a result of substantial organic acid concentrations inherent to the organic amendment (Andruschkewitsch et al. 2012). Organic acids lower soil pH, cause Al^{3+} toxicity, and restrict nutrient uptake by roots.

2.5.3.2   Further processing of biodigestate

Simon et al. (2015), report that the liquid portion of cow manure digestate increased wheat yield relative to compost, mineral, digestate-straw and cattle manure fertilisers. On the other hand, various studies show that digestate slurry often leads to lower yield increases than animal manure, especially cattle manure. This implies that liquid digestate is a much better fertiliser than digestate slurry. The liquid phase of digestate slurry contains a much higher proportion of nutrients compared to the solid phase. The higher nutrient content is accompanied by a more balanced nutrient supply to the plant as the content of elements like

K$^+$ and P are higher in the liquid fraction. Thus, further processing of digestate to separate the solid and liquid fractions leads to improved fertiliser efficiency. For instance, When oyster mushrooms were cultivated on soil that was amended with a combination of straw and digestate derived from *Jute caddis*, it was found that the yield increased by 42.6% when the fertilisers were disinfected with 0.1% KMnO$_4$ plus 2% formalin solution in hot water relative to when it was just disinfected with hot water (Banik and Nandi 2014) Both of these studies (Banik and Nandi 2014, Simon et al. 2015Sindicate that further processing of biodigestate, in these cases separation into liquid and solid fractions and disinfection leads to increased yields (Figure 2.2).
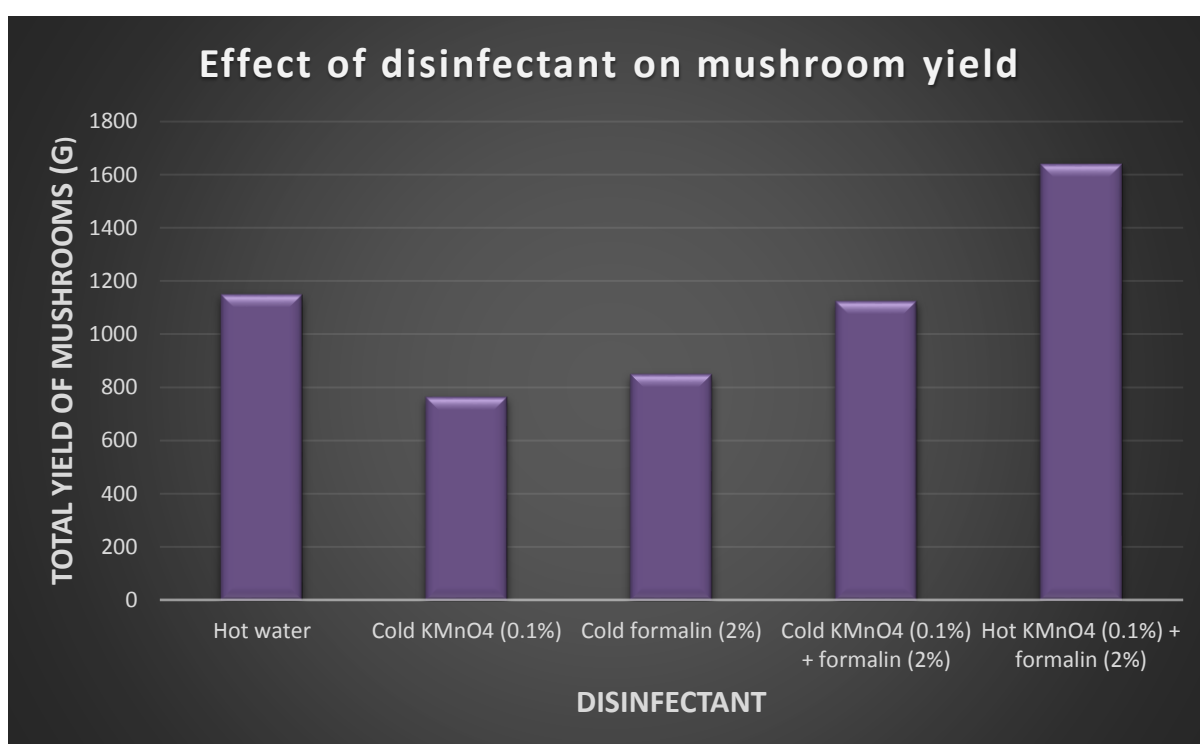
Figure 2.2. Effect of sterilising anaerobic digestate on its capacity to increase mushroom yield (Source: Simon et al. 2016).

2.5.3.3   *Type of feedstock influences digestate performance*

Andruschkewitsch et al. (2013) looked at three different grass species, *Trisetum flavescens, Lolium perenne* and *Festuca rubra* subsp. *Rubra* as feed sources for anaerobic digestate They found that digestate that was formed from the liquid fraction of grass silage resulted in higher harvestable DM yields in two of the grasses, while the other grass, *T. flavescens,* showed higher harvestable DM when the applied digestate was formed from a whole crop feedstock. *T. flavescens* is hairy and is thus more prone to aboveground tissue damage. Whole crop digestate

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properties, such as large particle size, may have facilitated this tissue damage and subsequent yield loss. Banik and Nandi's (2014) also showed the significance of digestate feedstock when the ability of digestate derived from various sources to increase mushroom yield when combined with rice straw was assessed. These results showed that digestate formed from *J. caddis* feedstock led to yields that were significantly higher than the yield of mushrooms cultivated on soils amended with digestate derived from cattle manure and poultry litter. Scrutiny of the data reveals that while *J. caddis* digestate had less nutrients than at least one of the other digestates, it had the highest C:N (Banik and Nandi 2014) This demonstrates that C:N plays an important role in plant growth and biomass accumulation.

2.5.4   Comparing anaerobic digestate to other fertilisers

Digestate improves yields when in combination with other mineral fertiliser (Kouřimská et al. 2012). Like in the case of most organic amendments, digestate is a slow-nutrient releaser (Romero-Güiza et al. 2016).The combined effect of digestate and mineral fertiliser, which makes nutrients readily available, may ensure that crops have a more constant supply of nutrients ref. However, digestate compares poorly to other organic amendments (Montemurro et al. 2010). In a three-year study by Montemurro et al. (2010), it was shown that when the yield of lettuce grown under five different nutrient management regimes was monitored and recorded on an annual basis, digestate outperformed the other fertilisers in the year in which rain distribution was markedly uneven. A plausible explanation may be that biodigestate mitigates leaching in the soil by increasing WHC or increasing the portion of water-stable aggregates in the soil. This leaves enough N available for uptake in the soil. However, evidence is inconclusive and more research is needed to illuminate our understanding. In addition, digestate drastically reduced lettuce in the following years owing to an imbalance in its nutrient composition (Montemurro et al. 2010).

2.6   Nutrition

Few studies have investigated the link between fertilisers and a plant's fruiting body quality and nutrition. The reduction of N supplementation in soil decreases toxicity by lowering NO_3^- accumulation in crops (Samater et al. 1998). Other than that, not much is known about the effects of fertiliser regime on crop quality and the relatively few studies that exist are contradictory. It was proposed that supplemental K^+ in fertiliser formulations could increase starch in potato tubers, but subsequent evidence could not corroborate this (Baniuniene and

Zekaite 2008). Quality enhancement also depends on the type of nutrient under consideration. Heeb et al. (2006) found that mineral fertilisers increased sugar content in tomatoes, while organic fertilisers increased acidity. Ascorbic acid and lycopene were unaffected. Again, Ilupej et al. (2015) obtained different results that showed that lycopene content in tomatoes increased with organic fertiliser use. While it is difficult to ascertain whether organic or inorganic fertilisers enhance nutrition, it is evident that a combination of the two leads to higher nutritional value (IIjebu et al. 2015).

2.6.1 *Biochar and crop nutrition*

Biochar is associated with an increase in vitamin C in peppers when N content is sufficient (Yao et al. 2015). The organic material can also reduce toxicity in turnips by displacing polycyclic aromatic hydrocarbons (PAHs) from soil binding sites (Khan et al. 2015). PAHs in contaminated soil accumulate in crops and pose a threat to human health (Khan et a. 2015). Biochar has a higher adsorptive capacity than soil (Takaya 2016). This allows for the mass movement of PAHs in polluted water to these biochar sites rather than soil adsorptive sites (Dutta et al.2017) . The mechanism by which biochar ensures reduced potentially toxic elements in crops is reportedly more complex as it depends on many aspects. Biochar also reduces barley's uptake of cadmium (Cd) (Moreno-Jiménez et al. 2016). Studies are contradictory and more research remains to be done before any concrete conclusions can be made about biochar's ability to influence the nutrient content and quality of crops.

2.6.2 *Anaerobic biodigestate and crop quality*

Anaerobic digestate does not generally affect crop quality (Losak et al. 2010; Leogrande et al. 2014). However, Banik and Nandi (2004) demonstrated that soil amendment with a mixture of digestate and straw improved the protein content, decreased carbohydrate levels and increased mineral content in oyster mushrooms. Furthermore, at least one other study shows a positive correlation between plant-based digestate and protein content than the correlation between poultry manure-based digestate and protein (Banik and Nandi 2014). Plant material has more N than poultry manure, which is richer in P. Nitrogen is the most essential mineral for amino acid biosynthesis (Guedes et al. 2010).

2.7   Concluding remarks

Organic amendments improve soil properties far beyond the capacity of chemical fertilisers, while a combination of both results in yields that are comparable to sole inorganic fertilisers at high rates. The upscaling of organic amendment practices requires agronomists to conduct further studies, especially in the case of novel organic amendments like biochar and anaerobic digestate. Furthermore, scientists need to optimise the nutrient balance of organic amendments like compost and biochar. While no balanced formulations exist for anaerobic digestate, biochar and compost, farmers should consider factors like feedstock, soil composition, crop species and their specific requirements, etc. when deciding which type of amendment to use. This will go a long way in ensuring that soil nutrient management that are both exclusively organic and mixed are sustainable in terms of soil fertility and yield.

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CHAPTER 3

Soil fertility and various nutrient management regimes

3.1   Abstract

Soil fertility is a growing concern amongst agriculturists. Inundating the soil with inorganic fertilisers is no longer a widely accepted norm with agronomists exploring more alternative soil conditioning practices that are more sustainable and conducive to soil conservation and the maintenance and improvement of the health of the environment. The study investigated the effect of 6 different soil nutrient management regimes on soil fertility. The treatment were as follows; unfertilised soil as control; 100% CM (NPK applied at 100 kgN.ha^{-1} in a 2:3:2 formulation); a sustainable, integrated co-application of biochar applied at a 2% rate and inorganic NPK (2:3:2) applied at a 50 kgN.ha^{-1} rate (2% BC + 50% CM); food waste compost (FWC), commercial organic fertiliser (COF) also applied at a 100 kgN.ha^{-1} and farmyard manure anaerobic digestate application of the liquid fertiliser (MAD). The results revealed that soil enriched with FWC had the highest mineral content and carbon (C) composition, followed by the integrated regime and 100% CM. Assimilable nitrogen (N) content, was however, highest under the 100% CM and COF regime. Optimal CEC, pH and acidity levels were observed in the FWC and 2% BC + 50% CM and the poorest levels were evident in the COF and MAD treatment. The sole chemical fertiliser treatment resulted in soil with 0.73 cmol.kg^{-1} concentration, which was significantly higher than the 0.00 cmol.kg^{-1} acidity level observed in the FWC, 2% BC + 50% CM and MAD regimes. Additionally, 100% CM and MAD decreased the pH to level below the control. CEC was lowest in the MAD regime (4.23 cmol.kg^{-1}) and highest in FWC (5.96 cmol.kg^{-1}). Water-holding capacity did not change with the application of different fertilisers. This was also the case for the soil aerobic microbe population and fungi population. Although the COF treatment enriched aerobic population and the chemical fertilisers enhanced fungal population the most. The 2% BC + 50% CM and MAD treatment reduced aerobic microbe populations, while COF and 2% BC + 50% CM reduced fungal populations. Although FWC resulted in the maximal soil mineral content, the nutrients appeared to be in excess. This, in combination with nutrient imbalances may reduce soil fertility and hinder nutrient uptake in crops resulting in suboptimal yields. FWC need to be applied in a calculated and formulated manner in order to obtain the best benefits from its utilization. 2% BC + 50% CM favourable effect and moderate nutrient composition, balanced by the supplementation of a balanced NPK fertiliser, make it a highly sustainable and suitable

alternative soil nutrient management regime. The liming effect of biochar counteracts the acidity-inducing and pH-lowering effect of chemical fertilisers. According to this study, farmyard manure-derived anaerobic digestate is not an adequate alternative for inorganic fertilisers. Commercial organic fertiliser must be applied at appropriate times and in possibly higher rates than inorganic fertiliser in order to increase their capacity to improve soil fertility.

3.2   Introduction

Soil fertility is essential in securing sustainable and sufficient crop production (Bationo and Mokwunye 1991, Yang 2006). Thus, land workers have to ensure that they implement practices that will best nurture the soil and the environment, while contributing substantially to food production. The chosen mode of soil fertilization should consider soil physical, chemical and biological properties (Paul and Mannan 2007). Organic and inorganic fertilisers have differing effects on soil fertility and quality (Mugwe et al. 2009). Responses associated with physical properties like aggregation and bulk density are gradual when compared to chemical and biological properties (Bhaduri et al. 2017). It is almost futile to assess physical properties after one season of organic and inorganic crop production (Doran and Zeiss 2000). Mineral content, pH, cation exchange capacity (CEC) and microbial population counts are a faster indicator of soil nutrient management systems (Doran and Zeiss 2000). Soil organic matter (SOM) is an overarching property in soil quality (Tiessen et al. 1994). Because of this, various properties can be used to track its relative abundance across different fertilization regimes (Larney and Angers 2012).

3.2.1   *Physicochemical soil properties*

Organic amendments increase available N, P, K in the soil (El-Hamid et al. 2013). Compost can increase N content by 102.54%, P, by 48.23% and K by 33.09% in soil when applied at a rate of 7.5 t.ha^{-1} (El-Hamid et al. 2013)ref. Compost is inherently high in organic matter (Rivero et al. 2004)ref. As a result, it increases CEC in soil (do Carmo et al. 2016). Cations like Ca^{2+}, Mg^{2+}, Mn^{2+}, Zn^{2+} and K^+ form during the decomposition. The combination of improved CEC leads to a higher mineral richness in the soil (Glaser et al. 2002, Ozores-Hampton et al. 2011). Organic amendments like biochar and manure tend to increase pH due mostly to the addition of anions to the soil followed by a decrease in free H^+, the conversion of anions to CO_2, or their innately alkaline nature (Ritchie and Dolling 1985, Larney and Angers 2012, Mandal et al. 2013); however, the converse can be true. For instance, the addition of compost to carbonated

soil can lead to a process called decarbonization or the reduction of carbon that confers acidity (Hattab et al. 2014). A higher rate also leads to higher water holding capacity (WHC), with differences not being as variable as those observed in chemical and biological properties (Vengadaramana and Jashothan 2012). This is due to improved soil structure and SOM, which holds water better than other material such as sand, silt and clay. It influences porosity through the formation of elongated pores, altering the number of pores and the interconnections between pores (Esmaeilzadeh and Ahangar 2014). The charges and overall CEC on organic matter mean that it can bind soil aggregates and improve its ability to hold and store water (Naeth et al. 1991). Furthermore, SOM acts as food for micro-organisms and large soil organisms that facilitate macro and micro-pore formation during their activity (Lehman et al. 2015).

3.2.2 *Microbes and soil organic matter*

Microbial and fungal populations increase with an increase in organic matter (Cobb et al. 2017) Not only do bacteria and fungi carry out nutrient cycling and transformation that improve structure and fertility in the soil, but they improves crops' ability to cope with stress in the environment (Pankhurst et al. 1995). Ozores-Hampton et al. (2011) claim that microbes optimize nutrient uptake, enhance drought tolerance and reduce disease incidence. This chapter discusses the impact of chemical fertilisers and alternative sustainable and organic nutrient regimes on soil fertility.

3.3   Objectives

This part of the study assessed:

a)   The mineral properties of biochar and compost.

b)   The soil physicochemical properties (pH, acidity, cation exchange capacity and water-holding capacity) in response to no fertilization, 100 $kgN.ha^{-1}$ in an NPK (2:3:2) inorganic fertiliser (100 % CM), a co-application of biochar at rate of 2% (w/w) and half the inorganic NPK used in the 100% CM fertiliser regime (2% BC + 50% CM), food waste compost (FWC), commercial organic fertiliser (COF) and manure anaerobic digestate (MAD).

c)   The fungal population and aerobic microbe populations in response to different soil nutrient treatments.

3.4   Methods and Material

3.4.1   *Experimental site*

The study was conducted on Welgevallen Experimental Farm, Department of Agronomy, Stellenbosch University, South Africa with the co-ordinates, 33.9427° S, 18.8664° E, on a 900 m^2 field. The area was previously under organic use. The experiment took place from December 2016 to June 2017.

3.4.2   *Site characteristics*

3.4.2.1   *Climatic conditions*

The climate is Mediterranean and the mean annual rainfall is 802 mm, with 80% falling during the winter months. The average temperature is 16.4 °C. The minimum and maximum temperatures in December 2016 were 11 °C and 29 °C, respectively. In January 2017, the minimum temperature was 13 °C and the maximum, 29 °C. February was the hottest month with a low temperature of 15 °C and a high of 34 °C. The temperature minimum dropped to 13 °C in March, while the maximum increased to 38 °C. Temperatures continued to drop in April to a low and high 9 °C and 36 °C, respectively. In May, the temperature minimum was 6 °C and temperature 31 °C. Mean monthly relative humidity ranged from 63% to 72% during this period. There was little to no rainfall during this 6 months period.

3.4.2.2   *Soil characteristics*

The soil was sandy loam, pH 5.31 and the acidity 0.38 cmol.kg^{-1}. The total cation count was 5.65 cmol.kg^{-1}. Soil C content was 1.25%; Ca and Mg content were 3.45 cmol.kg^{-1} and 1.19 cmol.kg^{-1} respectively. Na$^+$, P, Cu^{2+}, Zn^{2+}, Mn^{2+}, B, S and content, measured in mg.kg^{-1}, were 40; 206.17; 1.60; 4.26; 23.67; 0.22; 8.6 respectively.

3.4.3   *Experimental design*

The experiment was set out in a randomised complete block design layout with seven plots per block. The six treatments used in the experiment each had four replicates to coincide with the four blocks.

3.4.4   *Fertiliser regimes*

The control was unfertilised soil. There was a 100% CM treatment that consisted of a 100 $kgN.ha^{-1}$ application in an NPK (2:3:2) formulation; a 2% BC +50% CM treatment that represented a co-application of half the recommended rate of 100 $kgN.ha^{-1}$ i.e. 50 $kgN.ha^{-1}$ NPK (2:3:2) and woody plant biochar applied at 2% on a w/w basis; a FWC treatment consisting of 30% food waste compost and 70% dairy manure; a COF treatment consisting of commercial organic Talborne Vitagrow® fertiliser with N:P:K formulation of 2:3:2 applied at the same rate as the inorganic NPK fertiliser and MAD, which was anaerobic digestate derived from farmyard manure.

3.4.5   *Preparation of organic amendments*
3.4.5.1   *Manure anaerobic digestate*

Farmyard manure was placed into a sealed tank with little to no oxygen. Anaerobic microbes decomposed the organic material to produce digestate slurry and a liquid fraction that was used to fertigate the soil.

3.4.5.2   *Food waste compost*

Food waste compost was collected from residents in the Stellenboch vicinity and was composted on the Coetzenburg Mountain over several months.

3.4.5.3   *Biochar*

Woody plant material, mostly from dead tree trunks and woody plants, was collected and placed into a drum. The drum was not sealed, but woody material placed on top of the burning heap beneath restricted the oxygen to the rest of the burning material beneath. This created a relatively anoxic environment for the burning wood beneath. The burnt material was

activated by adding droplets of water that cooled off the material and stopped enzymatic reactions. This practice was suggested by a local biochar producer.

3.4.6   Soil bed preparation

The soil was tilled and each plot in each block was divided to form three ridges that were 60 cm apart. The length of the ridges was 4 m and the width 90 cm. The height was 25 cm. Plots were 40 cm apart from each other in the blocks. The blocks were a metre apart from each other.

3.4.7   Fertilisation

The NPK fertiliser in the 100% CM was applied in a split fashion. A fifth of the fertiliser was applied at time zero (at the transplanting of a sweet potato crop) and the rest was applied six weeks after the first increment. The same principle was applied in the integrated 2% BC + 50% CM and COF treatments, where a fifth was applied at time zero and the rest six weeks later. This was to reduce variation due to the timing of the applications. Seventeen litres of MAD organic liquid fertilisers were applied at 8 weeks after the growing season to prevent shoot burn in the transplanted sweet potato crop. Five centimetres of food waste compost (FWC) were applied to the soil at time zero. The soil was mixed in. Biochar was mixed in with the first 25 cm of soil at a rate of 2% on a weight per weight basis with fresh soil.

3.4.8   Soil and organic material sampling and analysis

Soil samples were collected at the end of the growing season (May 2017), but before harvest of the sweet potato crop. Samples were taken 10-15 cm deep and were analysed for pH, CEC, acidity and mineral content at Bemlab ® and Elsenburg Agricultural College.

One hundred and twenty grams of soil were dried at 60°C and placed into pre-weight containers. Thirty millilitres were added to the soils. The containers along with the soil inside were weighed three days after. The dry weight was subtracted from the wet weight of the containers and soil. Percentage WHC was determined by dividing this value by the dry soil weight and multiplying by a hundred.

The method used to determine cation exchange capacity was the ammonium acetate ($C_2H_7NO_2$) method (Chapman 1965), while pH was determined using the KCl and pH meter method (Reeuwijk 2002). Soil resistance was measured using the penetrometer method as detailed by

Herrick and Jones (2002). The total number of cations was computed by adding all the measured cations together. The hydrometer method adapted from Gee and Bauder (1979, 1986). Total C and S were determined using the Dumas method and a CHNOS analyser (Shea and Walts1939). The phenol-hypochlorite reaction method was used to determine total soil NH_4^+ (Weatherburn 1967), while a KCl method with a colometric reaction was used for the analysis of soil NO_3- (Hood-Nowotny et al. 2010). Ca^{2+}, Mg^{2+}, Na^+ and K^+ were extracted using $C_2H_7NO_2$ followed by a colometric reaction (Reeuwijk et al. 2002). An acid digestion reaction with $Na_2CO_3^-$ was used to determine total soil Fe^{2+}, Mn^{2+}, Cu^{2+} and Zn^{2+} (Smith and Bain 1982, Haluschak 2006). P was determined by using the citric acid method (Thompson 1995). The substrate-induced respiration method was used to determine aerobic bacterial populations (Anderson and Domsch 1978). Fungal biomass was indirectly measured by using the amount of ergosterol to indirectly determine the carbon content (Newell and Fallon 1991, Baath 2001).

3.4.9 *Statistical analyses*

A one-way analysis of variance (ANOVA) method was used to analyse the data on Statistica® version 13.2 software. The Tukey HSD (Honest Significant Difference) post-hoc test was used to separate means at a significant level of $P < 0.05$. This was selected over the Fisher LSD (Least Significant Difference) based on the criteria of the number of treatments and the elimination of statistical errors.

3.5 Results

3.5.1 *Compost and biochar mineral content*

Compost had higher mineral composition and content than biochar (Table 3.1). Compost had more or twice the concentration of NH_4, P, K, Fe, Cu, Zn, Mn, B and Al than biochar, while Ca, Mg and Na were comparable (Table 3.1).

Table 3.1 Mineral content and composition in food waste compost and biochar derived from woody plant material. *The values on the left of the ± show the standard deviation. CV% = the coefficient of variation. No ANOVA analyses were conducted on mineral composition of the organic material.*

Mineral	Compost	Biochar	CV %
Ammonium %	1.72 ± 0.14	0.38 ± 0.05	10.63
Phosphorus %	0.48 ± 0.03	0.16 ± 0.02	9.40
Potassium %	1.51 ± 0.11	0.93 ± 0.02	4.45
Calcium %	3.60 ± 0.72	3.62 ± 0.40	15.49
Magnesium %	0.38 ± 0.03	0.35 ± 0.06	12.00
Sodium (mg/kg)	1 390.00 ± 50.47	1 466.00 ± 125.28	6.09
Iron (mg/kg)	12 486.67 ± 2118.64	4 394.33 ± 4 601.88	60.85
Copper (mg/kg)	22.63 ± 2.73	12.05 ± 11.21	52.59
Zinc (mg/kg)	137.17 ± 12.12	42.92 ± 30.56	40.02
Manganese (mg/kg)	218.80 ± 21.02	88.30 ± 50.86	33.60
Boron (mg/kg)	56.26 ± 2.88	35.40 ± 2.41	6.19
Aluminium (mg/kg)	10 700.00 ± 1 473.92	6 666.67 ± 4 636.09	41.65

3.5.2   Soil physicochemical properties

The pH range for sweet potato is 5.6 to 6.5 (Lebot 2009). Unfertilised soil had pH levels that were 0.02 units below the lowest pH that allows sweet potato growth (Table 3.2). The 100% CM and COF treatments reduced soil pH to levels below those found in the unfertilised control (Table 3.2). All three treatments showed the highest exchangeable acidity with the 100% CM conferring 0.73 $cmol.kg^{-1}$ to the soil, COF 0.43 $cmol.kg^{-1}$ and the unfertilised control 0.15 $cmol.kg^{-1}$ (Table 3.2). Not only did the remaining treatments, 2% BC + 50% CM, FWC and MAD increase the pH, they also resulted in soils that showed little to no acidity (Table 3.2). The FWC treatment had the highest pH (Table 3.2). The FWC treatment showed significantly higher (P < 0.05) pH than all the treatments except for 2% BC + 50% CM, soils fertilised with 100% CM and COF were also significantly lower in pH than soil treated with 2% BC +50 %CM (Table 3.2). Acidity was significantly higher in 100% CM soils compared to all treatments with the exception of soils supplemented with COF (Table 3.2). COF soils also showed significantly higher pH levels than soils amended with the FWC, MAD and 2% BC + 50% CM. The commercial organic fertiliser reduced CEC to levels below the control. The greatest CEC was observed in soils amended with food waste compost. Only FWC soils showed a significance difference to COF soils. Water-holding capacity was similar across all treatments. The lowest recorded WHC was observed in soils amended with 2% BC + 50 % CM, while the highest was observed with 100% CM and FWC amended soils.

Table 3.2. Soil physicochemical properties at the end of the summer growing season. *The values on the left of the $\pm$ show the standard deviation. CV% = coefficient of variation. The p-value is given at a significance level of 0.05. NS = no significant difference.The Tukey post hoc test was used to determine the specific significant difference between means. Significant differences are denoted by the alphabet superscripts. Control refers to unfertilised soil; 100 % CM is the full recommended NPK (2:3:2) on a basis of 100 kgN.ha^{-1}; 2% BC + 50% CM is the 2% biochar rate (w/w) and half the recommended NPK rate; COF is the commercial organic fertiliser and MAD is the manure anaerobic digestate.*

Property	pH	Acidity (cmol.kg^{-1})	CEC (pH7) (cmol.kg^{-1})	WHC %
Control	5.58 ± 0.17^{bc}	0.15 ± 0.29^{bc}	4.91 ± 0.56^{ab}	30.87 ± 0.56^{a}
100% CM	5.18 ± 0.17^{c}	0.73 ± 0.09^{a}	5.02 ± 0.42^{ab}	31.44 ± 0.42^{a}
2% BC + 50% CM	6.23 ± 0.41^{ab}	0.00 ± 0.00^{c}	5.14 ± 0.25^{ab}	29.09 ± 0.67^{a}
FWC	6.50 ± 0.42^{a}	0.00 ± 0.00^{c}	5.96 ± 0.40^{a}	31.44 ± 0.50^{a}
COF	5.53 ± 0.32^{c}	0.43 ± 0.29^{ab}	4.23 ± 0.61^{b}	31.42 ± 0.34^{a}
MAD	5.70 ± 0.23^{bc}	0.00 ± 0.00^{c}	5.18 ± 0.31^{ab}	31.28 ± 0.54^{a}
CV%	4.89	46.51	8.64	3.76
p-value (0.05)	0.000	0.000	0.013	NS

3.5.3   *Soil mineral composition*

NH_4^+ and NO_3^- concentrations were highest in soils fertilised 100% CM (Table 3.3), followed by soils supplemented with COF. The MAD treatment maintained NH_4 content at the same level as the control and reduced NO^{3-} by 0.22 ppm. The integrated 2% BC + 50% CM treatment resulted in higher soil NH_4 levels than FWC, but FWC increased NO^{3-} levels more than the 2 BC + 50% CM treatment. The rest of the minerals showed a more uniform trend with FWC soils showing a significantly higher ($P < 0.05$) in total cation count, K^+, P, B and Mn^{2+} content than all the other soils placed under different nutrient management regimes (Table 3.4). Soil Ca^{2+}, Mg^{2+}, C content was also significantly higher in FWC soils compared to the remaining soils with the exception of soils amended with 2% BC + 50% CM (Table 3.3, 3.5). Na^+ was however, significantly lower ($P < 0.05$) in unfertilised soils and soils supplemented with COF and 100% CM compared to soils amended with FWC (Table 3.4). On the other hand the Zn^{2+} concentration was significantly lower in COF, MAD and control soils than FWC soils. Soil S content was significantly higher in the 100 %C and 2% B + 50% CM treatments than in the control and MAD treatments. Cu^{2+} showed no significant differences between the treatments. The highest concentration was recorded in 2% BC + 50% CM treatments and the lowest in the 100% CM. For the rest of the minerals, MAD reduced Ca^{2+}, K^+, P, Zn^{2+} and C content to even lower levels than the control (Table 3.3 – 3.6). In addition, both the COF and MAD treatments resulted in soils with an even lower B content than control soils. COF soils had the lowest Mg^{2+} and Na^+ content. These were also below the concentrations in unfertilised soil. Control, followed by MAD soils had the least S (Table 3.6).

Table 3.3. Soil mineral content under different soil nutrient management systems. *The values on the left of the $\pm$ show the standard deviation. CV% = coefficient of variation. The p-value is given at a significance level of 0.05. The Tukey post hoc test was used to determine the specific significant difference between means. Significant differences are denoted by the alphabet superscripts. Control refers to unfertilised soil; 100 % CM is the full recommended NPK (2:3:2) on a basis of 100 kgN.ha^{-1}; 2% BC + 50% CM is the 2% biochar rate (w/w) and half the recommended NPK rate; COF is the commercial organic fertiliser and MAD is the manure anaerobic digestate.*

Mineral	NH_4^+ ppm	NO_3^- ppm	Total cations (cmol.kg^{-1})	Ca^{2+} (cmol.kg^{-1})
Control	0.67 ± 0.03^b	0.55 ± 0.35^b	5.81 ± 0.81^b	3.73 ± 0.48^b
100% CM	1.15 ± 0.24^a	1.79 ± 0.76^a	7.01 ± 0.71^b	4.33 ± 0.54^b
2% BC + 50% CM	0.84 ± 0.20^{ab}	0.86 ± 0.72^{ab}	7.68 ± 0.63^b	5.09 ± 0.51^{ab}
FWC	0.69 ± 0.08^b	$0.97 + 0.16^{ab}$	$26.93 + 20.18^a$	21.68 ± 18.12^a
COF	0.91 ± 0.15^{ab}	1.14 ± 0.44^{ab}	6.78 ± 1.28^b	4.22 ± 0.97^b

MAD	0.67 ± 0.07^b	0.33 ± 0.13^b	5.65 ± 0.70^b	3.67 ± 0.44^b
CV %	14.80	47.00	23.09	25.66
p-value (0.05)	0.001	0.010	0.012	0.017

Table 3.4. Soil mineral content under different soil nutrient management systems. *The values on the left of the $\pm$ show the standard deviation. CV% = coefficient of variation. The p-value is given at a significance level of 0.05. The Tukey post hoc test was used to determine the specific significant difference between means. Significant differences are denoted by the alphabet superscripts. Control refers to unfertilised soil; 100 % CM is the full recommended NPK (2:3:2) on a basis of 100 kgN.ha^{-1}; 2% BC + 50% CM is the 2% biochar rate (w/w) and half the recommended NPK rate; COF is the commercial organic fertiliser and MAD is the manure anaerobic digestate.*

Mineral	Mg^{2+} (cmol.kg^{-1})	K^+ (mg.kg^{-1})	Na^+ (mg.kg^{-1})	P (mg.kg^{-1})
Control	1.31 ± 0.21^b	109.50 ± 66.03^b	78.75 ± 9.61^b	211.25 ± 29.13^b
100% CM	1.23 ± 0.30^b	145.75 ± 15.20^b	79.50 ± 15.70^b	285.25 ± 24.09^b
2% BC + 50% CM	1.44 ± 0.25^{ab}	277.00 ± 45.61^b	99.75 ± 17.21^{ab}	290.00 ± 45.66^b
FWC	2.71 ± 1.25^a	754.25 ± 296.61^a	138.5 ± 35.11^a	473.00 ± 169.96^a
COF	1.36 ± 0.49^b	173.25 ± 41.05^b	76.25 ± 20.63^b	254.25 ± 35.12^b
MAD	1.31 ± 0.21^b	102.5 ± 31.27^b	94.00 ± 11.66^{ab}	203.50 ± 16.59^b
CV %	26.01	27.78	19.00	15.98
p-value (0.05)	0.015	0.000	0.003	0.001

Table 3.5. Soil micronutrient content under different soil nutrient management systems. *The values on the left of the $\pm$ show the standard deviation. CV% = coefficient of variation. The p-value is given at a significance level of 0.05. The Tukey post hoc test was used to determine the specific significant difference between means. Significant differences are denoted by the alphabet superscripts. Control refers to unfertilised soil; 100 % CM is the full recommended NPK (2:3:2) on a basis of 100 kgN.ha^{-1}; 2% BC + 50% CM is the 2% biochar rate (w/w) and half the recommended NPK rate; COF is the commercial organic fertiliser and MAD is the manure anaerobic digestate.*

Mineral	Cu^{2+}(mg.kg^{-1})	Zn^{2+} (mg.kg^{-1})	Mn^{2+} (mg.kg^{-1})	B (mg.kg^{-1})
Control	1.75 ± 0.31^a	3.88 ± 1.22^b	21.59 ± 1.40^b	0.17 ± 0.09^b
100% CM	1.55 ± 0.26^a	7.18 ± 0.89^{ab}	23.96 ± 3.01^b	0.13 ± 0.09^b
2% BC + 50% CM	1.78 ± 0.25^a	8.4 ± 4.05^{ab}	25.56 ± 3.16^b	0.2 ± 0.30^b
FWC	1.7 ± 0.11^a	13.94 ± 6.29^a	33.98 ± 4.66^a	0.66 ± 0.25^a
COF	1.64 ± 0.30^a	4.12 ± 0.73^b	24.19 ± 5.88^b	0.2 ± 0.02^b
MAD	1.76 ± 0.21^a	3.86 ± 1.25^b	22.95 ± 1.59^b	0.13 ± 0.09^b
CV %	14.05	31.26	20.66	16.99
p-value (0.05)	NS	0.002	0.002	0.000

Table 3.6. Soil carbon (C) and sulphur (S) content under different soil nutrient management systems..
The values on the left of the ± show the standard deviation. CV% = coefficient of variation. The Tukey post hoc test was used to determine the specific significant difference between means. Significant differences are denoted by the alphabet superscripts. Control refers to unfertilised soil; 100 % CM is the full recommended NPK (2:3:2) on a basis of 100 kgN.ha⁻¹; 2% BC + 50% CM is the 2% biochar rate (w/w) and half the recommended NPK rate; COF is the commercial organic fertiliser and MAD is the manure anaerobic digestate.

Fertiliser regime	C (%)	S (mg.kg⁻¹)
Control	1.01 ± 0.08^b	9.53 ± 2.59^b
100% CM	1.14 ± 0.13^b	29.85 ± 4.64^a
2% BC + 50% CM	1.22 ± 0.33^{ab}	26.25 ± 10.50^a
FWC	1.9 ± 0.35^a	18.75 ± 2.75^{ab}
COF	1.13 ± 0.16^b	18.5 ± 5.00^{ab}
MAD	0.79 ± 0.57^b	10.64 ± 2.04^b
CV %	25.20	23.94
p-value (0.05)	0.003	0.000

3.5.4 *Soil biological properties*

No significant differences ($P < 0.05$) were observed in aerobic microbe and fungi population counts. The 2% BC + 50% CM and MAD treatments resulted in soils with the lowest aerobic microbe populations (Figure 3.1), while COF soils showed the highest populations. FWC and 100% CM soils showed similar populations. Fungi populations were densest under the 100% CM soil nutrient regime and lowest under the control (Figure 3.2), 2% BC + 50% CM and COF. FWC and MAD showed intermediate populations.
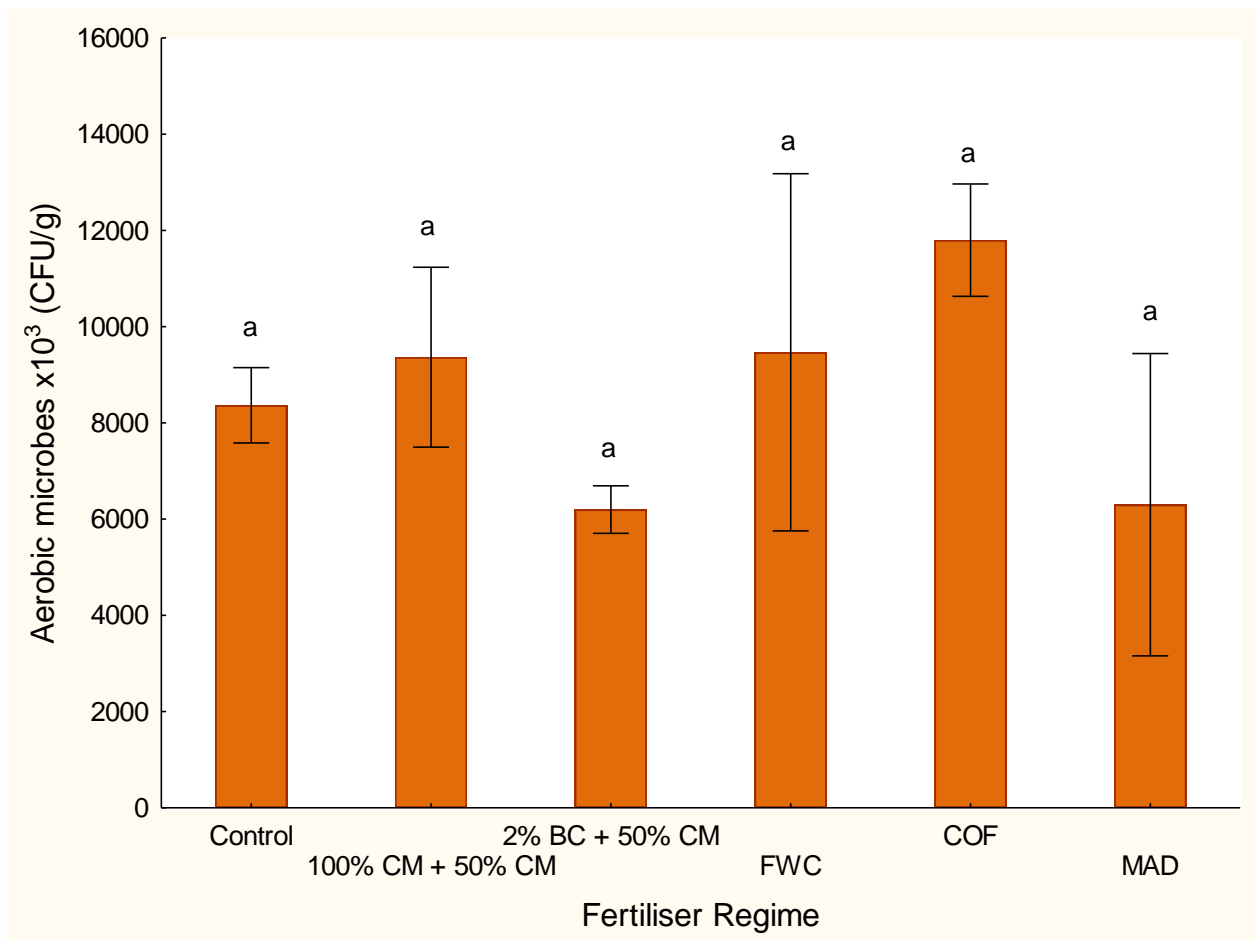
Figure 3.1. Aerobic microbe population under different soil nutrient management regimes. *The bars show the mean aerobic microbe populations, while the whiskers indicate the standard error of the mean. No significant differences were observed between the treatments. The control is the unfertilised soil; 100 % CM is the full recommended NPK (2:3:2) on a basis of kg N.ha-1; 2% BC + 50% CM is the 2% biochar rate (w/w) and half the recommended NPK rate; COF is the commercial organic fertiliser and MAD is the manure anaerobic digestate.*

Figure 3.2. Fungi populations under different soil nutrient management regimes. *The bars show the mean fungi populations, while the whiskers indicate the standard error of the mean. No significant differences were observed between the treatments. The control is the unfertilised soil; 100 % CM is the full recommended NPK (2:3:2) on a basis of 100 kgN.ha⁻¹; 2% BC + 50% CM is the 2% biochar rate (w/w) and half the recommended NPK rate; COF is the commercial organic fertiliser and MAD is the manure anaerobic digestate.*
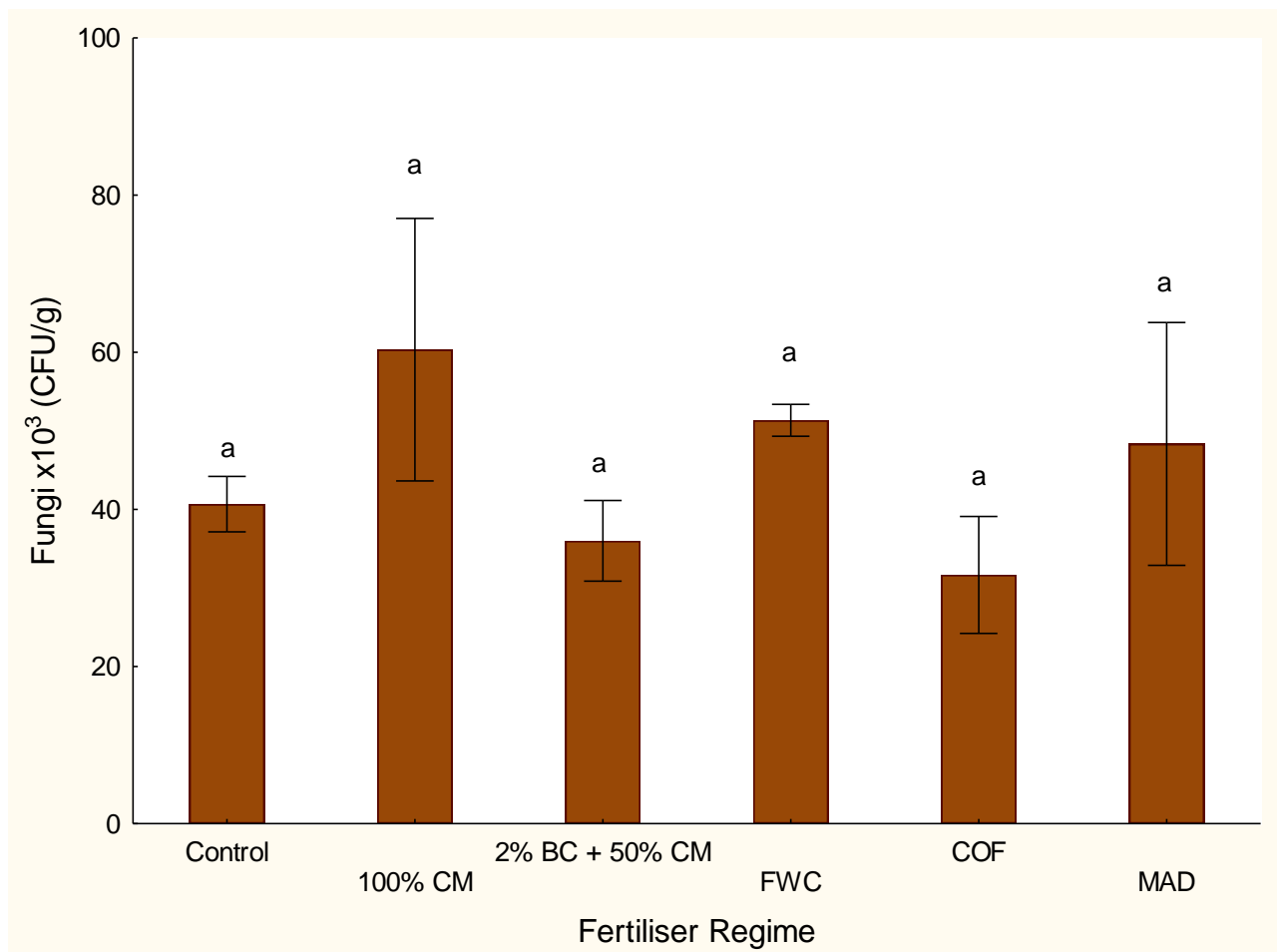
3.6   Discussion

3.6.1   *Food waste compost analyses*

Food waste compost contained a much richer mineral content and total cation count than biochar, which may have resulted in crop yield decreases. Excess nutrients or an imbalanced nutrient composition can hinder the availability and uptake of certain nutrients (Bindraban et al. 2015). While an imbalance in nutrients is reduced by the NPK fertiliser in the integrated 2% BC + 50% CM treatment, the same cannot be said for the sole organic FWC amendment. The relatively high NH_4^+ in the FWC fertiliser regime is advantageous for soils and vegetative growth, although biochar's 77.91 % lower NH_4^+ content is ideal because it was applied in conjunction with an industrial inorganic fertiliser. Adding ammonium to the soil increases the bioavailability and uptake of some minerals like phosphorus (Riley and Barber 1971). On the other hand, FWC's higher NH_4^+ content may result in soils that are enriched with the nutrient

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for longer periods (Gil et al. 2008). Thus, FWC will have a stronger positive residual effect on crop vegetative growth. P and K^+ content were are also higher in the compost. These are both essential macronutrients that play a vital role in sweet potato vegetative and tuber growth (Juan-wei et al. 2001, Kareem et al. 2013, Dumbaya et al. 2016). Their relatively high content in FWC in combination with slow nutrient release are also conducive to a strong long lasting effect on soil nutrient content and crop subsequent crop growth – possibly more than biochar whose content is lower. This effect could however be attenuated by excess cations and a nutrient imbalance (Bindraban et al. 2015).

3.6.2   *Soil physicochemical and mineral composition properties*

Adequate soil pH, acidity and CEC are essential for nutrient release and subsequent uptake in plants (Schoonover and Crim 2015). The FWC and 2% BC + 50% CM treatments resulted in optimal CEC, pH and acidity in the soils. These contribute significantly to nutrient availability and lead to positive crop growth and yield responses (Schoonover and Crim 2015). FWC's liming effect may be due to the Ca^{2+} content, which was observed to be particularly high in soils treated with this organic amendment (Naramabuye and Haynes 2006). This also has remarkable implications for vegetative crop growth (Opala 2017). The COF treatment performed poorly, with soils showing the lowest CEC and pH and the second highest acidity levels. This may result in yield penalties especially considering the relatively low mineral composition. Concurrently, FWC's physicochemical properties do not necessarily lead to the most fertile soil, as the high nutrient composition of some nutrients like Na^+ may hinder the uptake of other cations such as K^+ (ten Hoopen et al. 2010). This has vast implications for tuber yield as K^+ has a direct role in tuber growth (Jian-wei et al. 2001). Similarly, the physicochemical properties of the 100% CM treatment also do not necessarily mean that soil fertility is less favourable than soils under FWC and 2% BC + 50% CM nutrient management systems as these have the added advantage of being in a balanced formulation.

WHC showed no response to the application of different fertilisers and organic amendments. This was expected as physical properties take longer to respond to organic and sustainable practices than chemical and biological properties (Arévalo-Gardini et al. 2015). Unfortunately, this means that WHC could not be used as an indicator for soil organic matter.

C content was optimal in FWC and 2% BC +50% CM soils which is not surprising considering that both contain high C content. The COF and 100% CM treatments also increased C content, showing that while they are not as efficient at increasing C content in soils as the integrated

and compost amendments, they do have a somewhat positive impact on soil C content. A 0.9 percentage point increase in C content is impressive. Other studies show a remarkable increase in soil C content after the application of compost (Diacano and Montemurro 2010, Brown and Cotton 2011, Jien et al. 2015). The 100% CM treatment showed the highest NH_4^+ and NO_3^- content compared to the rest further confirming that it is the best immediately available source of nutrients in soil.

3.6.3 Soil biological properties

The soil aerobic microbe populations were perceptibly reduced by the biochar-inclusive and MAD regimes. This was expected as the amendments were processed under anaerobic conditions, which fostered anaerobic bacteria populations' rather than aerobic bacteria. What was unexpected was the surge in fungi population under chemical fertiliser treatment. This may be due to the high S content in these soils (Wainwright 1984). The soil fungal consortium includes a vast population of fungi associated with arylsulfatase activity (Cregut et al. 2013).

3.7 Conclusion

Overall, the MAD and COF treatments resulted in soils with poor physicochemical properties and mineral compositions. According to our study, these are inadequate substitutes for chemical fertilisers, at least for enhancing soil fertility in the short term. In contrast, FWC and 2% BC + 50% CM improved the soil physicochemical properties and mineral content beyond the capacity of 100 % CM and the control. However, the excessive nutrients in the FWC formulation pose a potential risk due to the inherent imbalanced nutrient composition.

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CHAPTER 4

Sweet potato (*Ipomoea batatas* (L.) Lam) growth and yield in response to different soil nutrient management systems

4.1   Abstract

Organic and inorganic soil nutrient management regimes influence sweet potato growth. While inorganic fertilisers confer adequate crop yields, organic and sustainable can be used as alternative nutrient regimes. The impact of five different fertiliser regimes on sweet potato growth and yield was assessed. The treatment were an inorganic control (NPK applied at 100 kgN.ha^{-1} in a 2:3:2 formulation); a sustainable, integrated co-application of biochar applied at a 2% rate and inorganic NPK (2:3:2) applied at a 50 kgN.ha^{-1}rate (2% BC + 50% CM); food waste compost (FWC), commercial organic fertiliser (COF) also applied at a100 kgN.ha^{-1}and farmyard manure anaerobic digestate application of the liquid fertiliser (MAD). Canopy growth after 6 weeks was showed significant differences across the treatments (P < 0.05). The most extensive coverage (73.67%) measured 6 week after transplanting and highest dry vegetative biomass, longest and highest total and marketable fresh tuber yields were observed in soils under the mixed fertiliser regime (2% BC + 50% CM). Fresh vegetative biomass and chlorophyll content was greatest under the FWC nutrient management system. The control also produced leaves with chlorophyll content that was comparable to the leaf chlorophyll content under the FWC treatment. The FWC, 2% BC + 50% CM and MAD treatments also resulted in the highest leaf numbers. MAD and COF application led to low vegetative growth, canopy spread and fresh and marketable tuber yields. Tuber number per plant was generally low, with sweet potatoes producing 5 tubers per plant in the FWC, 100% CM and 2% BC + 50% CM treatments and only 2 in the remaining treatments. Yield output was 26.41 t.ha^{-1}, 19.02 t.ha^{-1}, 14.99 t.ha^{-1}, 7.98 t.ha^{-1} and 4.99 t.ha^{-1} for the 2% BC + 50% CM, 100% CM, FWC, MAD and COF treatments, respectively. The harvest index was unaffected by the type of organic amendment or fertiliser.

Overall, FWC and the 2% BC + 50% CM treatment improved vegetative biomass yield, but the latter produced much higher tuber yield then the control and FWC treatments. Both appear to be highly suitable alternative soil nutrient regimes that can effectively limit inorganic fertiliser use. In contrast, the MAD liquid fertiliser showed little potential as an

organic amendment form. It should be regarded as a supplementary biofertiliser rather than a stand-alone organic amendment and more extensive studies need to be done in order to gain full understanding of its use and role in sustainable agricultural systems. In this study, the delayed application of COF made it difficult to reach a conclusive decision on the effect of COF on sweet potato yield. The organic fertiliser was stolen from the store room and had to be ordered and replaced. Sustainable and organic soil nutrient management systems like these explored in the current study are essential for the conservation of the soil and the protection of the environment.

4.2   Introduction

Sweet potato (*Ipomoea batatas*) and its wild relatives originated in Mexico and Venezuela in the tropical region of South America (Lebot 2009, Akinjoba 2014). It currently holds fourth place in the worlds most cultivated crops (Akinjoba 2014) with production taking place in over 100 developing countries. Members of the sweet potato family, *Convolvulaceae*, are generally widely cultivated in third world countries like India, Vietnam and Uganda (Edison et al. 2009, Lan and Ilangantileke 1992, Okonya et al. 2014). The crop yields more consumable energy per hectare of land per day than most prized staple crops like cassava, wheat and rice and is an excellent source of carbohydrates and vitamin A ref. In addition, its leaves are high in protein (Saraswati 2007). Yields can be as high as 120 t.ha^{-1} (Lebot 2009). Sweet potato is used in bread- and pastry-making, animal feed, alcohol production, syrups, dye, acetone and yeast (Lebot 2009, Jin et al. 2012, Osunlola and Fawole 2015). It is not only useful in the food and beverage industries, but some varieties even have defined role to play in health sciences and medicine. For instance, purple-fleshed sweet potatoes produce anthocyanin enhances vision by maintaining cell viability, promote cell survival and division and reducing damage to cells (Sun et al. 2015).

4.2.1   Description

In nature, sweet potato grows as a perennial herb, but is regarded as an annual summer crop in cultivated systems (Agriculture, Forestry and Fisheries Department of South Africa 2011). Its vines, usually between 3-10 mm wide, grow along the ground and are demarcated by internodes that can range from 2 to 20cm long (Lebot 2009). The vines vary in colour with some exhibiting a dark, purple tint and others a light green to dark green shade. Roots sprout from nodes that

touch the grounding giving sweet potato its creeper characteristics (Lebot 2009). Leaves grow spirally, with petioles that can be as long as 30 cm (Caribbean Agricultural Research and Development Institute 2010). Leaf formation is variable, even on the same plant and whilst some leaves have pointed tips, others are more rounded (Antonio 2011). Leaf colours exhibit the same range as vine colour (Lebot 2009). Flowers typically grow in clusters of up to 22 and are light pink to deep purple (Antonio et al. 2011). The roots are fibrous, extensive and develop from the cutting's node as well as nodes that connect with the soil (Lebot 2009). Five to ten below ground storage roots develop when adventitious roots become thicker (Caribbean Agricultural Research and Development Institute 2010). Roots can take several forms including fusiform, globular, round, and ovate (Caribbean Agricultural Research and Development Institute 2010). The surface can be rough, ridged or smooth ref. The cork-, vascular- and anomalous cambia determine storage root morphology (Lebot 2009).

4.2.2   *Growth phases*

Sweet potato growth takes place in 4 overlapping phases after seedlings are transplanted into the soil (Figure 4.1)
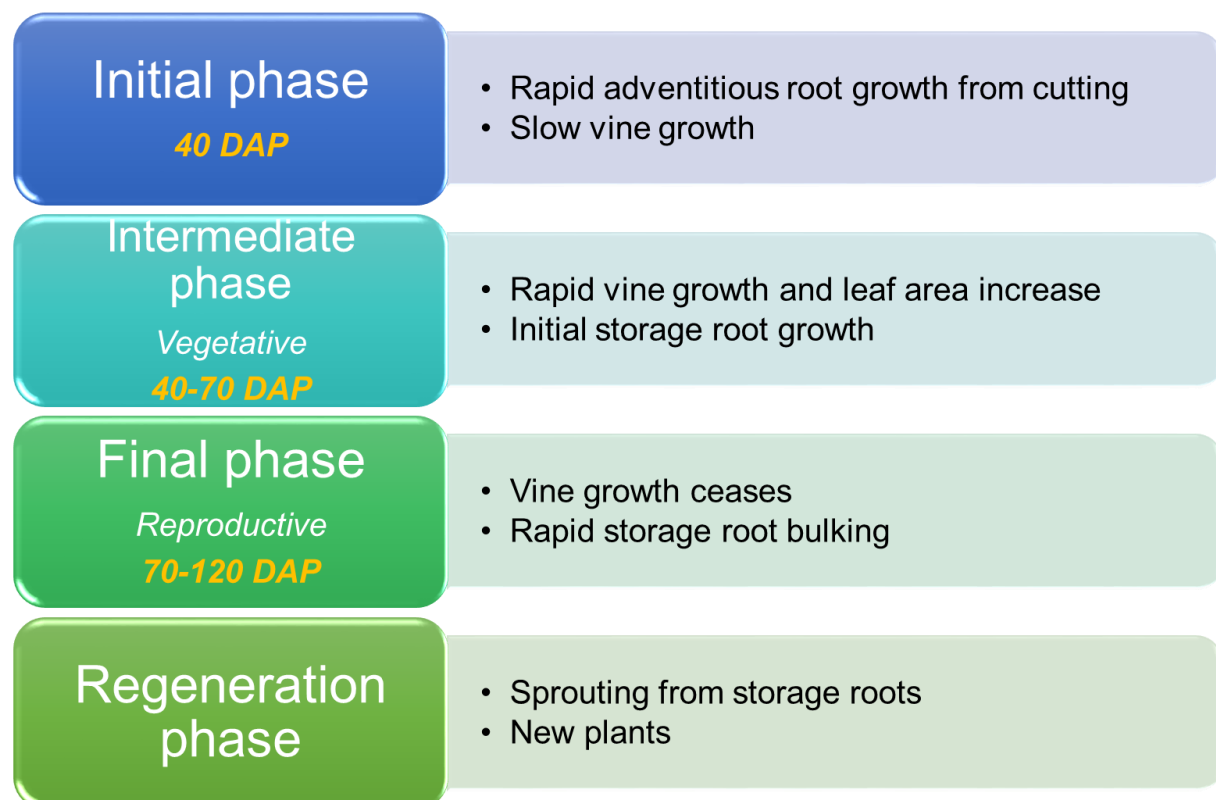
Figure 4.1 Growth cycle of sweet potato. *The DAP is days after planting. Sweet potatoes may also be transplanted. Transplanting shortens the growth period.*

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4.2.3 *Fertiliser regimes*

Sweet potato nutrient removal from the soil is corresponds to the yield. A yield of 50 t.ha^{-1} removes 215 kg.ha^{-1}, 38 kg.ha^{-1}, 376 kg.ha^{-1}, 65 kg.ha^{-1}, 27 kg.ha^{-1}, 18 kg.ha^{-1}and 0.67 kg.ha^{-1} of N. P. K$^+$, Ca^{2+}, Mg^{2+} and Fe^{2+}, from the soil, respectively (Lebot 2009). Thus, soil should contain sufficient available levels of the aforementioned minerals to avoid limiting sweet potatoes yields. Potassium is important for adequate root development (Jian-wei et al. 2001, Lebot 2009). Nitrogen supply should not be in excess because it encourages excessive vegetative growth and the subsequent diversion of carbohydrates from storage roots to the leaves and stems (Saraswati 2007). A combination of deficient K$^+$ and excess of N invariably leads to stunted root growth and development and therefore a reduction in yield (Lebot 2009).

Phosphorus is essential for adequate vine growth, photosynthesis, flowering, fruiting and maturation (Akinjoba 2014). The importance of P for tuber growth is not clearly elucidated compared to K$^+$ in root development (Lebot 2009). Akinjoba (2014), found that while P-based granular fertiliser produced the longest vines, a control treatment that contained no P, produced the highest tuber yield when compared to 3 other organic and inorganic P fertilisers. This essentially means that P supplementation may not be necessary for sweet potato growth. Indeed, sweet potato tuber is known to grow reasonably well in P-deficient soil (Kareem 2013).

Hartemink (2003) planted sweet potato after a fallow period during which some species were allowed to grow. They found that there was no significant difference in sweet potato tuber yield when N-fixing species preceded the crop. This may be because N favours vegetative growth rather than reproductive growth. Moreover Motsa et al. (2015) showed that fertiliser application only boosted tuber yield in only one of the three locations they used to cultivate sweet potato. They concluded that cultural practices are a larger determinant of sweet potato yield than fertilisers. The soil under cultivation was deficient in N and P as well as organic carbon. Furthermore, it comprised of 82.60% sand and only 13.4% clay with a low bulk density (BD). This highlights the importance location and edaphic properties have when applying a soil nutrient management regime.

Sweet potatoes perform well in organic soil nutrient management systems (Agbede 2010). Sole applications of manure and its biologically processed liquid form, anaerobic digestate can produce greater yields than sole mineral fertiliser applications (Agbede 2010, Oliviera et al. 2010).

Co-amendment with mineral fertilisers and biochar can improve tuber growth parameters like vine length and the number of leaves and yield as much as 100% (Wingwafi and Rao 2015). Some studies show that biochar can produce higher yields than conventional nutrient management systems although this largely depends on the soil health and fertility (Dou et al. 2012). Generally, nutrient uptake is enhanced allowing for a highly nutritional crop. Biochar amendments enhance important soil properties like BD and subsequently, porosity, which promote extensive and early root growth (Dou et al. 2012). This would account for more efficient nutrient uptake. Furthermore, biochar is inherently nutrient-filled and therefore is a source of nutrients.

4.2.4   *Suitability of sweet potato in sustainable, small-scale farming operations*

There are numerous cultivars that are drought-tolerant (Saraswati 2007), although water stress can result in significantly reduced tuber yields (Motsa et al. 2015). Sweet potatoes are drought-tolerant. They are able to grow well in soils deficient in P. In addition, they have relatively low N requirements and have a positive response to organic practices and amendments like biochar and compost. All these factors make sweet potatoes highly ideal for small-scale farming operations that are typified by dry land water systems and low agrochemical input affordability (Nwosisi et al. 2017).

4.3   Objectives

The main objectives of this study were:

a)   To investigate the impact of five nutrient management systems on sweet potato growth parameters i.e. canopy coverage, chlorophyll content, vine length per plant, fresh and dry vine weight per plant, the number of leaves per plant, root fresh and dry weights per plant, shoot fresh (FW) and dry weight (DW) per plant and the harvest index on a fresh and dry weight basis.

b)   To determine the total sweet potato fresh tuber yield in t/ha, the number of tubers produced per plant, the mean FW per tuber, the total tuber weight per plant and the unmarketable and marketable tuber yields under the different nutrient management systems.

4.4   Methods and Materials

Information regarding the experimental site, location and the climate conditions is included in Chapter 3 of the thesis. The treatments slightly differed from the soil fertility component of this study.

4.4.1   *Fertiliser regimes*

In the previous chapter, five treatments were compared to each other and the control was unfertilised soil. The same number of treatments were as in the former part of the study. The only difference is that the inorganic fertiliser applied at a rate of 100 kg N.ha^{-1} NPK (2:3:2) was used as a control in this current part of the study. The unfertilised soil control used in the first part of this study was therefore not included in the current experiment. The treatment for the inorganic fertiliser was changed from 100% CM to control. The other treatments remained the same: the biochar applied at a 2% rate (w/w) with 50 kgN.ha^{-1} NPK (2:3:2) (2% BC + 50% CM); food waste compost (FWC); commercial organic Talborne Vitagro® fertiliser with N:P:K formulation of 2:3:2 (COF) and farmyard manure-derived anaerobic digestate (MAD).

4.4.2   *Transplanting*

Sweet potato vines that were 15 cm in height were purchased from a local grower based in Paarl, Western Cape, South Africa. The cultivar, 'Bosbok' is widely sold in the Western Cape, South Africa and is characterised by purple skin and a cream-white flesh. Transplanting took place immediately after the soil was fertilised and amended with the various treatments (*see* Chapter 3). Subsequent fertiliser supplementation is also detailed in Chapter 3. A pointed stick was used to make 5 cm deep holes for the transplants. Each plot had three ridges that were approximately 60 cm apart. The ridges were 0.9 m wide and 4m long. The recommended spacing for sweet potato is 0.9 m apart with a 40 cm in row spacing. Each ridge had two rows instead of one row to increase the number from 9 plants per ridge to 18 plants per row ridge to ensure a sufficient number of crops would be available for collection throughout the growing season. The vines were transplanted at least 60 cm apart from each other.

4.4.3   Cultural practices

Weeding was done manually and no pesticides were used. Sprinklers were used to irrigate the crop for an hour each day.

4.4.4   Sampling

Garden tools were used to harvest crops from the first four rows.

4.4.4.1   Crop growth

4.4.4.1.1   Canopy coverage

Canopy coverage was measured 6 weeks after transplanting (WAT) and expressed as a percentage (%). Two people recorded the canopy coverage on a single ridge. This was done repeatedly for the remaining two ridges to give a total number of 6 readings per plot. These were averaged to give one figure per plot. Essentially each treatment had 4 values as per the number of replicates (one from each block).

4.4.4.1.2   Chlorophyll content

Chlorophyll content was measured using a SPAD 502 chlorophyll meter, Spectrum technologies, Inc. ®to give soil-plant analyses development (SPAD) values. The chlorophyll content of the third oldest leaf from one plant per ridge was measured. A mean SPAD value per plot was computed from three measurements collected from each of the three ridges in a plot. Plants and leaves were marked to allow for monitoring over several weeks. The first round of sampling took place 9 weeks after transplanting. Sampling preceded at three-week intervals for three more rounds plants were used.

4.4.4.1.3   Number of leaves, fresh and dry weights of the root, tuber, vine and leaves

Three sweet potato plants were collected from each plot (one per ridge) to give four replicates per treatment. Crops were collected at four-week intervals after the percentage canopy coverage was recorded. Sampling took places every +/-4 weeks. Plant height was recorded. The roots were removed from the plant and weighed. Tuberous roots were measured separately.

The leaves were counted and weighed (for total shoot weight) and the vine measured and weighed. The tuber roots were also counted and weighed. Plant organs were dried over three to ten days at 60°C and the dry weights measured.

4.4.4.1.4   Shoot fresh weight and dry weight

The shoot FW and DW were calculated as the sum of the vegetative components together.

4.4.4.1.5   Harvest index (HI)

Harvest indices for fresh and dry weights were calculated throughout the growing season. The following formula was used:

Total tuber weight per plant in grams/Total biomass per plant in grams

4.4.4.2   Crop yield

The final round of harvest took place in the autumn of 2017 on the fourth round of sampling. Harvesting was slightly delayed for this round to allow enough time for crops to respond fully to the second increments of the inorganic and organic fertilisers in the control and COF treatments, respectively. The procedure was identical to the one followed to measure crop growth parameters.

4.4.4.2.1   Mean tuber weight, number of tubers, tuber weight per plant and total yield

The total tuber number and weights per plant, the tuber diameter and length were measured. Each tuber from each plant was weighed to determine the mean weight per tuber.

4.4.4.2.2   Unmarketable and marketable yield

Tubers were divided into two categories: unmarketable and marketable. Unmarketable tubers weighed below 80 g. Unmarketable and marketable yields were expressed in t.ha^{-1} and in terms of percentage of total yield.

4.5 Results

4.5.1 Crop growth

4.5.1.1 Canopy coverage, chlorophyll content and number of leaves

Canopy coverage was similar in the 2% BC + 50% CM regime and the FWC treatments (73.67 % and 65%, respectively) (Figure 4.2 and Table 4.1). Leaf spread under these two treatments, was significantly higher ($P < 0.05$) than the leaf spread in the control, COF and MAD treatments, which only covered 39.92 % to 41.08 % of the land surface area.

Chlorophyll content increased for the first 9 weeks after transplanting (WAT) and dropped thereafter for all treatments with the exception of the MAD regime, which only showed a decline 15 weeks after transplanting (Figure 4.3). The COF nutrient regime yielded the highest leaf chlorophyll content 6 and 9 weeks after transplanting followed by the FWC nutrient regime. In the following weeks, the chlorophyll in the COF treatment showed a sharper decline than the rest of the treatments. Thereafter, the greatest leaf chlorophyll contents were observed in the control and the FWC soil nutrient regimes. Chlorophyll content from the MAD treatment was the lowest throughout the growing season. Chlorophyll only showed significant differences ($P < 0.05$) in the ninth week after planting (Figure 4.4). At this point, the MAD chlorophyll content, 29.78 was significantly lower ($P < 0.05$) than the chlorophyll content in sweet potatoes collected from the control and COF plots, 46.58 and 46.64, respectively. The leaf chlorophyll contents in sweet potatoes grown on plots amended with FWC and 2% BC + 50% CM were similar and did not differ significantly from the leaf chlorophyll contents of sweet potatoes cultivated under the control, COF and MAD fertiliser regimes. At 15 weeks after transplanting, the FWC and control treatments yielded identical leaf chlorophyll concentrations (36.76 SPAD), followed by the 2% BC + 50% CM treatment (32.71 SPAD).

The number of leaves increased for all treatments up to the third sampling round, 12 weeks after transplanting (Table 4.1). Thereafter, leaf number dropped in the control, FWC, COF and 2% BC + 50% CM treatments. The organic FWC treatment produced the highest number of sweet potato leaves throughout the growing season except at harvest, 16 weeks after transplanting. At 4 and 12 WAT, the biochar-inclusive and COF treatments produced the second highest number of leaves after the FWC, while the control produced leaf count that was variable throughout the growing season. It produced 70 leaves at 4 WAT and 16 WAT, the second lowest number of leaves at each sampling round. At harvest, more-or-less 16

weeks after transplanting, the MAD treatment produced 164 leaves, followed by the compost treatment, which produced 139 leaves. The other treatments produced much fewer leaves, although these were not significantly different. This may be due to the large coefficient of variation of 29.82% and the high standard deviation. Statistical differences were only observed 4 weeks after transplanting. FWC sweet potatoes produced significantly higher leaves (120) than the control (70) and MAD treatments (56) at a significance level of $P < 0.05$.
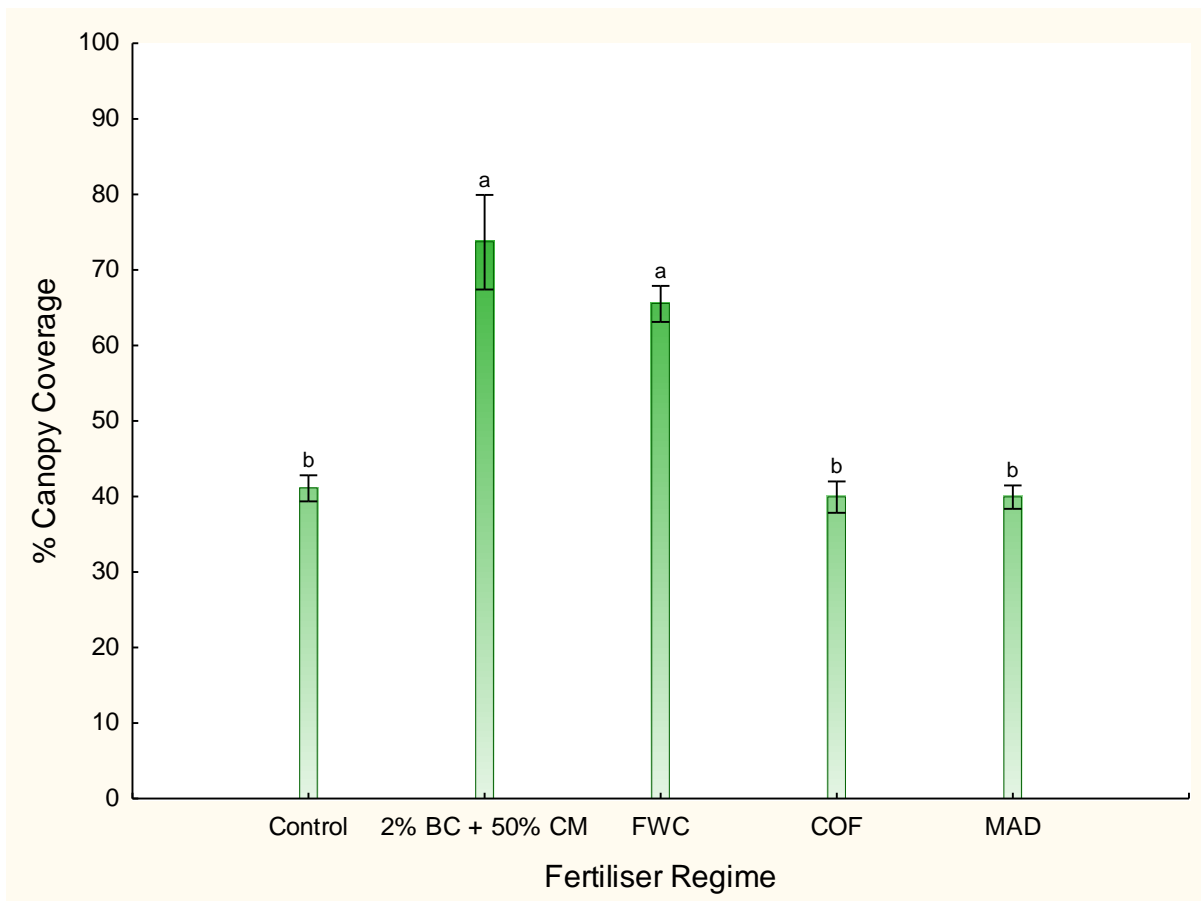
Figure 4.2. Canopy coverage 6 weeks after planting. *The bars show the mean percentage canopy coverage under different treatments, while the whiskers denote the standard error of the mean. The letters indicate significant and insignificant (P < 0.05) differences between the various fertiliser regimes. Control refers to the full recommended NPK (2:3:2) on a basis of 100 kgN.ha^{-1}; 2% BC + 50% CM is the 2% biochar rate (w/w) and half the recommended NPK rate.*
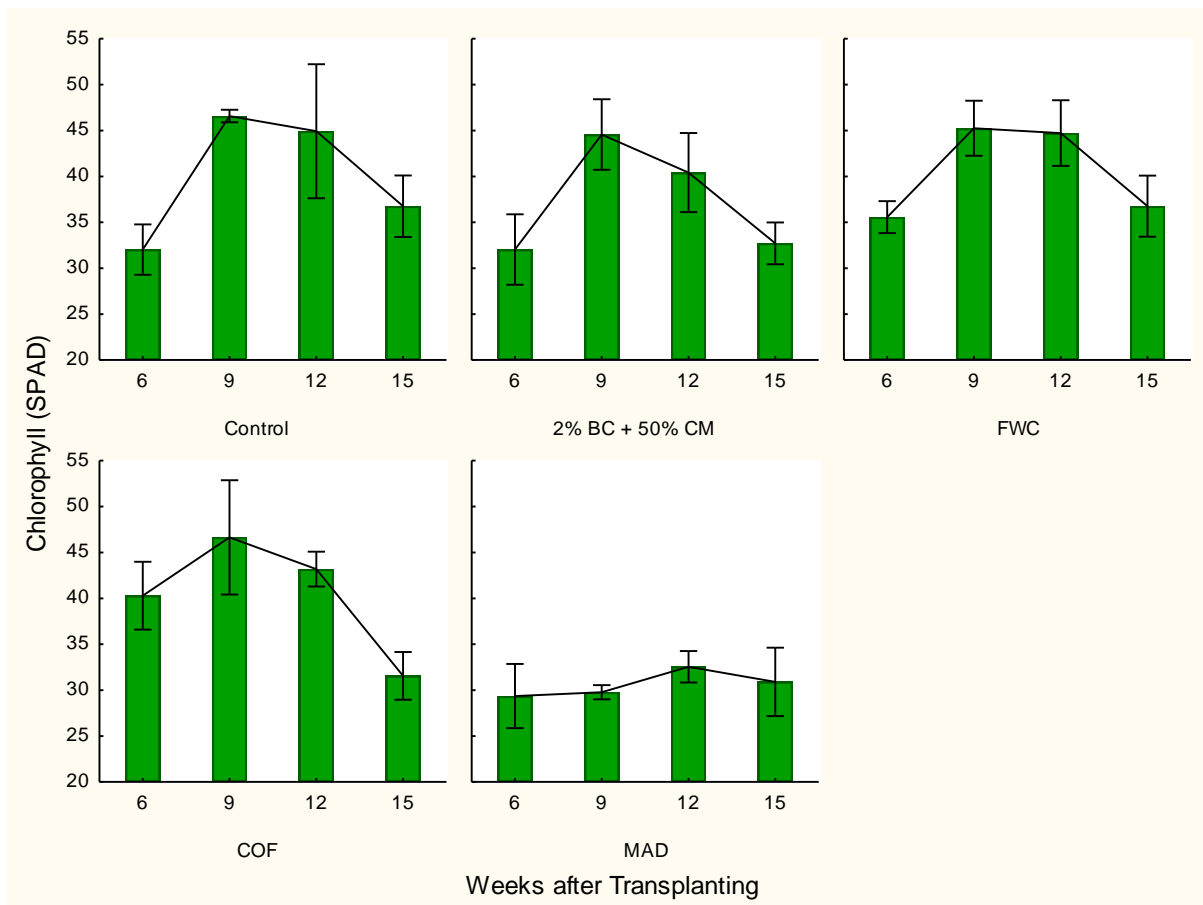
Figure 4.3 Chlorophyll content over time. *The bars denote the mean chlorophyll SPAD readings under each treatment over time. The whiskers indicate the standard error of the mean. Control refers to the full recommended NPK (2:3:2) on a basis of 100 kg N.ha⁻¹; 2% BC + 50% CM is the 2% biochar rate (w/w) and half the recommended NPK rate; COF is the commercial organic fertiliser and MAD is the manure anaerobic digestate.*
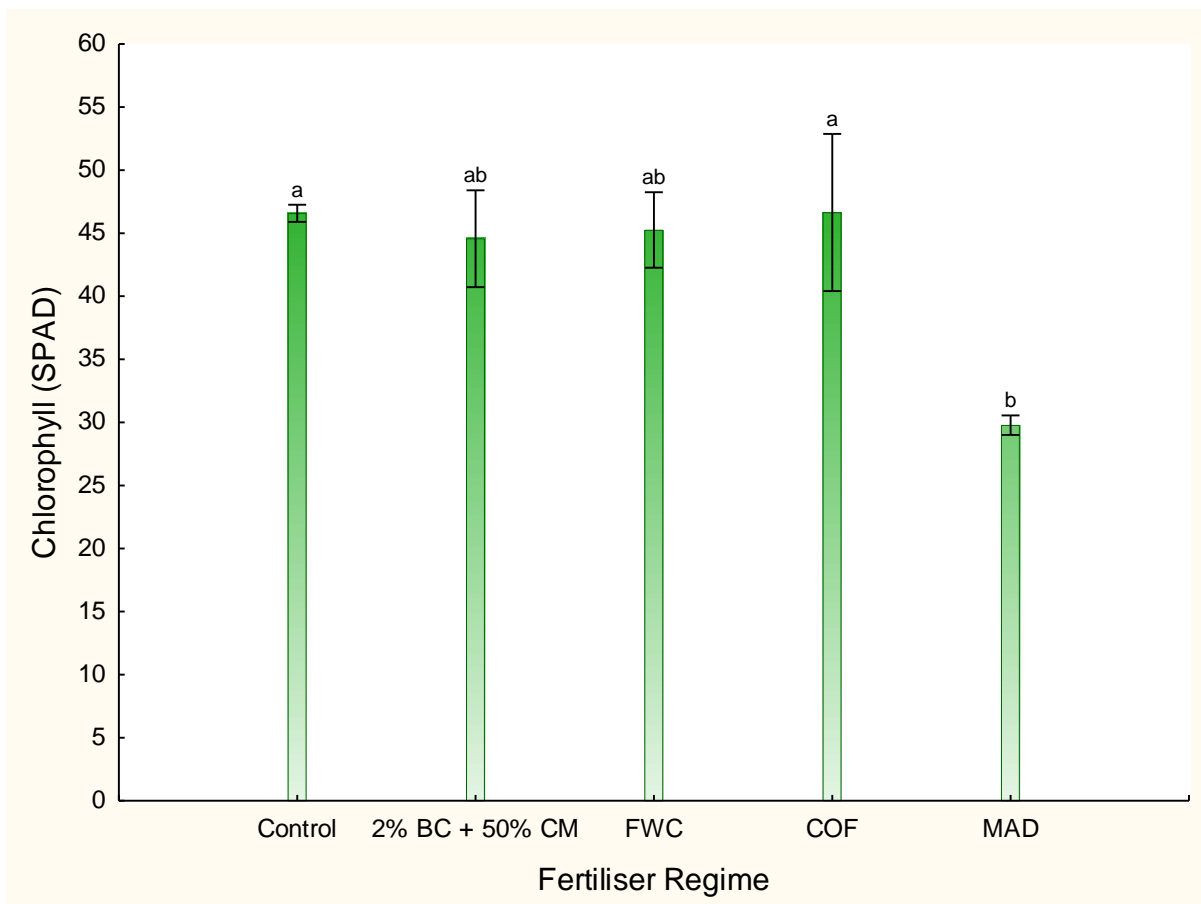
Figure 4.4. Chlorophyll content 9 weeks after transplanting. *The bars denote the mean chlorophyll SPAD readings under each treatment 9 WAT. The whiskers indicate the standard error of the mean. The letters indicate significant and insignificant (P < 0.05) differences between the various fertiliser regimes according to a Tukey HSD post hoc test. Control refers to the full recommended NPK (2:3:2) on a basis of 100 kg N.ha^{-1}; 2% BC + 50% CM is the 2% biochar rate (w/w) and half the recommended NPK rate; COF is the commercial organic fertiliser and MAD is the manure anaerobic digestate.*

Table 4.1 Number of leaves over the growing season and canopy coverage 6 weeks after transplanting (WAT). *The values on the right of the ± show the standard deviation. CV% = coefficient of variation. The p-value was computed at a significant level of 0.5. NS = no significant difference. The superscript letters show the significant differences (P < 0.05) according to the Tukey HSD (honest significant difference) post hoc test. Control refers to the full recommended NPK (2:3:2) on a basis of 100 kg N.ha^{-1} 2% BC + 50% CM is the 2% biochar rate (w/w) and half the recommended NPK rate; COF is the commercial organic fertiliser and MAD is the manure anaerobic digestate.*

Parameter	Number of leaves.plant^{-1}				% Coverage
Fertiliser Regime	**4 WAT**	**8 WAT**	**12 WAT**	**16 WAT**	**6 WAT**
Control	70 ± 3.18^b	69 ± 19.60^a	135 ± 21.46^a	70 ± 15^a	41.08 ± 2.98^b
2% BC + 50% CM	83 ± 15.60^{ab}	100 ± 27.25^a	143 ± 70.06^a	109 ± 38^a	73. 67 ± 10.85^a
FWC	120 ± 37.18^a	156 ± 19.02^a	159 ± 16.11^a	139 ± 11^a	65.50 ± 4.13^a
COF	79 ± 8.2^{ab}	94 ± 35.13^a	133 ± 3.20^a	58 ± 19^a	39.92 ± 3.61^b
MAD	56 ± 7.17^b	123 ± 51.26^a	132 ± 12.48^a	164 ± 86^a	39.92 ± 2.70^b
CV%	15.43	29.40	17.34	29.82	8.82
p-value (0.05)	0.019	NS	NS	NS	32.80

4.5.1.2   *Vine length, fresh and dry weights of vines and shoots*

The fertiliser regime did not affect vine length significantly (P < 0.05) at any point during the growing season (data not shown). At harvest, the COF regime produced the longest vine (72.50 cm) and the MAD treatment resulted in the shortest vines (58.56) (Table 4.3). Sweet potato vine fresh weight (FW) per plant increased until harvest only in the 2% BC + 50 % CM and decreased 16 WAT in the control, FWC and COF treatments (Table 4.2). Vine FW fluctuated in the MAD treatment. The FWC treatment produced the highest vine FW compared to the control and the rest of the treatments, except at 12 WAT, where the 2% BC + 50% CM treatment showed higher vine FW. The control consistently yielded lower yields than the integrated and FWC treatments and showed varying trends regarding the remaining two organic treatments (COF and MAD). There were significant differences (P < 0.05) in vine FW at all points in the growing season except at 16 WAT. At 4 WAT, FWC vine FW was 84.71 g and significantly different from the rest of the regimes. AT 8 WAT, the FWC vine FW was significantly higher (P < 0.05) than the vine FW in the control, integrated and COF treatments, but similar to the MAD treatment. The COF treatment also yielded significantly lower (P < 0.05) vine FW than the MAD treatment. In the 12th week after transplanting, only the FWC vine FW was significantly different to all the other treatments, while the rest were all insignificantly different to each other.

The vine dry weight (DW) per plant was significantly different (P < 0.05) throughout the entire growing season (Figure 4.5). At 4 WAT, FWC was significantly higher (P < 0.05) than the DW

in all the other treatments excluding the control. The control treatment resulted in vine DW that was significantly higher ($P < 0.05$) than the vine DW in the COF and MAD fertiliser regimes. The MAD regime also produced significantly lower ($P < 0.05$) vine DW than 2% BC + 50% CM. Vine DW was highest in the FWC nutrient regime and lowest in the MAD treatment. Conversely, at 8 WAT, vine DW was highest in the MAD treatment. Both COF and the control produced vine DW that were significantly lower ($P < 0.05$) than the MAD treatment. At 12 WAT, only FWC showed a significant difference to COF. At harvest, the 2% BC + 50% CM (46.48 g.plant^{-1}) was significantly higher ($P < 0.05$) than the inorganic control (20.98 g per plant). There was a remarkable increase of 332.78% in vine DW in the 2% BC + 50% CM regime between 12 WAT and 16 WAT. Figure 4.3 shows that the integrated and COF treatments produced the highest DW, while the lowest were observed in the control and MAD treatments at harvest. The trends observed in vine FW yields per plant differed to the trends observed in vine DW yield. For instance at 8 WAT, the FWC treatment produced 148.56 g vibe FW and MAD 106.67 g, while the former only yielded 11.92 g FW and the latter 18.95 g.

Table 4.2 Sweet potato vine fresh weight over the growing season. *The values on the right of the $\pm$ show the standard deviation. CV% = coefficient of variation. The p-value was computed at a significant level of 0.5. NS = no significant difference. The superscript letters show the significant differences ($P < 0.05$) according to the Tukey HSD (honest significant difference) post hoc test. Control refers to the full recommended NPK (2:3:2) on a basis of 100 kg N.ha^{-1} 2% BC + 50% CM is the 2% biochar rate (w/w) and half the recommended NPK rate; COF is the commercial organic fertiliser and MAD is the manure anaerobic digestate.*

Fertiliser Regime	4 WAT	8 WAT	12 WAT	16 WAT
Control	30.19 + 1.68^b	53.62 + 13.53^{bc}	90.99 + 27.81^b	89.23 + 16.76^a
2% BC + 50% CM	43.50 + 2.82^b	86.19 + 16.84^{bc}	129.26 + 59.41^b	162.57 + 91.59^a
FWC	84.71 + 7.32^a	148.56 + 24.25^a	264.23 + 58.42a	157.34 + 65.86^a
COF	38.03 + 9.40^b	40.99 + 18.41^c	85.33 + 33.18^b	46.23 + 17.25^a
MAD	27.79 + 5.96^b	106.67 + 31.43^{ab}	131.32 + 4.75^b	78.34 + 42.36^a
CV%	13.36	27.10	28.22	41.67
p-value (0.05)	0.000	0.001	0.003	NS
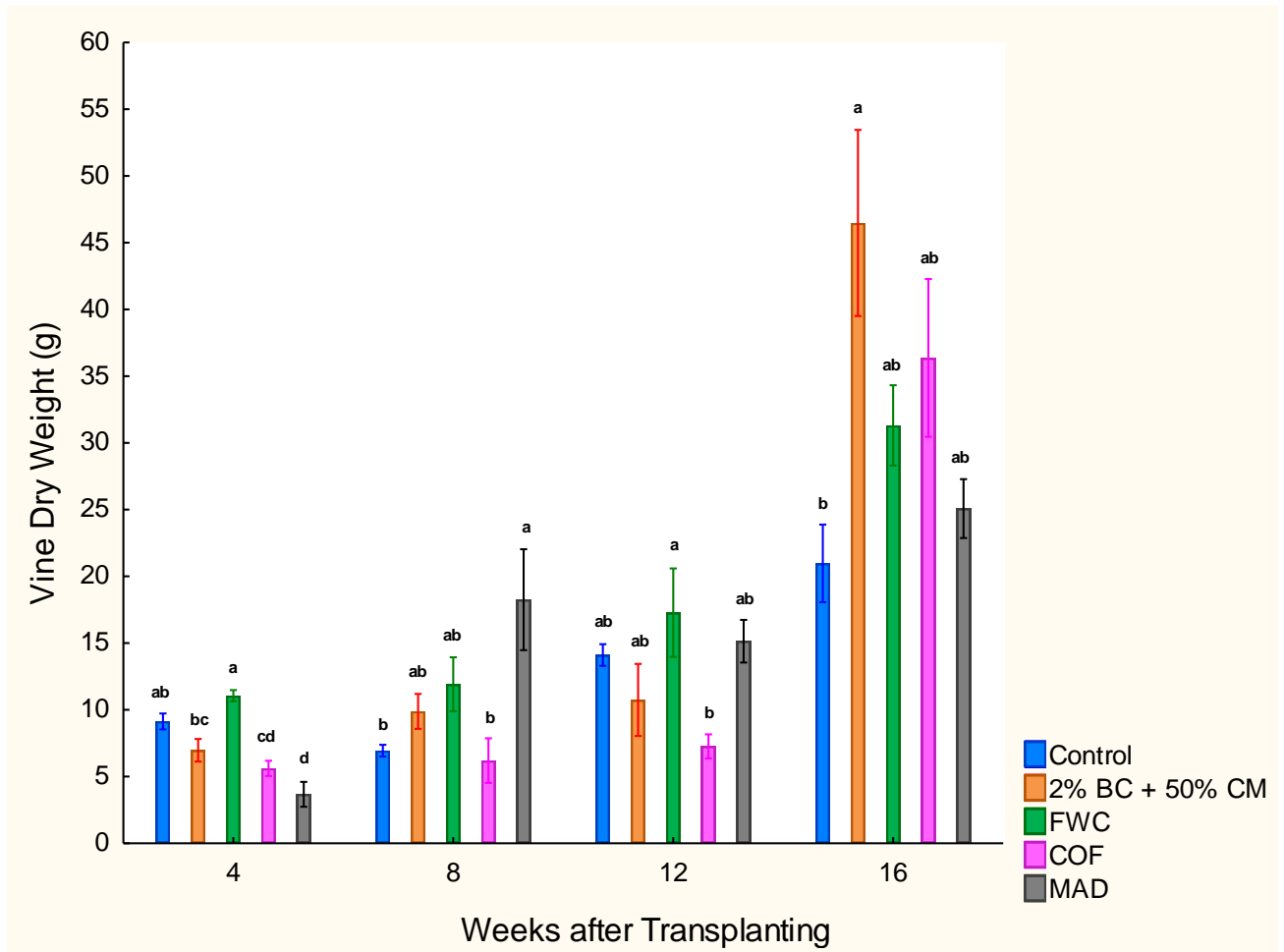
Figure 4.5. Sweet potato vine dry weight over the growing season. *The bars denote the mean vine dry weights under each fertiliser regime, while the whiskers show the standard error of the mean. The superscript letters indicate significance and non-significance at a 95% confidence interval. The Tukey HSD post hoc test was conducted to determine these differences. Control refers to the full recommended NPK (2:3:2) on a basis of 100 kg N.ha^{-1}; 2% BC + 50% CM is the 2% biochar rate (w/w) and half the recommended NPK rate; COF is the commercial organic fertiliser and MAD is the manure anaerobic digestate.*

Shoot FW was consistently highest in the FWC treatment, followed by the mixed fertiliser treatment (data not shown). The remaining treatments produced similarly low fresh weight yields. At

4 WAT, the FWC shoot FW was significantly different (P < 0.05) to all the other treatments. Although significantly lower than the FWC, the shoot FW in the 2% BC + 50% CM was significantly higher than the shoot FW in the three remaining treatments. The control, COF and Mad treatments all produced weights that were similar to each other. Eight weeks after planting, FWC and 2% BC + 50% CM shoot FW were significantly higher than the shoot FW in the MAD treatment. Twelve weeks after transplanting, the FWC treatment shoot FW was significantly higher than the FW in all the other soil nutrient regimes, while the 2% BC + 50% CM treatment produced shoot FW that was significantly higher than the control and COF treatments. The MAD treatment was also significantly higher in shoot FW than the COF treatment. At harvest, there were no significant differences although shoot FW was highest in the food waste compost treatment and lowest in the commercial organic fertiliser (Table 4.3).

Similarly to shoot FW, shoot DW showed significant differences (P < 0.05) in the first three rounds of sampling (data not shown), but not at harvest (Table 4.3). The trends at 4 WAT were identical to those observed for shoot fresh weights for the same period where shoot DW under the FWC regime was significantly higher compared to all the other regimes; the integrated treatment also resulted in shoot DW that was significantly higher than the control, COF and MAD treatments. The latter 3 regimes were all statistically similar. At 8 and 12 WAT, the mixed fertiliser system yielded slightly higher DW than the compost treatments and these were both significantly greater than the three other treatments in terms of shoot DW. At both periods, DW was similar for the control, COF and Mad treatments. At harvest, biochar continued to produce the highest shoot DW, but the COF treatment produced higher DW than the control and the FWC treatments. The lowest shoot DW was observed in the MAD treatment

Table 4.3. Vine length, vine dry weight (DW), shoot fresh weight (FW) and dry weight (DW) at harvest. *The values on the right of the ± show the standard deviation. CV% = coefficient of variation. The p-value was computed at a significant level of 0.5. NS = no significant difference. The superscript letters show the significant differences (P < 0.05) according to the Tukey HSD (honest significant difference) post hoc test. Control refers to the full recommended NPK (2:3:2) on a basis of 100 kg N.ha⁻¹ 2% BC + 50% CM is the 2% biochar rate (w/w) and half the recommended NPK rate; COF is the commercial organic fertiliser and MAD is the manure anaerobic digestate.*

Fertiliser regime	Vine length	Vine DW	Shoot FW	Shoot DW
Control	67.44 ± 16.14^a	20.98 ± 5.04^b	126.43 ± 12.58^a	34.34 ± 2.53^a
2% BC + 50% CM	69.56 ± 11.75^a	46.48 ± 12.08^a	159.9 ± 79.12^a	60.62 ± 8.46^a
FWC	64.00 ± 5.84^a	31.31 ± 5.22^{ab}	221.07 ± 84.52^a	35.41 ± 12.31^a
COF	72.50 ± 22.29^a	36.37 ± 10.23^{ab}	93.26 ± 5.93^a	41.49 ± 4.12^a
MAD	58.56 ± 21.77^a	25.08 ± 3.83^{ab}	157.87 ± 50.48^a	32.34 ± 0.68^a
CV%	23.57	22.02	27.20	14.08
p-value (0.05)	NS	0.022	NS	NS

4.5.1.3   *Fresh and dry tuber growth*

Fresh root tuber growth increased throughout the growing season, except for food waste compost, which showed a decrease in FW between 12 WAT and harvest (Figure 4.6). At 4 WAT, no significant differences were observed; the highest tuber FW was observed under the control and the lowest, under the MAD treatment. At 8 WAT, compost produced the highest tuber FW, although this was not significant. The highest tuber FW - producing soil nutrient management system after FWC was 2% BC + 50% CM, followed by the MAD treatment. Four weeks later, the FWC continued to produce the highest tuber fresh yields, followed by the mixed fertiliser system, the control and the MAD treatment. COF continued to yield the least tuber fresh yield. The last round of harvest saw a drastic change when 2% BC + 50% CM yielded the greatest fresh tuber yield, followed by the control and FWC. Furthermore, the COF treatment produced a higher fresh yield than MAD. The 2% BC + 50% CM treatment was significantly different to all the other treatments (Figure 4.7).
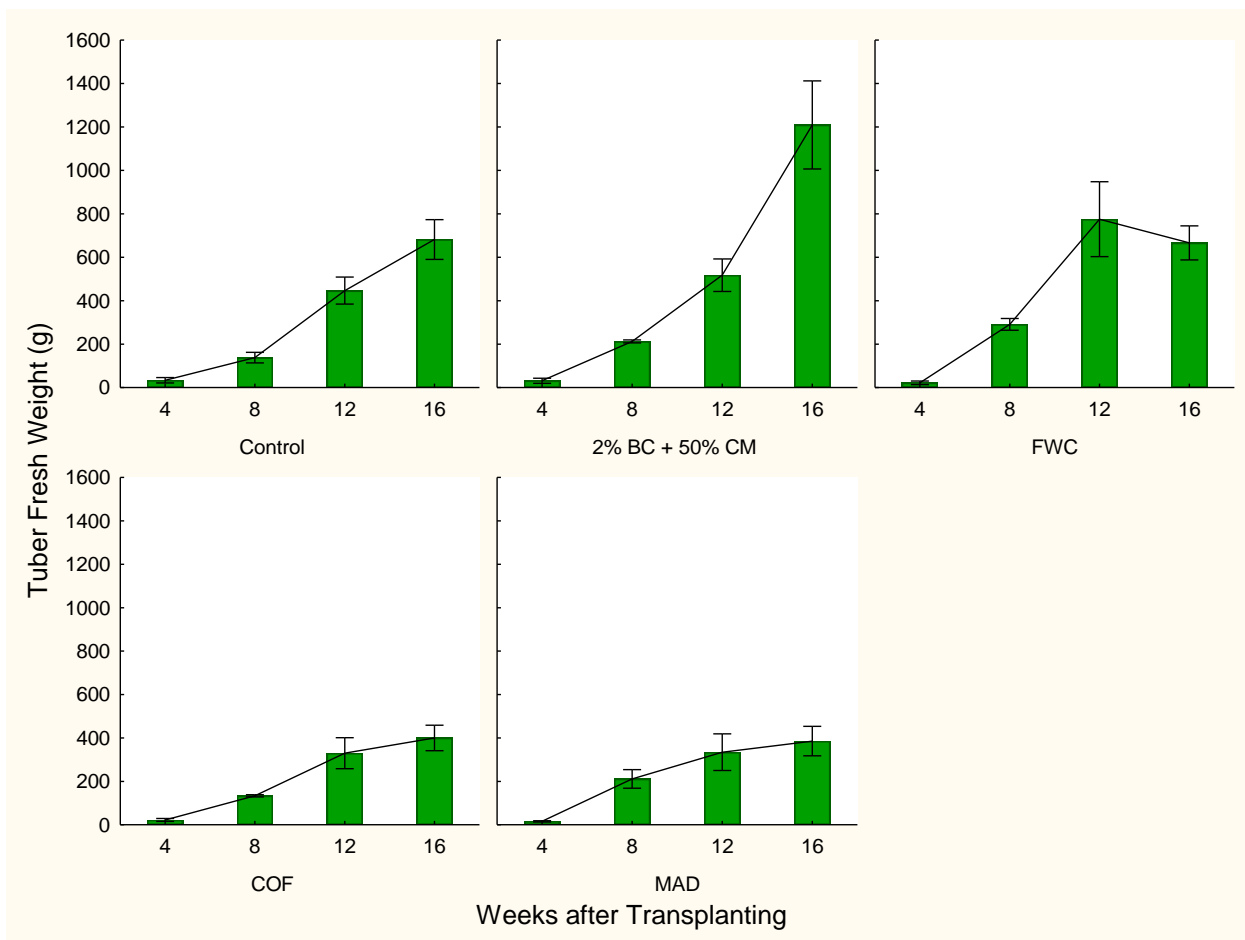
Figure 4.6 Fresh tuber growth over the growing season. *The bars denote the treatment tuber fresh weight means, while the whiskers show the standard error of the mean. Control refers to the full recommended NPK (2:3:2) on a basis of 100 kgN.ha⁻¹; 2% BC + 50% CM is the 2% biochar rate (w/w) and half the recommended NPK rate; COF is the commercial organic fertiliser and MAD is the manure anaerobic digestate.*

Figure 4.7. Tuber fresh weights at harvest. *The bars denote the treatment tuber fresh weight means, while the whiskers show the standard error of the mean. Letters show significant and non-significant differences (P > 0.05). Control refers to the full recommended NPK (2:3:2) on a basis of 100 kgN.ha^{-1}; 2% BC + 50% CM is the 2% biochar rate (w/w) and half the recommended NPK rate; COF is the commercial organic fertiliser and MAD is the manure anaerobic digestate.*
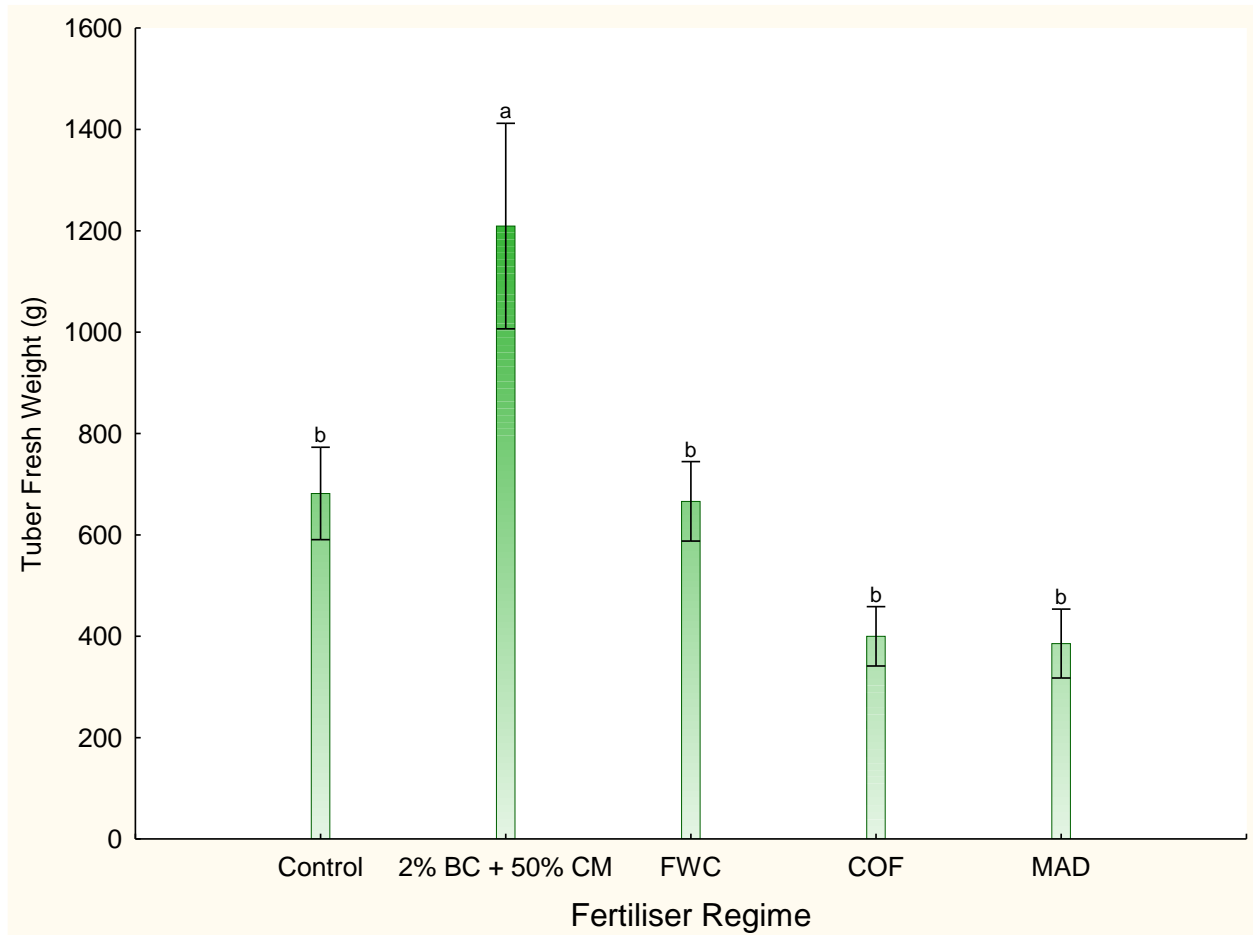
Tuber DW failed to show any significant differences ($P < 0.05$) between treatments at any single point during the growing season (Figure 4.8) At 4 WAT, dry tuber yield was highest in the control treatment and lowest in the MAD treatment. Four weeks later, it was highest in the integrated treatment, followed by compost and lowest in the control. At 12 WAT, the highest dry tuber weight was observed under the FWC regime, followed by the control and integrated treatment. The tuber DW was lowest and proximate in the COF and MAD treatments. At harvest, the greatest dry yields were observed under the 2% BC + 50% CM nutrient regime, followed by the control and FWC. Once again the MAD and COF produced comparable, low yields (Figure 4.9).

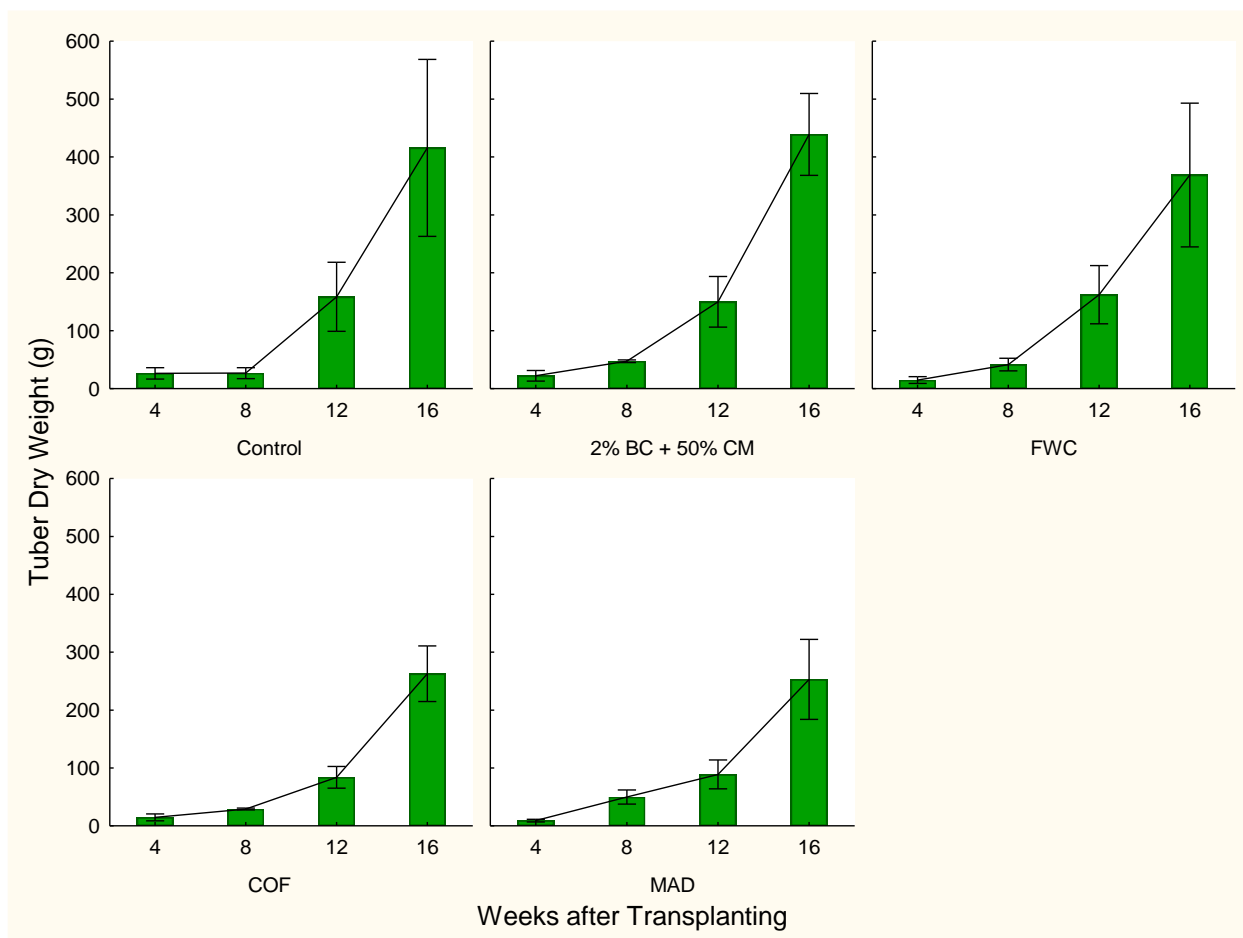**Figure 4.8**. Dry tuber growth over the growing season. *The bars denote the treatment tuber dry weight means, while the whiskers show the standard error of the mean. Control refers to the full recommended NPK (2:3:2) on a basis of 100 kgN.ha^{-1}; 2% BC + 50% CM is the 2% biochar rate (w/w) and half the recommended NPK rate; COF is the commercial organic fertiliser and MAD is the manure anaerobic digestate.*

Figure 4.9. Dry tuber growth at harvest. *The bars denote the treatment tuber dry weight means under the different regimes, while the whiskers show the standard error of the mean. Control refers to the full recommended NPK (2:3:2) on a basis of 100 kgN.ha^{-1}; 2% BC + 50% CM is the 2% biochar rate (w/w) and half the recommended NPK rate; COF is the commercial organic fertiliser and MAD is the manure anaerobic digestate.*

4.5.1.4   *Harvest index (HI)*

Harvest index measurements showed no significant differences. Both fresh and dry harvest indices increased for all treatments barring the COF treatment which showed a decrease between 8 and 12 WAT (Figure 4.10 and 4.11). The trends, in terms of the order of increasing or decreasing HI by treatment, were similar for DW and FW. At 4 WAT, COF showed the best dry and fresh harvest index, while the FWC showed the lowest. At 8 WAT, FWC showed the highest harvest index for fresh weights, while the COF treatment showed the most favourable HI when dry weights were considered. This time however, MAD was associated with the least HI. At both 12 and 16 WAT, biochar-inclusive treatment showed the best HI, while the COF performed the worst.
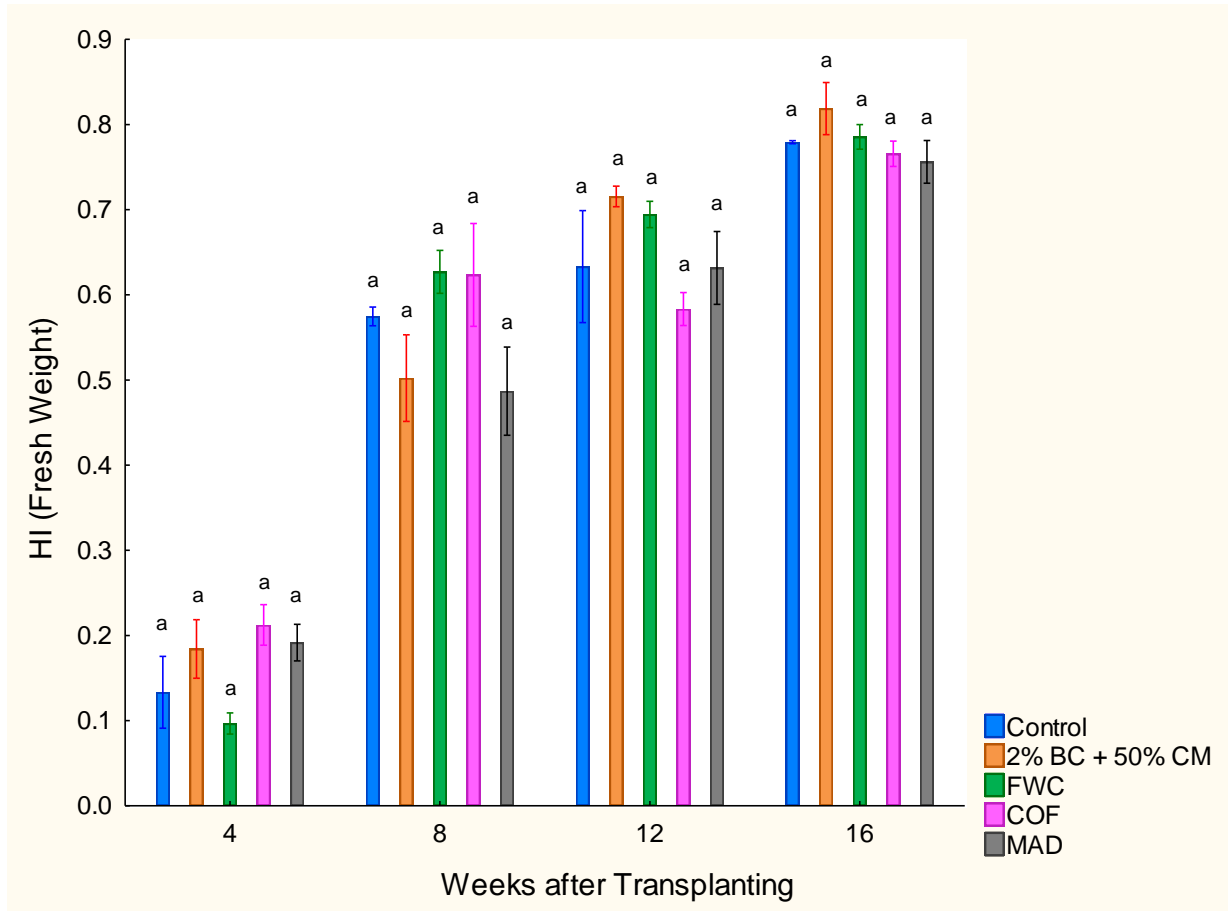
Figure 4.10. Harvest index (HI) over time on a fresh weight basis. *The bars denote the harvest index for each treatment, while the whiskers show the standard error of the mean. No significant differences were observed and no post hoc tests were conducted.. Control refers to the full recommended NPK (2:3:2) on a basis of 100 kgN.ha^{-1}; 2% BC + 50% CM is the 2% biochar rate (w/w) and half the recommended NPK rate; COF is the commercial organic fertiliser and MAD is the manure anaerobic digestate.*
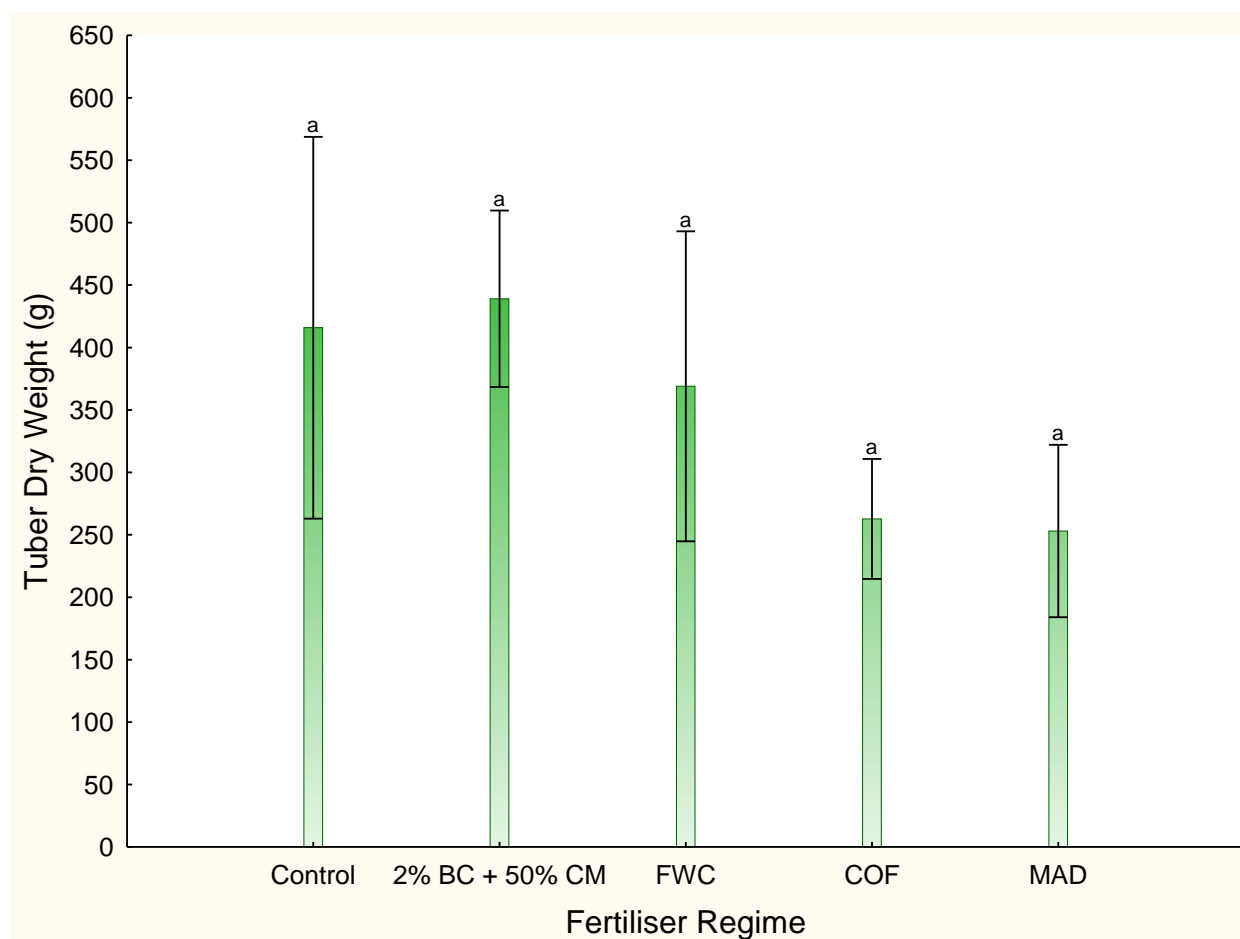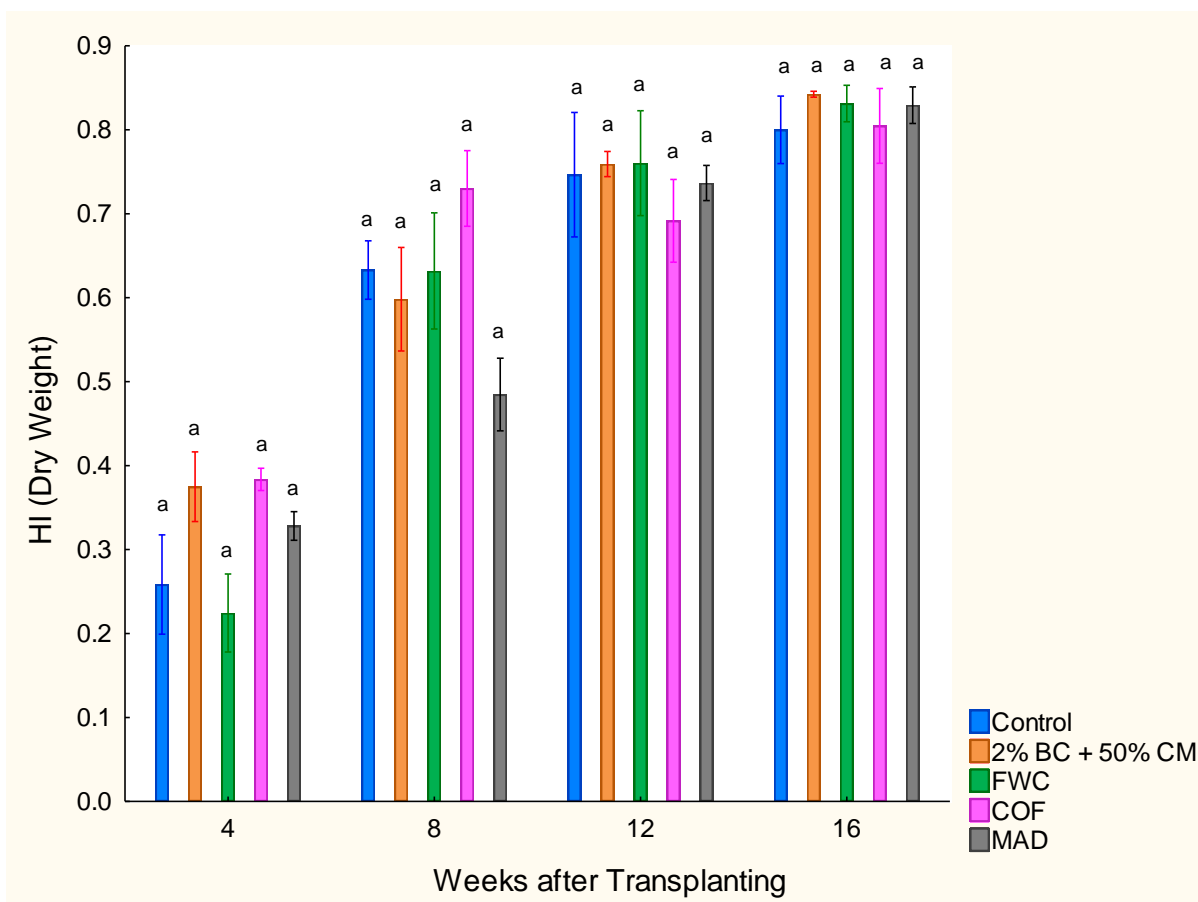
Figure 4.11. Harvest index (HI) over time on a dry weight basis. *The bars denote the harvest index for each treatment, while the whiskers show the standard error of the mean. No significant differences were observed and no post hoc tests were conducted.. Control refers to the full recommended NPK (2:3:2) on a basis of 100 kgN.ha^{-1}; 2% BC + 50% CM is the 2% biochar rate (w/w) and half the recommended NPK rate; COF is the commercial organic fertiliser and MAD is the manure anaerobic digestate.*

4.5.2   Crop yield

4.5.2.1   Tuber dimensions

Tuber diameter at harvest did not show any significant differences (P < 0.05). The highest diameter was recorded in the MAD and biochar-amended treatments (Table 4.4), while the shortest were recorded for the FWC and COF treatments. The control had an intermediate tuber diameter. Tuber length was significantly lower (P < 0.05) in the COF treatment and highest in the 2% BC + 50% CM treatment, followed by the FWC treatment. Once again, the control produced tubers of intermediate length.

Table 4.4. Tuber dimensions at harvest. *The values on the right of the $\pm$ show the standard deviation. CV% = coefficient of variation. The p-value was computed at a significant level of 0.5. NS = no significant difference. The superscript letters show the significant differences (P < 0.05) according to the Tukey HSD (honest significant difference) post hoc test. Control refers to the full recommended NPK (2:3:2) on a basis of 100 kg N.ha^{-1} 2% BC + 50% CM is the 2% biochar rate (w/w) and half the recommended NPK rate; COF is the commercial organic fertiliser and MAD is the manure anaerobic digestate.*

Fertiliser Regime	Tuber Length	Tuber Diameter
Control	16.03 $\pm$ 0.91^a	3.61 $\pm$ 0.58^a
2% BC + 50% CM	18.26 $\pm$ 1.48^a	4.15 $\pm$ 0.97^a
FWC	17.36 $\pm$ 1.23^a	3.06 $\pm$ 0.59^a
COF	10.78 $\pm$ 1.40^b	3.29 $\pm$ 1.63^a
MAD	15.89 $\pm$ 0.98^a	4.78 $\pm$ 1.25^a
CV%	6.19	26.87
p-value	0.0002	NS

4.5.2.2   *Number of tubers per plant, tuber fresh weight and fresh yield per plant*

The number of tubers per plant were significantly low (P > 0.05) in the COF and MAD fertiliser regimes compared to the three other treatments, which produced the same number (Table 4.5).

The mean fresh weight of a single tuber was not significantly different (P < 0.05) across all treatments, although the lowest was recorded for the COF treatments and the highest, the 2% BC + 50% CM treatment followed by the control (Table 4.5).

Tuber fresh yield was greatest in the integrated treatment, which was significantly higher (P < 0.05) than both the COF and MAD treatments in terms of the fresh yield.plant^{-1} (Table 4.5). The control managed to yield a greater portion than the FWC treatment.

4.5.2.3 *Total tuber yield*

Yield per hectare was greatest in the integrated treatment and lowest in the COF treatment, followed by the MAD regime (Table 4.5). The control yielded the second highest fresh produce. The biochar-inclusive treatment produced significantly higher (P < 0.05) tuber fresh yields than the MAD and COF treatments, while the control produced significantly higher yields than the COF treatment.

Fresh tuber yield was significantly higher under the 2% BC + 50% CM regime compared to COF and MAD regimes. The control was significantly higher than the COF treatment in terms of fresh tuber yield.

Table 4.5 Fresh tuber yield and yield components. *The values on the right of the $\pm$ show the standard deviation. CV% = coefficient of variation. The p-value was computed at a significant level of 0.5. NS = no significant difference. The superscript letters show the significant differences (P < 0.05) according to the Tukey HSD (honest significant difference) post hoc test. Control refers to the full recommended NPK (2:3:2) on a basis of 100 kg N.ha^{-1} 2% BC + 50% CM is the 2% biochar rate (w/w) and half the recommended NPK rate; COF is the commercial organic fertiliser and MAD is the manure anaerobic digestate..*

Fertiliser Regime	No. of tubers.plant^{-1}	Tuber fresh weight (g.tuber^{-1})	Tuber fresh yield (g.plant^{-1})	Total tuber fresh yield (t.ha^{-1})
Control	5 ± 0^{ab}	194.61 ± 78.55^{a}	760.78 ± 366.12^{ab}	19.02 ± 9.15^{ab}
2% BC + 50% CM	$5 \pm 1a$	227.30 ± 84.27^{a}	1056.23 ± 299.56^{a}	26.41 ± 7.49^{a}
FWC	5 ± 1^{ab}	179.50 ± 42.18^{a}	581.81 ± 139.09^{ab}	14.55 ± 3.47^{ab}
COF	2 ± 0^{bc}	88.91 ± 18.30^{a}	199.42 ± 44.57^{b}	4.99 ± 1.11^{b}
MAD	2 ± 0^{c}	155.64 ± 22.96^{a}	295.28 ± 71.12^{b}	7.38 ± 1.78^{b}
CV%	21.43	38.09	29.37	29.37
p-value (0.05)	0.005	NS	0.0516	31.27

4.5.2.4 *Unmarketable and marketable yields*

There were no significant differences (P < 0.05) in the total fresh tuber yield or its composition percentage (%) across all treatments (Table 4.6). The lowest was 0.41 t.ha^{-1} under the MAD regime and the highest was found in the integrated and compost treatments at
1.55 t.ha^{-1}. The lowest percentage composition was found in the 2 % BC + 50% CM treatment at 6.32%, while the highest was found in the COF treatments at 26.48% of total yield.

Marketable yield % composition was not significantly different (P < 0.05) for the soil nutrient regimes (Table 4.6). All the treatments produced yields that were above 90% except for COF, which produced a 73.52% marketable yield. Actual marketable yield was significantly lower in the MAD and COF treatments compared to the 2% BC + 50% CM treatment.

Table 4.6. Fresh tuber unmarketable and marketable yield. *The values on the right of the $\pm$ show the standard deviation. CV% = coefficient of variation. The p-value was computed at a significant level of 0.5. NS = no significant difference. The superscript letters show the significant differences (P < 0.05) according to the Tukey HSD (honest significant difference) post hoc test. Control refers to the full recommended NPK (2:3:2) on a basis of 100 kg N.ha^{-1} 2% BC + 50% CM is the 2% biochar rate (w/w) and half the recommended NPK rate; COF is the commercial organic fertiliser and MAD is the manure anaerobic digestate..*

Fertiliser Regime	Unmarketable yield (t.ha^{-1})	Marketable yield (t.ha^{-1})	% Unmarketable yield	% Marketable yield
Control	1.03 $\pm$ 0.98[a]	17.99 $\pm$ 9.82[ab]	7.26 $\pm$ 8.29[a]	92.74 $\pm$ 8.29[a]
2% BC + 50% CM	1.56 $\pm$ 0.23[a]	24.85 $\pm$ 7.72[a]	6.32 $\pm$ 2.29[a]	93.68 $\pm$ 2.29[a]
FWC	1.55 $\pm$ 1.46[a]	12.99 $\pm$ 2.92[ab]	9.97 $\pm$ 10.10[a]	90.03 $\pm$ 10.10[a]
COF	1.28 $\pm$ 0.55[a]	3.71 $\pm$ 1.26[b]	26.48 $\pm$ 14.12[a]	73.52 $\pm$ 14.12[a]
MAD	0.41 $\pm$ 0.42[a]	6.97 $\pm$ 2.16[b]	6.85 $\pm$ 8.13[a]	93.14 $\pm$ 8.13[a]
CV%	69.83	34.62	84.72	10.11
p-value (0.05)	NS	0.008	NS	NS

4.6   Discussion

4.6.1   Crop growth

4.6.1.1   Canopy coverage

Canopy development is more rapid in a sweet potato crop fertilised with a co-application of biochar applied at a 2% rate (w/w) and inorganic fertiliser applied at a 50 kgN.ha^{-1} in an NPK (2:3:2) formulation closely followed by food waste compost. The vigorous leaf growth in the mixed nutrient regime is likely a result of the synergistic effect of a chemical fertiliser that acts as an immediate source of nutrients and an organic amendment that facilitates slowed and therefore, constant nutrient availability (Abd-Ella et al. 2010, Dhomane et al. 2011). Two important ways that biochar enhances nutrient bioavailability are through its liming effect and its capacity to reduce nutrient leaching (Biederman and Harpole 2013). As previously discussed soil fertilised with the recommended rate of NPK, was the richest in plant assimilable N, namely, ammonium (NH_4^+) and nitrate (NO_3^-). The combination of readily available and assimilable N and biochar's inherently sufficient carbon content optimises the C/N ratio, which determines the rate of mineralisation and nutrient availability. The slower release of nutrients in the purely organic FWC soil amendment regime may have caused an initial delay in canopy development.

The canopy coverage in the other organic treatments, COF and MAD, was significantly lower ($P < 0.05$) than the other two alternative nutrient management systems, but similar to each other and the control or recommended rate of 100 kgN.ha^{-1} in a 2:3:2 NPK fertilisers. While the low canopy spread is understandable for the MAD treatment, where the soil remained unfertilised for at least 6 WAT and was only treated with 17L of digestate liquid fertiliser per plant, it is somewhat surprising that the same levels were observed in the COF and inorganic control treatments. N is associated with excessive vegetative growth ref. The NPK control fertiliser and the commercial organic fertiliser were split. Initially, applied 16 kgN.ha^{-1} was applied, while the remaining 74 kgN.ha^{-1} was applied 8 WAT. The first increment may have been insufficient, which could have attributed to the crop's lagged response to these two fertilisers. Canopy coverage, which occurred in the descending order of 2 % BC + 50% CM or FWC > Control (100% CM) is consistent with literature. (Yagoub et al. 2012, Schulz and Glaser 2012) who also found that organic amendments or integrated (partially organic fertiliser regimes), generally lead to greater canopy growth.

4.6.1.2   Chlorophyll content

The leaves of the plants subjected to the control chemical fertiliser treatment appeared visually pale green compared to the FWC, COF and 2% BC + 50% CM, treatments despite. This is surprising as the control produced pale green leaves in comparison to all the other treatments. Seemingly, the pale leaves should have indicated low levels of chlorophyll in the NPK treatments. Limantara et al. (2015) reported a similar result when they investigated the chlorophyll content of different cabbage cultivars of varying shades of green. The control had high available N content, which is likely to have led to the high chlorophyll content, while soils supplemented with FWC had a lower concentration than both the control and COF. However, FWC soils had the highest Mg^{2+}content. Mg^{2+} is essential Mg-chelatase, an enzyme that is involved in the biosynthesis of chlorophyll (Zhang et al. 2006). The decrease in chlorophyll content between 12 weeks after transplanting and 15 weeks after transplanting in all treatments may be attributed to the change in season. Chlorophyll content peaks in summer and decreases in winter due to low light reception (Mauro et al. 2011, Hyyryläinen et al. 2015, Sheikh et al. 2017). The chlorophyll decline was delayed in the MAD treatment.

4.6.1.3 *Number of leaves*

The number of leaves in a sweet potato crop depends on leaf production, which occurs throughout the growing season and as well as cultivar (Somasundaram and Mithra 2008). Environmental conditions and stresses such as drought and salinity also moderate leaf number, although not as extensively as the afore-mentioned factors ref.

The number of leaves per plant 16 WAT was proximate to each other further confirming that the leaf number and area are predetermined factors. The mutable parameter is perhaps the rate at which crops are able to produce the maximal number of leaves for a specific cultivar. According to the current study, simple, imbalanced and unformulated organic and integrated treatments (MAD, 2% BC + 50% CM and FWC), promote rapid leaf production, while the control NPK treatment and industrially formulated COF both showed a slowed leaf production rate, with leaf number only equalling the other treatments at harvest. Amara and Maroud (2013) reported a significant difference in leaves produced at 70 days after planting when sweet potato was grown in inorganic and organic soil nutrient management systems. They concluded that organic amendments yielded higher leaf number than mineral fertilisers. Our study was more prolonged and used cuttings instead of seeds. Thus, there was more time to allow crops in different nutrient management systems to produce maximal leaf numbers. It is therefore more plausible to state that organic amendments could have facilitated rapid or early leaf production.

4.6.1.4 *Vine length, dry weight and fresh weight*

The fertiliser regime did not affect vine length significantly (P < 0.05) at any point during the growing season. Brobbey (2015) obtained similar results. Sweet potatoes produce vines that are typically over 1 m long (Mebratu 2014, Essilfie 2015). However, vine lengths in this study were all below 1 m at harvest. Vine length is highly dependent on cultivar and cultural practices such as spacing and planting density (Essilfie 2015). We planted 2 rows on each ridge approximately 60 cm apart to produce enough crops per plot for destructive sampling. This may have contributed to the relatively low vine length. It was observed that vines collected from plots amended with FWC and 2% BC + 50% CM, were thicker than the more spindly vines obtained from soil supplemented with COF, which had the longest vine. This suggests that COF favours vine elongation, while the FWC and the integrated treatments, which were shorter, favoured vine thickening. On the other hand, vine DW per plant was highest in the biochar-inclusive treatment, followed by the COF and the FWC treatments (46.48, 36.37 and 31.31 g.plant^{-1}, respectively. The FWC treatment had the lowest vine DW:FW ratio. Two ideas arise from this observation. The first is that FWC improves water uptake most efficiently when compared to the control and other alternative soil nutrient systems. This would account for the high vine FW. Secondly, the sustainable and integrated regime shows the optimal balance between vine length and biomass (fresh and dry) production. The MAD treatment produced vines with both the shortest length and least DW, while FW was intermediate suggesting that it is not a suitable alternative to the control NPK treatment, at least in terms of vegetative growth.

Compared specifically to the control, vine FW was 190% and 41.77% higher in the FWC and 2% BC + 50% CM regimes respectively. These two nutrient management that showed the greatest potential for serving as a suitable alternative to inorganic fertilisers when all 3 vine parameters were taken into account. All the treatments enhanced vine dry weight beyond the control's capacity, although only the 2% BC + 50% CM treatment was significantly different (P < 0.05) from the control. This further cements the superior role and suitability of sustainable and inherently integrated, nutrient systems in crop production.

4.6.1.5 *Fresh and dry shoot weight*

Shoot fresh weight (FW) and dry weight (DW) did not differ significantly (P < 0.05) at harvest. While shoot DW was more pronounced with the latter treatment, the COF treatment produced a higher shoot DW than the FWC treatment. This is similar to what was observed for vine growth. Compost has immense potential for improving water uptake in the vegetative organs

of sweet potatoes grown in water-scarce areas. Equally important is its apparent failure to produce as much dry shoot mass as the integrated treatment, which was 71.20% higher and the COF which was 17.71% higher. The disproportion between FWC's FW and shoot DW can have positive or negative implications depending on the partitioning of carbohydrates to storage roots and tuber growth. All three produced higher shoot DW than the control (34.34 g.plant^{-1}), while the MAD treatment produced the lowest. The MAD treatment was in all probability deficient in N and C content and was essentially a biofertiliser. It should be applied in conjunction with another amendment or fertiliser to amplify its effects. Nevertheless it competed favourably with the control which only produced 6.05% more shoot mass. Moreover, it produced a greater FW of 157.87 g per plant than the control which only produced 126.43 g.plant^{-1}

From these findings, an integrated nutrient management system that combines 50 kgN.ha^{-1} with biochar applied at a rate of 2% (w/w) is optimal for vegetative growth more so for dry mass accumulation than fresh biomass production. Walter and Rao (2015) also found that DW was higher in a biochar-mineral fertiliser treatment than in a sole mineral fertiliser application. Similar evidence was reported for food waste compost, particularly in reference to FW. Schulz and Glaser (2012) also compared the effects of mixed biochar - mineral fertiliser systems, compost and sole inorganic treatments on sweet potato growth. They found that biomass production was highest in the integrated system, followed by the compost treatment. Commercial organic fertiliser is also an adequate alternative to chemical fertilisers.

Chlorophyll content also has a substantial effect on shoot weight. High chlorophyll content is associated with enhanced photosynthetic rates. Higher photosynthetic rates lead to increased photosynthate and carbohydrate production. The notion that higher chlorophyll leads to higher photosynthate production and therefore, higher vegetative or reproductive biomass does not hold true for the COF and the control -the richest in chlorophyll content in the first 9 WAT- as leaf production and shoot weight were less than those yielded in the FWC and 2% BC + 50% CM treatments. This implies that chlorophyll's largely positive, linear relationship with the rate of photosynthesis (Fleischer 1935) may be influenced by certain factors, at least in sweet potato. Tsuyama et al. (2003) established that there are instances of deviation from this linear trend, although they failed to identify the specific factors that moderate the relationship between the rate of photosynthesis and chlorophyll content. Flesicher (1935) suggested that minerals like Mg^{2+} directly influence the extent to which chlorophyll content affects the rate of photosynthesis.

4.6.1.6   *Tuber growth*

Fresh tuber growth was only significant at the end of the growing season. At 4 WAT, the mineral fertiliser control produced the largest tuber root FW and DW, followed by the integrated nutrient regime. Chemical fertilisers offer an immediate source of nutrients, which must be constantly replenished to maintain its effects. Interestingly, the FWC treatment, which had the most number of leaves and vine FW at the time, produced only 21.68 g tuber.plan[-1]. The integrated treatment showed a more balanced trend as it produced the second highest number of leaves, second highest vine FW and tuber FW at 4 WAT. Tuber FW also correlated well with tuber DW for this treatment (22.23 g.plant[-1]). Only the FW of the control treatments and tuber DW were higher than those harvested from the 2% BC + 50% CM treatment. The slowed nutrient availability typical of organic amendments caused initial tuber growth penalties. However, this changed in the ensuing weeks where the FWC and 2% BC + 50% CM treatments produced the two highest fresh tuber root yields. Although the dry tuber weights in these two treatments were still higher than the DW in the control, the COF treatment produced the highest tuber DW 8 WAT, suggesting that the commercial organic fertiliser, which had the lowest number of leaves and vine FW at 8 WAT partitioned most of its photosynthetically produced starch or carbohydrates from the shoot to the tuber root. This trend did not continue past the week 8. In fact, tuber DW declined to the same level as the DW observed in the MAD treatment. Rates higher than the 100 kgN.ha^{-1} were applied to the plots could further enhance and prolong this positive effect. In addition, applications should be more frequent and at more crucial stages. Applying chemical fertiliser at a later stage in the growing season possibly contributed substantially to the tuber FW and DW at harvest.

Both biochar and the control yield weights outcompeted tuber weights in the FWC treatment. The almost sudden tuber growth spurt in the biochar-containing treatment may also indicate that either the rate of nutrient release was slower in biochar than in food waste compost or that the tuber bulking process was slower in biochar treatments.

4.6.1.7   *Harvest index (HI)*

The HI is the ratio between the harvested organs and the total plant biomass. The range of the HI in our study was similar to those obtained by Esselfie et al. (2015). Although not significantly different throughout the study, the HI corresponded well with the earlier hypothesis that COF performed exceptionally well in terms of the relationship between shoot

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and tuber weight 8 weeks after transplanting. The HI was highest (0.73) in the organic fertiliser. This was also the case in the first sampling round when vegetative growth was still prevalent resulting in a low maximum of 0.38. The COF treatment may result in early carbohydrate partitioning from the leave to the roots. Leading up to the harvest, the 2% BC + 50% CM (0.84) and FWC (0.83) treatments showed the highest HI for FW and DW, suggesting a slower tuber bulking process than in the COF treatment. The control produced the lowest HI based on DW at harvest, but a higher HI than COF and MAD on a fresh weight basis. Sweet potato carbohydrate partitioning from the leaves to the tubers appears to apparently respond positively to organic amendments. Although the high assimilable N rates in the control-fertilised soil imply an adequate source of nutrients, it is crucial to keep in mind that HI correlates negatively to the vine weight and positively to tuber weight. This is particularly the case when P is added at an equally high or a level exceeding such as was the case in the NPK (2:3:2) fertiliser. In conditions where N and P supply is excessive, vegetative growth is high, unfavourable and draws assimilates away from the storage roots that act as sinks.

4.6.1.8 *Tuber weight per plant yield and total yield*

The integrated treatment produced fresh tuber yields that were 38.85% higher than the conventional regime control. This is comparable to results obtained by other researchers (Lui et al. 2014; Walter and Rao, 2015). The co-application also reduced chemical fertiliser requirements by 50%, making it a viable alternative to exclusively inorganic fertiliser regimes. In addition, to improving soil physicochemical properties, biochar confers beneficial changes in the microbial activity in the soil and supplies microorganism with nutrients.

The yields obtained in the compost treatment were lower than the control. However, it is worth noting, however, that these systems were completely organic i.e. the soils were not supplemented with N or K^+. The biggest issue with the FWC may have been an imbalance in nutrients, an excess in minerals like Na^+ (highest in FWC soils), which leads to salinity and cations that hinder the uptake of essential and non-essential cations, relatively lower dry matter production and excessive vegetative growth. The benefit of compost, especially over chemical fertilisers may be due to its ability to enrich microbial populations and activities in the soil. This particular advantage may have been nullified in this study as the chemical fertiliser control apparently had similar microbial populations. Alternatively, the nutrient imbalance of compost, or a combination of this and the aforementioned inefficiencies may have partially contributed to its less pronounced impact compared to the control. The MAD and COF treatments showed

the least amount of potential. Anearobic digestate is a relatively new form of organic amendment. Consequently, agronomists and other land workers do not fully understand its potential as a soil amendment. Some researchers refer to it a as a biofertiliser, while others a conventional organic amendment. When we consider it as a conventional liquid fertiliser, we minimise the threat it poses to soil health, microbial activity and life. A change in the soil microbiome through population changes, interactions and the secretion of fungal and bacterial substances may have adverse effects on crop growth and yield. Furthermore, anaerobic digestate should not be applied alone.

4.6.1.9   *Crop marketable and unmarketable yields*

Marketable yields refer to yield that are above a certain size, weight or quality. In the current study, the criterion was only size. Sweet potato tubers weighing less than 80 g were categorised as unmarketable. The unmarketable yield in t.ha^{-1} was similar across all the treatments, but differed significantly ($P < 0.05$) in terms of percentages. Only approximately

6.5 % of the total fresh tuber yields were unmarketable. The COF treatment produced the highest percentage of unmarketable yields (26.48 %). The marketable yield, similar to the unmarketable fresh yield did not differ in terms of percentage, but differed signficantly ($P < 0.05$) in terms of yield. The highest producing treatment was the 2% BC + 50% CM treatment, followed by the control and the compost nutrient regimes. It was previously found that biochar with NPK perceptibly increased marketable yields compared to single applications of each component (Walter and Rao 2015).

4.7   Conclusion

The COF treatment yielded poorly. Crop growth, tuber yield and yield components were much lower than in the control treatment. This was likely a result of the delayed application of the second increment, which was beyond our control. The MAD treatment was comparable to the COF treatment. Anaerobic digestate liquid should not be applied alone and should be applied in the same manner as a biofertiliser i.e. in conjunction with organic amendments. The nutrient composition of compost may have hindered its performance, although yields were comparable to those obtained in the control. Therefore, a suitable sustainable alternative to chemical fertilisers, especially in soils that are dry and lacking in OM. Integrated biochar

and mineral fertiliser systems are extremely viable and could reduce inorganic fertiliser requirements by 50%. Seemingly, it improved tuber fresh yields in conventional inorganic system by a remarkable 38.85 %, although this is tempered by climatic conditions and genotype.

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CHAPTER 5

Sweet potato nutrition under different soil nutrient management systems

5.1   Abstract

Sweet potatoes are highly nutritional and constitute one of the world's most important crops, especially in developing countries. Very little information is available on the impact of different fertiliser regimes on sweet potato (*Ipomoea batatas* (L.) Lam) tuber moisture, crude fiber, protein and starch content. We investigated the impact of 5 different soil nutrient management regimes on these nutritional qualities. The five treatments were an inorganic fertiliser applied at the recommended rate of 100 $kgN.ha^{-1}$ in an NPK formulation (100% CM), an integrated fertiliser regime with co-applications of $kgN.ha^{-1}$ and biochar applied at a 2% rate (w/w) (2 % BC + 50% CM), a food waste compost (FWC), commercial organic fertiliser (COF) and anaerobic digestate derived from manure (MAD). Control plots were unfertilised. The field experiment was conducted on twenty-four $20m^2$ plots in a randomised complete block design. Each treatment, including the control had four replications. Only protein showed a significant difference (P <0.05). Inorganic fertiliser yielded 2.12% mean protein content in dried tubers. This was significantly higher than the protein contents in sweet potatoes cultivated on control (unfertilised) and MAD-amended soils. Although, tubers obtained from the 100% CM treatments were not significantly different from the remaining treatments, the tubers had a 46.21% higher protein content than tubers obtained from the 2% BC+ 50% CM treatment, which yielded the second highest protein concentration. Nitrogen is essential for amino acid synthesis, which constitute the building blocks for protein. Moisture, crude fiber and starch content were unaffected by the type of fertiliser regime, but were highest in the FWC and 2% BC + 50% CM treatments. Our results indicate that sustainable, integrated soil nutrient regimes and organic amendments have the potential to produce sweet potatoes that are either similar or higher in energy and crude fiber than conventional inorganic fertilisers. This has remarkable implications for the sustainable production of healthy foods, especially small-scale farming operations. Moisture content is marginally reduced in organic and semi-organic regimes, which may lead to increased dry matter accumulation. Unfortunately, the reduced protein content poses a problem for countries where tuber crops like sweet potato constitute a significant part of the diet and make a notable contribution to total protein consumption.

5.2   Introduction

Sweet potato is highly nutritious and has a high carbohydrate and dietary fiber content (Lebot 2009, Agriculture, Forestry and Fisheries Department of South Africa 2011, Kareem 2013). It is high in vitamins A (orange-fleshed bio fortified varieties), C and B6. Purple-skinned varieties are rich in β-carotene - the precursor for vitamin A. They also contain considerable levels of antioxidants, protein and minerals like phosphorus, potassium, calcium, iron, zinc and folic acid to name a few. Numerous developing countries consider it to be a vital crop in the alleviation of malnutrition. Its protein content is amongst the highest in staple crops and it ranges from 2% to 10% (Hattori et al. 1985). In addition it is recognised as having one of the highest energy production rate per unit of land area and time (Feuntes and Chujoy 2009).

Sweet potato is a highly tolerant crop and can be cultivated under a range of climatic and edaphic conditions (Lebot 2009, Department of Agriculture, Forestry and Fisheries RSA 2011, Reoma et al. 2014). It is highly suitable for sustainable and/or organic soil nutrient management systems that characterize many small-scale farming operations (Miyazaki et al. 2013) Sweet potato's nutritional quality is one of its notable selling points. Farmers and agronomists should not adopt any soil enrichment practices that may compromise its nutrition. Extensive research must be done to fully comprehend the impact of inorganic and alternative soil nutrient regimes.

According to Hornick (1992), there is no consensus regarding the differential effects of organic and inorganic fertilisers on the nutritional quality of crops. Jarvan and Edesi (2009) state that healthy food can be produced in organic and inorganic soil nutrient management systems and that in most cases the problem is the potential toxicity of certain elements, rather than nutrient deficiencies in crops.

Important and easily measurable nutritional compounds in sweet potatoes are sugar or starch content, crude fiber, protein and moisture. Dou and colleagues (2014) established that biochar enhances sugar content more than mineral fertilisers. Their reasoning was that pyroligneous acid contained within the biochar increases sucrose concentration. Crude fiber appears to be inversely proportional to inorganic fertiliser application (Ukom et al. 2009), while protein responds positively to nitrogen fertilization up to a certain rate, specifically 80 kgN.ha^{-1}, after which it remains constant. The spike in protein levels with the application of inorganic fertilisers is not surprising as nitrogen constitutes is needed for the initial steps in the amino acid biosynthesis process. Ultimately, there is little to no evidence to assert that inorganic and organic fertilisers have a significant impact on tuber nutrition. This knowledge is essential in

assisting sustainable and organic agriculture strengthen their plea for these type of systems as an alternative to conventional, inorganic systems.

5.3   Objectives

The objectives of this part of the study were:

a)   To determine tuber moisture content across the six different soil nutrient management systems.

b)   To assess the protein, crude fiber and starch percentage composition on a dry matter basis.

5. 4   Materials and Methods

The information regarding the experimental site, conditions, design and treatment preparation is provided in Chapter 3.

5.4.1   Sampling for nutrition analyses at harvest

Three sweet potato plants were harvested from each plot representing one of four replicates from six fertiliser treatments in the autumn season of 2017. The control referred to sweet potatoes grown on unfertilised soil. The rest of the treatments were sweet potatoes grown on soil fertilised with the full recommended rate of 100 kgN.ha^{-1} in a chemical fertiliser with an NPK formulation of 2:3:2 (100% CM); biochar applied at a rate of 2% on a w/w basis and supplemented with half of the recommended rate of the NPK fertiliser (2% BC + 50% CM); food waste compost (FWC); commercial organic Talborne Vitagrow® fertiliser with N:P:K formulation of 2:3:2 (COF) and farmyard manure anaerobic digestate (MAD). The biochar was produced from dry, woody, and plant material through pyrolysis (combustion under higher temperature and anoxic conditions). All three plants from a single plot were placed into a single brown paper bags. The plants were stored in a 4°C refrigerator. The tubers were removed from the shoots. The most representative tuber, in terms of size and shape, was chosen from each bag. Twenty-four tubers were selected to represent four replicates for each of the six treatments. The sweet potatoes were peeled and sliced lengthwise into 3-5 mm layers. Sweet potatoes were analysed for moisture, crude fiber, protein and starch content. Crude fiber, protein and starch content were all measured on a dry matter basis.

5.4.2   Moisture content

Twenty-four aluminium foil containers either rectangular (12.7 cm x 7.1 cm x 2.8 cm) or circular (10.2 cm x 3.2 cm) in shape were weighed on a microgram scale. These were labelled according to the six treatments and their four replicates. The tuber slices were placed inside the labelled aluminium foil containers on the scale and the weights recorded. In cases where sliced tubers exceeded a fresh weight of 250g, some tuber slices were discarded to fallow for efficient drying. The tubers were dried in a 60°C oven over a period of 5 days. Subsequently, the aluminium tin foil containing the dried tuber slices were weighed on the same microgram scale used to measure the fresh weight. The container weights were subtracted from the weights of the aluminium tin containers and tuber slices to obtain the weights of the slices alone. Moisture content expressed as a percentage was determined using the formula below.

$$Moisture \% = \left[\frac{Tuber\ fresh\ weight - Tuber\ dry\ weight}{Tuber\ fresh\ weight}\right] * 100$$

5.4.3   Crude fiber

After drying, the slices were milled into semi-fine powder. Thereafter, 1g of each sample was weighed into two 50ml plastic containers. These were placed in a VELP Raw Fiber Analyzer® with 6 compartments. In the first extraction round, a boiled 0.128 M sulphuric acid reagent (6.96 ml 98% H_2SO_4 in 993.04 ml water) was poured into the column and 50ml containers containing the sample. The reagent inside the columns was maintained at 65°C. After 30 minutes, the reagents were suctioned through a vacuum process and the columns were washed with boiled distilled water three times. In the second extraction round, a boiled 0.313 M sodium hydroxide reagent (12.5 g NaOH in one litre of distilled water) was poured into the columns and containers with the samples. The same procedure was followed. In the last extraction round, 20 ml acetone was poured down the column three times to ensure maximum collection and quality of the sample through the removal of detergent and water. The samples were dried overnight in a 100°C oven. On the next day, the 50 ml plastic beakers containing the sample residues were placed in a desiccator for 30 minutes after removal from the oven and weighed. Thereafter, sample residues were ashed in a 500°C Labofurn 1.4 litre Kiln Contracts (PTY) Ltd® for six hours. The residues were cooled to below 250°C and

placed into the desiccator for 30 minutes. The containers along with the samples were weighed again. The crude fiber percentage was determined using the formula below.

$$Crude\ fiber\ \% = (A - B) * 100$$

A is the weight of the residue in the container after drying at 100°C and B is the weight of the residue after ashing at 500°C. The crude fiber analysis methods used were the Weende method (Wilcox 1949) and the Van Soest method (Van Soest et al. 1991).

5.4.4   *Protein content*

The Kjeldahl method (AOAC 990.03) was used to determine protein content. Milled samples of 0.1 g were weighed into small aluminum crucibles in duplicates and placed into a Leco FP528® Nitrogen Analyzer. The values were recorded on FP528 software and the N percentage output was averaged to give a single nitrogen percentage value that was used to calculate protein content. Protein % calculations took moisture content into account and were given on a dry matter basis. The standard 6.25 nitrogen to protein conversion rate was used to determine protein content.

$$Protein\ \% = Nitrogen\ \% * \left[\frac{100 - Moisture\ \%}{100} \right]$$

5.4.5   *Starch content*

Thirty millilitres of 0.1 M acetic acid buffer (pH 5) were added to forty-eight 20 ml test tubes (duplicates of 24 samples). Thereafter, 300 µl of α-amylase were added. After vortexing, 0.2 g of sample were added to the solution in each test tube. The mixtures were placed in a 100°C water bath for 1 hour. The mixtures were vortexed at 10, 30 and 50 minutes. After removal from the water bath, the test tubes were placed in cold water for 5 minutes and were left at room temperature for 30 minutes to allow the mixtures to cool down to 50°C or below. Subsequently, 300µL of amyloglucosidase enzyme solution was added. After further vortexing, the test tubes were placed in a 50°C water bather for 2 hours. The solutions were mixed vigorously after each hour. The assay was then transferred into a 100 ml volumetric flask using cotton wool as a filter on the flask's opening. Distilled water was poured into the flask to bring the assay solution to volume. After rigorous shaking, one millilitre of the solution was collected and centrifuged at 1000 x g for 10 minutes. Ten microliters of the samples were placed in duplicates into a microplate. GOPOD solution of volume 300µl was added to each of the 96

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samples. The microplate was incubated at 50°C for 20 minutes before reading the absorbance at 505nanometres. The starch content was calculated using an absorbance value-concentration standard curve and a starch unfermented template provided by the Animal Science Department at Stellenbosch University. The procedure used was the digestion method for resistant starch (McCleary et al. 1992).

5.4.6   *Statistical analysis*

A one-way analysis of variance (ANOVA) method was used to analyse the data on Statistica® version 13.2 software. The Tukey HSD (Honest Significant Difference) post-hoc test was used to separate means at a significant level of $P < 0.05$. This was selected over the Fisher LSD (Least Significant Difference) based on the criteria of the number of treatments and the elimination of statistical errors.

5.5   Results

The results indicate that there was no significant difference ($P > 0.05$) in the moisture, crude fiber and starch content of sweet potato tubers harvested from different soil nutrient management systems (Table 5.1). The commercial organic fertiliser, however, appears to have yielded tubers with the lowest moisture content and crude fiber content at 73.10% and 2.73%, respectively. Crude fiber was similarly low in the control, 100% CM, COF and MAD treatments. Conversely, food waste compost (FWC) produced tubers with the highest moisture at 77.93%, crude fiber content at 3.40% and starch content at 50.80%. Starch content was lowest in tubers grown on unfertilised soil (control) at 34.12%. The biochar and chemical fertiliser combination (2% BC + 50% CM) soil nutrient management system produced tubers with the second highest crude fiber and starch content. The recommended rate of inorganic fertiliser NPK (100% CM) yielded tubers with the highest percentage composition of protein at 2.12 % and was significantly different ($P < 0.05$) from the control and anaerobic digestate amendment, which produced sweet potatoes with the lowest protein content. The rest of the treatments, 2% BC + 50% CM, FWC, and COF yielded similar protein compositions and did not differ significantly to ($P > 0.05$) in sweet potato protein levels from the 100% CM fertiliser regime and control and MAD treatments.
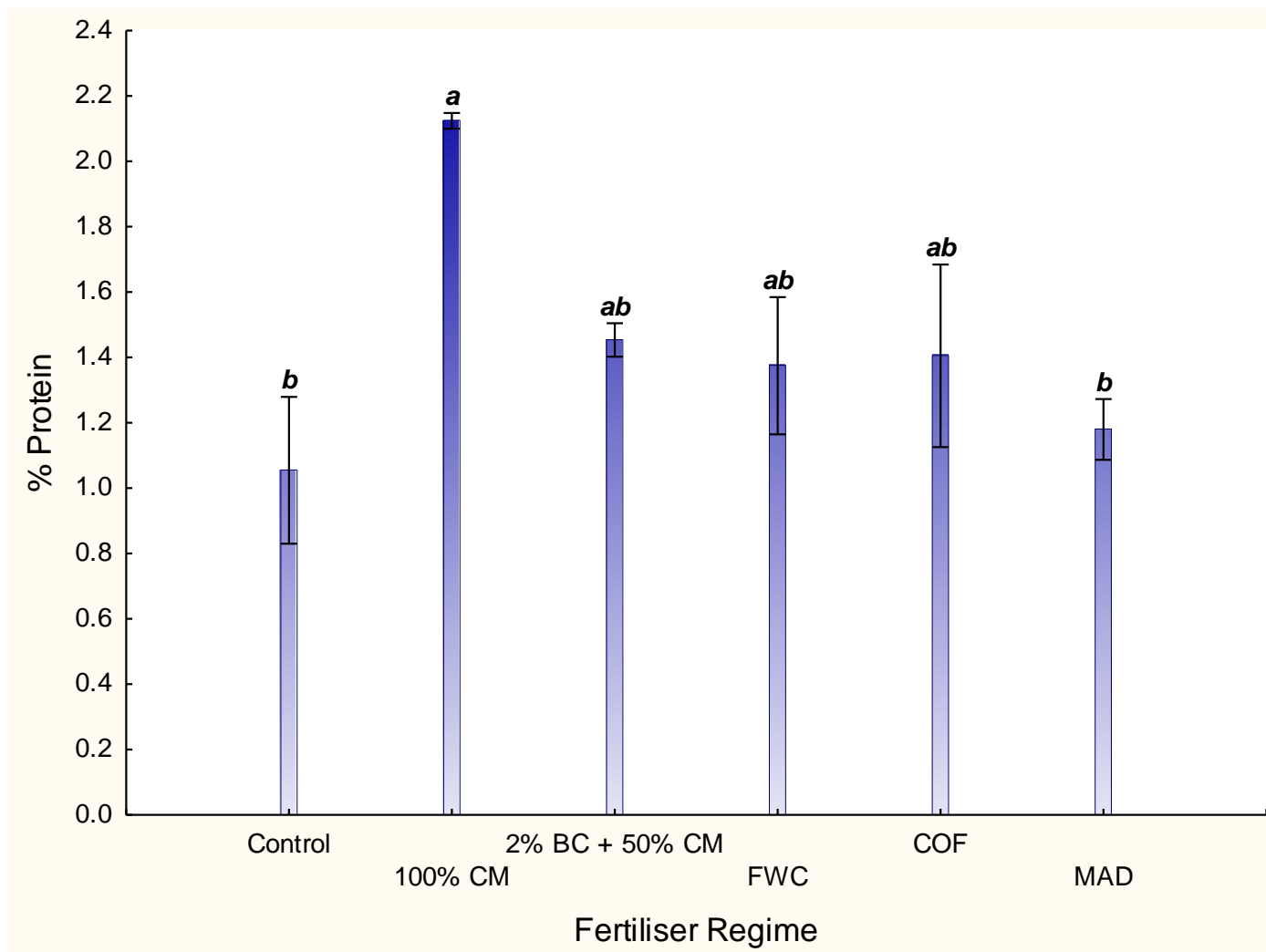
Figure 5.1. Protein content in sweet potato tubers under different fertiliser regimes. *The bars denote the means of % protein for each fertiliser regime, while the whiskers represent the standard error of each mean . Control refers to unfertilised soil; 100 % CM is the full recommended NPK (2:3:2) on a basis of 100 kgN.ha⁻¹; 2% BC + 50% CM is the 2% biochar rate (w/w) and half the recommended NPK rate; COF is the commercial organic fertiliser and MAD is the manure anaerobic digestate.*

Table 5.1 Moisture, crude fiber, protein and starch percentage composition. *The values on the right of the ± show the standard deviation. CV% = coefficient of variation. The p-value was computed at a significant level of 0.5. NS = no significant difference. The superscript letters show the significant differences (P < 0.05) according to the Tukey HSD (honest significant difference) post hoc test. Control refers to the full recommended NPK (2:3:2) on a basis of 100 kg N.ha^{-1} 2% BC + 50% CM is the 2% biochar rate (w/w) and half the recommended NPK rate; COF is the commercial organic fertiliser and MAD is the manure anaerobic digestate*

Fertiliser regime	Moisture %	Crude fiber %	Protein %	Starch %
Control	76.57 ± 7.55[a]	2.81 ± 0.60[a]	1.05 ± 0.39[b]	34.12 ± 14.05[a]
100% CM	76.52 ± 1.69[a]	2.90 ± 0.29[a]	2.12 ± 0.04[a]	46.83 ± 14.47[a]
2% BC + 50% CM	76.59 ± 2.78[a]	3.22 ± 1.11[a]	1.45 ± 0.09[ab]	48.54 ± 18.37[a]
FWC	77.93 ± 3.10[a]	3.40 ± 1.06[a]	1.38 ± 0.36[ab]	50.80 ± 11.82[a]
COF	73.10 ± 16.66[a]	2.73 ± 0.28[a]	1.41 ± 0.48[ab]	47.05 ± 19.37[a]
MAD	74.90 ± 1.98[a]	2.94 ± 0.28[a]	1.17 ± 0.16[b]	46.08 ± 19.92[a]
CV %	7.52	19.55	19.92	36.26
p-value	NS	NS	0.016	NS

5.6   Discussion

5.6.1   *Moisture content*

The moisture content in this study was considerably high (73.07% to 77.93%) (Table 5.1) relative to the moisture content observed in sweet potato tubers in other studies where the percentage composition is typically within the 60 to 70% range (Mabretu 2014, Esselfie 2015). A possible reason is that the an irrigation system was used in the experiment whereas most growers operate under dry land systems. Sweet potato is regarded as a subtropical and tropical crop that can grow in drought-affected areas where dry land systems are in place (Braun et al. 2003, Motsa 2015, Saitama et al. 2017). Water-limiting conditions can decrease the moisture content in sweet potatoes and moderate the influence that organic and inorganic fertilisers have on moisture and dry matter content (Saraswati 2007). Furthermore, studies report results that vary to a great extent, which makes it challenging to discern the precise relationship between inorganic and organic nutrient regimes as well as tuber moisture

content. For instance, some studies like those performed by Igbokwe et al. (2005), Ukom et al. (2009), Nwite (2016) and O'Beirn (1990) report a significant increase in moisture content and a decrease in dry matter content under inorganic fertilisers, while Baniuniene and Zekaite (2008), Gichuhi et al. (2014) report the converse. Sweet potato moisture content is tempered by the genotype and prevailing environmental conditions.

5.6.2   *Crude fiber*

Studies vary greatly in their documentation of the influence of inorganic fertilisers and organic amendments on crude fiber. Most report that there is no significant difference (Igbokwe et al. 2005; Kareem 2013, Gichuhi et al. 2014). The current study indicates the same trend .In the cases where researchers report significant differences in crude fiber accumulation in sweet potato cultivated under different soil nutrient management systems, inorganic fertilisers are observed to adversely impact biosynthesis, while organic amendments generally maximise it (Ukom et al. 2009; Nwite 2016). Although the current study failed to show a definite effect of fertiliser type, it demonstrated a relatively strong positive correlation between organic amendments and crude fiber content. The FWC treatment led to the most notable increase in crude fiber at 3.40% of dry matter content. In their extensive study where they evaluated the effect of no fertiliser treatment, NPK application and organic amendment with poultry dropping, Neem leaf, Moringa leaf, rice husk dust and rice husk ash on sweet potato growth and nutrient composition, Ukom et al. (2009) found that the leaf treatments resulted in the highest crude fiber composition. This is in agreement with our findings that show that the FWC and biochar-inclusive organic amendments that both plant material, are most likely to increase crude fiber biosynthesis beyond the capacity of inorganic and other organic nutrient regimes like biologically decomposed manure (MAD) and commercial organic fertiliser. Cellulose constitutes a considerable component and easily the largest component of crude fiber in plants; however, there is very little existing knowledge on its synthesis. Delmer and Amor (1995) suggest the importance of carbon in the insoluble material's biosynthesis. This is hardly surprising as the compound consists of strongly bonded B-1-4 glucans (Kudlicka and Malcolm 1996). FWC and biochar were the highest in carbon and accordingly, organic content, which may be the reason for their slightly higher crude fiber accumulation.

5.6.3   *Protein content*

Sweet potatoes are generally acknowledged to have a higher protein content than their tuberous

and staple counterpart like cassava and yam (Mukhtar 2010). Protein composition, depending on the specific cultivar, can be as high as 10% (Walter et al. 1985; Ukom et al. 2009). Walter et al. (1985) state that as much as 85% of N contained within sweet potatoes forms part of the total protein content, with the rest contributing to non-protein- nitrogen (NPN). This explains the significantly higher (P < 0.05) protein levels in the inorganic 100% CM treatments where NPK was applied at 100 kgN.ha^{-1} and the significantly lower protein contents in tubers harvested from soil that was not supplemented with N When the NPK fertiliser and consequently the N rate, were reduced by half and combined with biochar, the crude protein levels also decreased to the level of the commercial organic fertiliser and the food waste compost, further demonstrating the importance of N supplementation or at least balanced NPK application in sweet potato

protein quality. The mineral fertiliser increased protein content by 101.91%, 46.21%, 53.62%, 50.35% and 81.20 % relative to the control, 2% BC + 50% CM, FWC, COF and MAD soil nutrient management systems, respectively (Table 5.1). Although the 2% BC+ 50% CM and COF fertiliser regimes yielded tuber protein levels that had a marginal difference from each other and the protein levels observed in FWC tubers, they produced the second and third highest protein content. Nwite (2016) showed that NPK fertilisers resulted in higher tuber protein concentrations than organic amendments such as rice husk, poultry manure and Moringa leaves, although the differences were not significant. It is therefore not surprising to find that the lowest protein content in tubers grown on treated soils was observable in manure anaerobic digestate and food waste compost treatments. It has been stated in literature that K and P supplementation do not affect protein concentration in sweet potatoes (Wang et al. 2016). Thus, it is reasonable to attribute the substantial increase in protein in the 100% CM fertiliser regime, followed by the 2% BC + 50% CM treatment, more to nitrogen supply than a balanced NPK application. Molecular nitrogen is converted to or added in assimilable form, specifically nitrate or ammonium (Masclaux-Daubresse et al. 2010). Keto acids combine with ammonia in reductive reactions that produce an amino acid, which form the basic building blocks for proteins (Umbarger 1978). Indeed, Ukom et al. (2009) found that increasing nitrogen application along with single applications of phosphorous and potassium increased protein in sweet potato. Interestingly, they reported that protein stopped responding to increasing nitrogen at 80 kgN.ha^{-1}. In other words, higher rates did not lead to a significant increase in tuber protein. This is in congruence with results obtained by Phillips and Warren (2005). Kareem (2013) obtained substantially different results from the current study. The author investigated the effects of inorganic and organic fertilisers on sweet potato tuber protein content with an unfertilised control. He found that the control resulted in the highest protein content. A

possibility is that while farmers recommend an NPK regime with a nutrient composition of 2:3:2, Kareem (2013) used an NPK fertiliser with formulation 15:15:15. This explanation, would however, somewhat nullify our previous statement that phosphorous and potassium content do not significantly affect protein content. In addition, a 1:1:1 ratio does not differ greatly from our ratio of 2:3:2. Several decades ago, Walter et al. (1985) stated that not enough research has been done on the relationship between fertiliser (including organic amendments) and sweet potato protein content. This is still unfortunately the case, preventing researchers from making accurate conclusions.

5.6.4   *Starch*

Numerous studies demonstrate that starch, carbohydrate or sugar content increase with the addition of organic amendments and decrease with the application of mineral fertiliser application (Ukom et al. 2009; Jarvan and Edesi 2015; Nwite 2016). The simplest molecule in starch is glucose, Glucose is formed from carbon, hydrogen and oxygen (University of Dehli nd, Pfister and Zeeman 2016). The more carbon that is available, the more glucose plants synthesise (Pfister and Zeeman 2016) This accounts for the trend observed in the study where the highest starch content was obtained in the FWC, 2% BC + 50% CM and COF treatments and lowest content in the control. The differences were, however, not significant.

The control nutrient regime, NPK, produced tubers with lower starch content than the biochar-containing treatment. The tuber growth recorded in previous sections of this work, show higher tuber growth in the biochar treatment than in the chemical fertiliser. Kandi et al. (2011) reported that an imbalanced supply of nitrogen to sweet potato crops may result in adverse effects on tuber growth. Furthermore, biochar is a pyroligneous acid that enhances sugar content (Dou et al. 2012). Organic amendments may also promote carbohydrate- partitioning to the roots, at least to a greater extent than inorganic fertilisers. Baniuniene and Zekaite (2008) noticed a different pattern in a trial that assessed the influence of mineral fertilisers with and without manure supplementation. They found that adding manure significantly decreased starch content and that the most favourable starch yield accompanied sole mineral fertiliser applications. In fact, the addition of manure also reduced tuber yields. This is precisely what was observed in the current study where the MAD treatment reduced starch content. These reductions may be a result of manure and manure-derived digestate with imbalanced nutrient compositions and unfavourable C/N ratios that can lead to nutrient immobilization. This would mean that unlike in protein content, nutrient balance, especially in the essential minerals NPK, is essential and plays a vital role in starch content.

5.7   Conclusion

The case for the influence of protein levels by soil nutrient regimes is for the most part evident. Inorganic fertilisers, specifically nitrogen, increase tuber protein content to a greater extent than organic fertilisers. The adoption of organic agriculture or sustainable agricultural cropping systems such as the combination of biochar with mineral fertilisers reduce protein content in sweet potato relative to inorganic fertilisers. This is the only adverse effect of sustainable, alternative soil enrichment practices on nutritional quality. Organic fertilisers reduce moisture content and subsequently enhance dry matter accumulation, although this effect is marginal. Organic amendments also maintain starch and crude fiber levels and even increase them marginally compared to chemical fertilisers, which further substantiate them as an adequate alternative or supplement to chemical fertilisers. The maintenance or enhancement of nutrition in low inorganic input has low input systems also holds great benefit for small-scale farming operations.

5.8   References

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CHAPTER 6

Summary and conclusion

6.1   Overview

Growing demand for food that is also nutritious places pressure on food producers, specifically farmers, to increase yield output (Tilmana et al. 2011). Agriculture, however, needs to be sustainable in order to meet the needs of current and future generations. One of the many solutions that form part of a broader strategy to ensure sustainable crop production is to maintain or improve soil and environmental health by limiting the use of inorganic fertiliser, which are more often than not detrimental to soil health end subsequently led to yield decrease over time (Schroder 2014). More sustainable soil nutrient management systems have the added benefit of enhancing soil fertility, improving crop yields, over the long-term (Diacono et al. 2010). Moreover, there often ideal for small-scale farmers, who form the vast majority of farmers, both globally and in African countries (Matsumoto and Yamano 2010, Radebe 2014). The alternative soil nutrient regimes are cheaper and are likely to reduce input requirements over time. Sustainable fertiliser regimes are not necessarily organic and require the complete elimination of chemical fertiliser. Integrated systems like the co-application of biochar and mineral fertiliser reduce the inorganic fertiliser requirement without causing yield reductions (Diacono et al. 2010).

This study investigated the use of organic and integrated soil nutrient management systems as key strategies in sustainable crop production of sweet potato (*Ipomoea batatas (*L.*)* Lam). This crop was chosen on the basis of its highly nutritious quality. The cultivar, Bosbok, was selected based on its widespread use in the Western Cape and the rest of South Africa.

The current study showed that the integrated use of biochar and mineral fertiliser is an effective and excellent alternative to sole chemical fertiliser applications. Biochar's alkaline property reduces the acidifying effect of chemical fertilisers, thus enhancing soil pH levels and reducing soil acidity beyond the capacity of mineral fertiliser regimes (Jeffrey et al. 2017). The current study showed that soil cation exchange capacity improves even more under this type of nutrient management system compared to sole mineral fertiliser regime. Minimal acidity, pH level of ~6.25 and relatively high CEC are conducive to nutrient release and uptake in plants (Jeffrey et al. 2017). The organic matter in biochar enhances soil carbon content and the composition of most minerals, although N and Sulphur are typically higher in chemical fertiliser application (Larney and Angers 2012)

When biochar is applied in conjunction with inorganic fertiliser, it outperforms sole organic amendments like compost in terms of yield. One of the main reasons for this may be that adding a formulated, balanced NPK fertiliser compensates for the imbalanced nutrient composition in biochar (Krauss 2004). Biochar is known to alter the soil microbiome (Jenkins et al. 2017). This effect may be positive or negative depending on the nature of the change. This study showed that the integrated biochar-mineral fertiliser systems decrease the aerobic microbe population in the soil. This was expected as biochar production is an anaerobic process (Lone et al. 2015). According to this study, fungi populations respond similarly to inorganic and organic fertilisers, at least in the short term. In addition, biochar increased organic matter, leading to improved soil structure, texture and water related properties, although the study did not investigate these.

Food waste compost can improve soil pH (6.5 in the study) and reduce acidity to the same extent as an integrated biochar-mineral fertiliser system. More impressively, it increased CEC to beyond the ability of both sole inorganic NPK and co-applications of biochar and mineral fertiliser. However, compost's mineral composition can only be controlled by managing the input material (A and L Canada Laboratories nd). In most cases, compost is derived from whatever organic material was available to add to the heap. This uncontrolled and unmonitored production of compost's results in an end product that is imbalanced in nutrient composition. This may adversely affect the release, adsorption and plant uptake of certain minerals (ten Hooper et al. 2010). For instance, high Na^+ may compete with Ca^{2+} or K+ and subsequently lower, their uptake by the plant, hindering growth and reducing yields (ten Hoopen et al. 2010). Furthermore, the food waste compost in this study contained high P content as well as NH_4^+ (Riley and Barber 1971). These enhance vegetative growth. Unchecked concentrations of both can decrease reproductive organ biomass accumulation by prompting the overgrowth of vegetative organs (Lebot 2009). Applications need to more precise than what is typically found in normal farming situations. Most farmers advise vegetable growers to apply 2.5cm to 5 cm thick layers of compost to soil (Agriculture, Forestry and Fisheries Department of South Africa 2011). This prescription does not consider compost type, nor nutrient composition. Most minerals in food waste-amended soils were found in higher concentration then in soil amended with any other fertiliser regime. The unchecked administration of organic amendment of unknown mineral in not ideal and must be moderated to further increase the sustainability of food waste compost use. Food waste compost increased soil C content the most and is an

excellent source of organic matter. It enriches microbe end fungal populations in soil, although the extent was similarl to the mineral fertiliser. MAD reduces acidity, but has an undesirable effect on pH end CEC. It also decrease soil carbon content and does little to improve the nutrient composition. The low efficacy of MAD may be a result of insufficient volumes or an innate nutrient composition. The effect on the aerobic microbe population in soil was similar to that observed in the integrated treatment; the digestate was also processed in a closed tank. There was no remarkable effects on the fungal population. The manure-derived anaerobic biodigestate is a poor alternative to mineral fertiliser when considering soil fertility maintenance and improvement. It is better suited as a biofertiliser than an organic amendment and should be applied in conjunction with inorganic or organic fertiliser or amendments. Alfa et al. (2014) established that biodigestate is able to improve soil fertility when composted and used as a biofertilizer.

Commercial organic fertilisers are generally regarded as an acceptable alternative to inorganic fertilisers (Riley and Barber 1971, Patel 2012). While it did result in lower acidity levels then the mineral fertiliser application, it still increased it compared to the unfertilised control. It lowered the pH and CEC. With the exception of the C content and assimilable N, it failed to enrich the mineral composition to as large a degree as the food waste compost and the integrated biochar- inorganic fertiliser system. The rate of N application was identical to the mineral fertiliser, thus it may be that organic fertiliser must be applied at higher rate. In general, it was a poor substitute for an inorganic fertiliser.

Co-application with biochar at even a low rate of 2% reduced mineral fertiliser requirement by half. This was evident in the 2% BC + 50% CM treatment, where yields were increased when compared to the application of the full recommended rate in the 100% CM treatment. Sweet potato vegetative growth was superior to sole mineral fertiliser applications in term of fresh and dry vine weights, shoot biomass production, vine length, the number of leaves, end tuber growth. In addition, biochar and mineral fertiliser applications produced comparable and/or greater fresh yield (total and marketable) than those produced in mineral fertiliser system and well-established organic system like food waste compost. Food waste compost increased fresh vine and vegetative biomass production more than other organic or integrated system, but yielded lower dry matter then other organic and integrated amendment. The gap between fresh and dry weight implies that compost improves water uptake in crops and may be ideal for use in drought-stricken areas. It also produce high chlorophyll content in leaves, similar to the mineral fertiliser. Food waste compost produce comparable yields to mineral fertiliser

although, they were slightly lower. Like biochar, it is a suitable replacement for chemical fertiliser. Yield penalties may have been incurred due to the imbalanced nutrient composition in FWC-amended soil and excessive vegetative growth thus there is still room for improvement in compost use as suggested above.

Vegetative growth was variable in the MAD and COF treatments, although both did show harvest indices that were equivalent to those observed under the inorganic control and the FWC and 2% BC + 50% CM treatments. At one point, the commercial organic fertiliser produced higher dry biomass yield than the food waste compost despite a higher corresponding fresh weight in compost. Sweet potato tuber yield responded poorly to amendment with manure-derived anaerobic digestate and commercial organic fertiliser. Perfectly timed application according to growth stage and increased rate may improve its effect. Anaerobic digestate should be applied with other organic amendments or inorganic fertilisers to enhance its effect on yield.

Sweet potato moisture, starch and crude fiber content were unaffected by organic end inorganic fertiliser regimes, although crude fiber had a more positive correlation with organic or sustainable amendment then inorganic fertilisers. Protein increased with the application of mineral fertilisers and decreased in their absence. This is a result of the higher assimilable N in formulated NPK applications.

6.2   Future recommendations and areas for improvement

This study was only over the short term (one growing season) and did not evaluate the residual effect of the integrated and organic soil nutrient management systems. Investigating these type of systems this effect could provide a more solid case for integrated biochar and mineral fertiliser co-applications and food waste compost as sustainable alternatives to chemical fertilisers. Unfortunately, the project, which was initially regarded as a pilot study, has been terminated. Anaerobic digestate should be further explored as a biofertilisers. Studies that assess the effects of MAD in conjunction with other fertiliser are much needed. Exploring the different rates of biochar would also lend some depth to these type of studies, while reproducibility over a number of growing seasons would lend credibility to the results.

6.3   Synopsis

Integrated soil nutrient management systems that incorporate biochar and mineral fertilisers are a viable alternative to chemical fertilisers and can significantly improve soil fertility and

sweet potato yields. Food waste compost is also an adequate replacement, although the unformulated nutrient composition and undefined application rate pose potential risks for yield penalties. On its own, manure anaerobic digestate is a poor organic amendment and should be used in conjunction with other soil conditioners. It holds very little benefit for soil fertility and sweet potato growth and yield. The delayed application of commercial organic fertiliser in this study may have resulted in its poor performance. It is likely that efficiently timed application would have enhanced soil fertility and crop yield benefits. It is therefore impossible to conclude that commercial organic fertiliser is not a viable alternative. Organic or sustainable soil nutrient regimes, do not appear to reduce sweet potato nutrition. The only concern regarding the nutritional value of sweet potato is the decrease in protein content that accompanies the reduced nitrogen content inherent of inorganic NPK fertilisers.

Small scale farmers have much to benefit from incorporating biochar and food waste compost into their farming systems. This is not only sustainable for the soil, broader environment and future crop yields, but reduces the cost of agrochemical inputs. The appeal is for agronomists, farmers and other stakeholders not to neglect the role of organic and integrated soil management systems in fostering a sustainable food production system.

6.4 References

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ABBREVIATIONS

Abbreviation	Explanation
100% CM	Full recommended rate of chemical fertiliser NPK
2% BC + 50% CM	Biochar at a rate of 2% + half the recommended rate of chemical fertiliser
FWC	Food waste compost
COF	Commercial organic fertiliser
MAD	Manure anaerobic digestate
FYM	Farm yard manure
NPK	Nitrogen-phosphorous-potassium
NH_4^+	Ammonium
NO_3^-	Nitrate
HNO_3	Nitric acid
KNO^3	Postassium nitrate
$CaCO_3$	Calcium carbonate
$BaCO_3$	Barium carbonate
NaCl	Sodium chloride
NaOH	Sodium hydroxide
K+	Potassium ion
Ba	Barium
Cd_2^+	Cadmium ion
Al_3^+	Aluminium ion
Pb_2^+	Lead ion
Na^+	Sodium ion
C	Carbon
S	Sulfur
P	Phosphorous
SOM	Soil organic matter
SOC	Soil organic carbon
CEC	Cation exchange cation
WHC	Waterholding capacity
HI	Harvest index
BD	Bulk density
WUE	Water use efficiency
FW	Fresh weight

Abbreviation	Explanation
DW	Dry weight
t.ha-1	Tons per hectare
G	grams
mg.kg^{-1}	Milligrams per kilogram
Ppm	Parts per million
SPAD	Soil-plant analyses development
WAT	Weeks after transplanting
ANOVA	Analysis of variance
Tukey HSD	Tukey honest significant difference
AOAC methods	
UN	United Nations
FAO	Food and Agriculture Organisation
RSA	Republic of South Africa
FSSA	Fertiliser Society of South Africa
GMO	Genetically modified organism

APPENDIX

Chapter 3

Table 3.2	F-value	p-value
pH	10.189	0.000
CEC	4.700	0.013
Acidity	12.368	0.000
WHC	1.129	0.381

Table 3.3	F-value	p-value
NH_4^+	6.444	0.001
NO_3^-	4.275	0.010
Total cations	4.062	0.012
Ca^{2+}	3.714	0.017

Table 3.4	F-value	p-value
Cu^{2+}	0.479	0.787
Zn^{2+}	6.200	0.002
Mn^{2+}	5.865	0.002
B	12.151	0.000

Table 3.5	F-value	p-value
Mg^{2+}	3.831	0.015
K^+	15.919	0.000
Na^+	5.473	0.003
P	6.85	0.000

Table 3.6	F-value	p-value
C	5.631	0.003
S	9.045	0.000

Microbes	F-value	p-value
Aerobic microbes	0.927	0.497
Fungi	1.097	0.411

Chapter 4

Table 4.1	F-value	p-value
Canopy	24.301	0.00
Leaf number at 4 WAT	4.944	0.0185
Leaf number at 8 WAT	3.011	0.072
Leaf number at 12 WAT	0.331	0.851
Leaf number at 16 WAT	3.109	0.066

Table 4.2	F-value	p-value
Vine FW 4 WAT	42.742	0.000
Vine FW 8 WAT	11.665	0.009
Vine FW 12 WAT	8.916	0.003
Vine FW 16WAT	2.596	0.100

Table 4.3	F-value	p-value
Vine length	0.309	0.866
Vine dry weight	4.701	0.022
Shoot fresh weight	2.084	0.158
Shoot dry weight	2.160	0.148

Table 4.4	F-value	p-value
Length	16.953	0.000
Diameter	1.239	0.355

Table 4.5	F-value	p-value
No. of tuber.plant^{-1}	7.712	0.006
Tuber fresh weight g.tuber^{-1}	1.753	0.215
Tuber fresh yield g.plant^{-1}	7.276	0.005
Total tuber fresh yield t.ha^{-1}	7.276	0.005

Table 4.6	F-value	p-value
Unmarketable %	2.49	0.110
Marketable %	2.490	0.110
Unmarketable t.ha^{-1}	0.928	0.485
Marketable t.ha^{-1}	6.312	0.008
Total yield t.ha^{-1}	7.276	0.005

Shoot fresh weight	F-value	p-value
Shoot FW 4 WAT	75.119	0.000
Shoot FW 8 WAT	7.169	0.005
Shoot FW 12 WAT	27.722	0.000
Shoot FW 16 WAT	2.084	0.158

Shoot dry weight	F-value	p-value
Shoot DW 4 WAT	36.788	0.000
Shoot DW 8 WAT	1.290	0.337
Shoot DW 12 WAT	13.043	0.001
Shoot DW 16 WAT	2.160	0.148

Tuber fresh weight	F-value	p-value
Tuber FW 4 WAT	0.637	0.648
Tuber FW 8 WAT	6.512	0.008
Tuber FW 12 WAT	3.252	0.060
Tuber FW 16 WAT	8.739	0.003

Tuber fresh weight	F-value	p-value
Tuber FW 4 WAT	0.637	0.648
Tuber FW 8 WAT	6.512	0.008
Tuber FW 12 WAT	3.252	0.06

Tuber FW 16 WAT	8.739	0.003

Tuber dry weight	F-value	p-value
Tuber DW 4 WAT	0.921	0.489
Tuber DW 8 WAT	1.516	0.270
Tuber DW 12 WAT	0.845	0.528
Tuber DW 16 WAT	0.728	0.593

Harvest index fresh weight	F-value	p-value
HI 4 WAT	2.713	0.091
HI 8 WAT	2.246	0.137
HI 12 WAT	2.042	0.164
HI 16 WAT	1.431	0.293

Harvest index dry weight	F-value	p-value
HI 4 WAT	3.167	0.063
HI 8 WAT	2.837	0.083
HI 12 WAT	0.316	0.861
HI 16 WAT	0.368	0.826

Chapter 5

Table 5.1	F-value	P-value
Moisture	0.191	0.962
Crude fiber	1.047	0.403
Protein	4.486	0.015
Starch	0.993	0.433