AGRI-MAT AND GRASS MULCH EFFECTS ON SELECTED SOIL PHYSICAL AND CHEMICAL PROPERTIES, RUNOFF, CROP GROWTH AND YIELD IN SOUTH AFRICA

by

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DECLARATION

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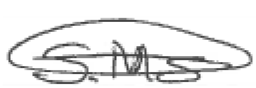

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AGRI-MAT AND GRASS MULCH EFFECTS ON SELECTED SOIL PHYSICAL AND CHEMICAL PROPERTIES, RUNOFF, CROP GROWTH AND YIELD IN SOUTH AFRICA

KEY TERMS:

Agri-mat mulch; Grass mulch; Aggregate stability; Incubation study; Glasshouse experiment; Integrated nutrient management; Conservation Agriculture; Porosity; Soil moisture; Soil temperature; Aeration; Erosion; Runoff; Rainfall simulation; Crop growth; Crop yield;

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We love God because He loved us first (1 John 4:19), and we know that all things work together for good to those who love Him (Romans 8:28). Glory be to God, whom by His power working inside of us, is able to do far beyond anything we can ask or imagine (Ephesians 3:20).

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LIST OF ABBREVIATIONS

ANOVA = Analysis of Variance

ARC = Agricultural Research Council

AG = Agri-mat

N = Nitrogen

NT = No tillage

LSD = Least Significant Difference

FC = Field Capacity

CF = Compound Fertilizer

DA = Dry Algae

GA = Ground Agri-mat

GG = Ground Grass

KZN = Kwa-Zulu Natal

WAP = Weeks After Planting, B = Agri-mat made with Bagasse

BA = Agri-mat made with Bagasse and Algae

SOC_c = Soil organic carbon

D_b= Dry bulk density

GP = Gauteng Province,

PAW = Plant Availability

CT = Computed Tomography

INM = Integrated Nutrient Management

NO_3^- = Nitrate

NH_4^+ = Ammonium

PWP = Permanent Wilting Point

DM = Dry Matter

SOC = Soil Organic Carbon

OC = Organic Carbon

SOM = Soil Organic Matter

SAA = Sub-Saharan Africa

CO_2 = Carbon Dioxide

O_2 = Oxygen

R = Replication

CA = Conservation Agriculture

CEC = Cation Exchange Capacity

EC = Electrical Conductivity

K = Potassium

ET_o = Evapotranspiration

t. ha^{-1} = Tons per hectare

mS/cm = Millisiemens per centimeter

meq/100g = milliquivalent per 100 grams

Z_n = Zinc

H = Harvest

DAT = Days after planting

PH = Plant Height

LW = Leaf Width

LL = Leaf length

NL = Number of Leaves

Mg = Magnesium

Trt = Treatments

Cntrl = Control

P = Phosphorus

Fe = Iron

Na = Sodium

MPPH = Mini Portable Pressure Head

MWD = Mean Weight Diameter

ABSTRACT

The current research work was conducted to understand the dynamics of nutrients from the organic-inorganic (algae, agri-mat, grass and lime ammonium nitrate) amendments into soil through mineralization, their movement thereafter from the soil to the crop. In addition, the effect of organic materials on some soil physical and chemical properties and crop productivity was investigated through a series of different but interconnected laboratory, glasshouse and field experiments. The first experiment was carried out through a 2-month incubation study to investigate nutrient release (mineralization) capacity of inorganic-organic treatment combinations and organic amendments alone on sandy loam and loam soil. The objective of the incubation study was to determine the nitrogen-mineralization rate of different organic mulching materials singularly and when combined with lime-ammonium nitrate under two soil types. The incubation study was conducted in the laboratory at Agricultural Research Council – Soil, Climate and Water in Arcadia, Pretoria. The experiment consisted of sandy loam and loam soil, each treated with the following seven treatments T1 = control, T2 = 5g of dry algae per 100g of soil, T3 = 5g of ground agri-mat per 100g of soil, T4 = 5g of ground grass per 100g of soil, T5 = 75kgN.ha^{-1} using Lime Ammonium Nitrate (LAN) + 2.5g of dry algae per 100g of soil (50%NF + 50%DA), T6 = 75kgN.ha^{-1} using LAN + 2.5g of ground agri-mat per 100g of soil (50%NF + 50%GA), T7 = 50%NF + 50%GG. Each treatment was replicated three times and the experiment was laid out in a completely randomized design. Three experimental units per treatment were drawn at 0, 3, 7, 15, 30, 45, and 60 days for mineral-N (NH_4^+ **-**N and NO_3^- **-**N) content determination. The results from the incubation study indicates that all the treatments where organic amendments were added had higher mineralization rates compared to the treatments where organic amendments were applied singularly. The highest amounts of Nitrate-N (619 mg.kg^{-1}) and Ammonium-N (507.9 mg.kg^{-1}) were both recorded in the 50% dry algae (DA) and 50% compound fertilizer treatment combination at day 15 under sandy loam soils.

Following the incubation study, a 2-month glasshouse experiment was conducted to study effect the following five treatments: T1 = control, T2 = 50%DA + 50%CF, T3 = 50%GA +

50%CF, T4 = 50%GG + 50%CF, T5 = 150 kgN.ha^{-1} using LAN (100%CF) on spinach growth and yield using the same two soil types. All five treatments were replicated three times for each of the two soil types and the experiment was laid out in a completely randomized design. The treatments with sole application of organic amendments were replaced with sole application of nitrogen fertilizer (LAN) in the glasshouse experiment due to their low mineralization rates as observed in the incubation study. The sole nitrogen fertilizer treatment in the incubation study was excluded since nitrogen is already in plant available form in lime ammonium nitrate. The glasshouse experiment was conducted in a glasshouse at Agricultural Research Council – Vegetable and Ornamental Plants, in Roodeplaat, Pretoria. The objective of the glasshouse experiment was to determine the combined effects of different organic mulching materials with lime-ammonium nitrate (LAN) in comparison to sole application of LAN on spinach growth and yield.

The findings from the glasshouse experiment indicates that the (50%DA + 75 kgN.ha^{-1}) treatment produced higher values for plant height [34.3 cm (PTA soil) and 41.3 cm (DBN soil)], leaf length [25 cm (both DBN and PTA soils)], number of leaves [14.7 cm (PTA soil) and spinach yield [202.06 g.pot^{-1} (PTA soils) and 72.19 g.pot^{-1} compared to other treatments. The glasshouse experiment results might not give precise indication of the field conditions due to various factors (i.e, glasshouse environment with shorter growing period, restricted root growth due to pot size, etc). Therefore, two-season (winter and summer) field experiments were conducted concurrently at two different agro-ecological zones of South Africa and repeated twice. The objective of the field experiments was to assess the effect of agri-mat and grass mulch on soil water regime, temperature and crop yield. The field experiments were conducted in Agricultural Research Council – Vegetable and Ornamental Plants in Pretoria and in AgroEco Hub, Newlands West, Durban. The following five mulch treatments were established in each site: i) Full Agri-mat mulch cover (100%AG), ii) Half agri-mat mulch cover (50%AG), iii) Bare (Control), iv) 6 tons.ha^{-1} of grass mulch (6t.GM), and v) 3 tons.ha^{-1} grass mulch (3t.GM). Each treatment was replicated three times to make 15 plots per site and both sites were arranged in randomized complete block design. The objective of these experiments was to determine the effects of agri-mat and grass mulch on soil water regime, temperature and crop yield

In both sites, maize was planted during the summer season and spinach was planted during winter.

For each season, the experiments were running concurrently with one-week difference in planting dates – planting in Pretoria was conducted a week after planting was finished in Durban. For both seasons, in each site, the experiment was conducted under the same plots with five mulching treatments that were replicated three times. Soil moisture and temperature sensors were installed at the beginning in all 15 plots in each site. The results from the field experiments suggest that mulching with 100% agri-mat treatment can increase crop yields for better food security by improving soil water and moderate soil temperature. Alternative to maize or wheat straw as valuable crop residues, smallholder farmers can adopt agri-mat mulch as a cheap and effective soil cover practice to conserve moisture in their evaporation prone soil in order to increase crop yield and improve food security. At the end of the field experiments, soil samples were collected from the plots where spinach and maize were planted with the objective to assess the effect of agri-mats and grass mulch on aggregate size distribution and stability of two different soil types. Air dried soil aggregates of approximately 10 mm per treatment in triplicates were selected from both experimental sites (in each plot, which were laid in a Completely Randomized Block Design) for image scanning and analysis using a Nikon XTH 225L micro-focus CT X-ray unit. The experiment also adopted the fast wetting method to determine the aggregate stability of a loam and sandy loam soil, which were under agri-mat and grass mulch for two consecutive years.

The X-ray CT analysis results show that, due to the higher frequency of storage pores (0.5-50 µm) and feeding root pores (100 - 200 µm) in the loam soil compared to the sandy loam soil, the loam soil has better capacity to accommodate more roots and had higher volumes of water reservoir for plants and microbes. In addition, the 100% agri-mat mulch treatment improved the water holding capacity of the loam soil by decreasing total macro-porosity, making it less porous compared to other treatments. The aggregate stability test results indicate that the 100% agri-mat mulching cover has a greater stabilizing ability compared to all other mulching materials (6t.GM, 3t.GM, 50%AG and Control) in both soil types. The last experiment was conducted in a laboratory to assess the effectiveness of agri-mats made with different organic materials in controlling soil water erosion using Mini Portable Pressure Head Rainfall Simulator. The objective of this laboratory experiment was to investigate the effectiveness of utilizing different mulching materials on water infiltration and runoff. Agri-mats water infiltration and runoff test was conducted in a laboratory at Tokyo University of Agriculture and Technology, in Fuchu city, Tokyo – Japan. Results shows that when algae were used as an additional organic material during the fabrication process, agri-mat delayed runoff by absorbing more moisture than it losses. The agri-mats that were fabricated only with 100% Bagasse had a lower water infiltration rate compared with agri-mats made with 90% Bagasse and 10% Algae. The 100% dry sugarcane bagasse agri-mat treatment had higher ru-mats noff rate of 16.8 mm. hr^{-1} compared to mere 1.7 mm. hr^{-1} recorded under the agri-mat 90% Bagasse and 10% algae during the first 10 minutes of rainfall simulation test. In addition, the agri-mat made with bagasse only released magnesium at a rate of 105.7 mg. hr^{-1} compared to 6.6 mg. hr^{-1} lost from the agri-mat board made with both bagasse and algae.

Agri-mats are a novel and innovative pro-smallholder farming effective mulch technology that promises to be a cheaper alternative approach to prevent sediment loss and conserve soil moisture. Agri-mats are fabricated using forestry waste, bagasse, algae, grasses, etc., thus allowing smallholder farmers to sell crop residues after harvest for profit generation whilst the soils remain covered with agri-mats. Agri-mats can last on the field for up to two years or more, depending on the climatic factors (rainfall and temperatures), soil type and quality of the organic material used during the fabrication process, before they completely decompose. The findings from this study show that in all treatment combinations (organic amendments + inorganic fertilizer), the mineralization rate was significantly higher compared to treatments where only organic amendments were applied in both soil types. In addition, the inorganic amendments improve the efficiency of organic fertilizers and vice versa, through a positive interaction on physical, chemical and biological characteristics of the soil. The findings from the glasshouse

experiment indicates that the inorganic-organic treatment combination (50%DA+50%CF) can replace full inorganic nitrogen fertilizers without compromising spinach growth, yield and quality.

The results from the aggregate stability test show that, in reference to the control, all mulching treatments increased the stability of soil aggregates from unstable to medium stability after a period of two years for both loam and sandy loam soil. Moreover, this research study indicates that agri-mats can play a crucial role in building soil structure that is resistant to soil erosion by improving the stability of soil aggregate and physical architecture of the soil. The results from agri-mats infiltration and runoff test experiment indicates that agri-mats allow more water to infiltrate through agri-mats than being lost as runoff. In addition, the current study shows that adding algae as one of the organic materials during the fabrication process improve the agri-mat water absorption and holding capacity and thus reduce nutrient loss through runoff. Field experiments indicates that the 100% agri-mat mulch treatment can improve crop yields and leaf nutrient quality for better food security by improving soil water regime and moderating soil temperatures, irrespective of soil type, agro-ecological zone and type of crop. However, further research is needed to assess economic viability of agri-mats relative to crop residue costs to ensure there is science-based evidence for investment/input decision making especially for poor-resource smallholder farmers who wants to maximize profits. Moreover, the recommendations drawn from all future agri-mats research findings should be based on prevailing site conditions, such as climate and soil type where the research studies were conducted.

Keywords: *agri-mat, grass mulch, water infiltration, runoff, crop growth and yield, soil type, aggregation, food security.*

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STRUCTURE OF THE THESIS

Briefly, the thesis is organized in the following order;

Chapter one is the general introduction and background of this study.

Chapter two is the literature review, which describes briefly the problem of soil degradation and various factors that cause and exacerbate it, and offer solutions mostly by promoting agri-mat as a sustainable and innovative technology. The full literature review was published in the Agronomy journal and can be found in the appendix B section.

Chapter three describes the process of mineralization and crop nutrition through an incubation study and glasshouse experiment.

Chapter four describes the role of agri-mats and grass mulch on some soil physical and chemical properties as well as crop yield under two different soil types.

Chapter five investigates the effect of agri-mat and grass mulch on aggregate stability and their influence in soil physical architecture of two soil types with different textural classes using X-ray CT.

Chapter six investigates the infiltration and runoff rate of different types of agri-mats and their effectiveness in combating runoff through water infiltration and runoff tests.

Chapter seven is the general discussions and conclusion of the current study and give recommendations for future studies based on observations of the current study.

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CHAPTER ONE: GENERAL INTRODUCTION

BACKGROUND

Soil degradation negatively affects global food security and agricultural sustainability especially on bare soils of the arid and semi-arid regions (Vaezi *et al*., 2017). The current global estimates indicate that severe to moderate erosion affects approximately 80% of agricultural land, which exacerbate soil degradation (Pimentel and Burgess, 2013). According to Vaezi et al. (2017), soil degradation is a consequence of the bare or scarcely covered soils in semi-arid lands. Furthermore, they assert that semi-arid regions occupy about 40% of the world's terrestrial surface. According to Barnard and du Preez, (2004), the decline in soil organic matter is the basic cause of most of the degradation of soils: all the soil physical, chemical and biological problems follow a decline in organic matter content. The study was carried out in two sites, namely Pretoria (Gauteng Province) with loamy sand soil texture and Durban (Kwa-Zulu Natal) with loam soil texture. Although soil degradation is a big problem across South Africa, historical records by researchers in agriculture indicates that soil organic matter (SOM) levels in provinces such as Gauteng, Eastern Cape, Limpopo and Kwa-Zulu Natal have been declining at a higher rate, especially under the aforementioned soil textural classes (Barnard and du Preez, 2004; Le Roux et al., 2007; Du Preez *et al*., 2011; Swanepoel *et al*., 2018).

Soil erosion by water is more prominent relative to wind erosion and is considered a major environmental concern. Erosive rainfall, which lead to soil erosion, exacerbate the loss of valuable plant nutrients together with soil sediments through runoff, as well as soil water necessary for crop productivity especially in bare soils with no vegetation cover (Zuazo and Pleguezuelo, 2008). Vegetation cover, topographical position of slope, rainfall intensity and soil type are among several factors that influence the extremely dynamic process of water erosion (Mohamadi and Kavian, 2015). The behaviour of the soil to erosion disturbances is influenced by, inter alia, vegetation cover (live or dead), soil type, topographical position of slope, precipitation, wind speed (or energy) and soil structure (Pimentel and Burgess, 2013; Mohamadi and Kavian, 2015).

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According to Vaezi et al. (2017), soil erosion is a three-phase process that consists of detachment of soil particles from the soil mass, transportation of detached particles by either raindrop impact or surface water flow, and sedimentation. Soil sediment and water loss together with valuable soil nutrients pose the greatest threat to land productivity and may lead to unsustainable agricultural production systems in severe cases (Montenegro *et al*., 2013). To prevent water and sediment loss, policy makers needs to impose stringent measures to land users and food producers in order to keep up with food and nutritional demands of the rapidly growing world population. The world population is projected to reach about 8.5 billion people by the year 2030, which indicates that more cropland will be needed, approximately 81 to 147 million ha for sufficient food, fuel, and fiber (Gomiero, 2016). Moreover, global projections by Food and Agricultural organisation (FAO) indicates that the demand for new croplands during the year 2050 will further increase by approximately 3.2 billion ha due to world population growth which is estimated to reach about 9.5 billion people. However, only a fraction (1.6 billion ha) of the global land mass is being utilized for agricultural purpose whilst a total of 13.2 billion ha is available and suitable for cultivation and agricultural production (Pimentel and Burgess, 2013).

The pertinent question therefore is, what are the sustainable agricultural practices that can be employed in order to meet food demands and achieve global food security in 2050 with minimal or zero impact on the environment? Rattan Lal, presenting during the Nobel Conference 54 held at Gustavus Adolphus College in Minnesota, USA, on the 2nd of October 2018 suggests that, among other strategies that can be employed, is “increasing agronomic productivity from existing land, restoring degraded lands, enhancing biological nitrogen fixation by legumes and converting some agricultural land for nature conservancy without any conversion of natural land to agroecosystems, through eco-intensification and restoration of soil health”. According to Shahid and Al-Shankiti. (2013), the improvements in crop production are projected to come primarily from reclamation of degraded marginal lands and eco-intensification on existing cultivated land through better use of natural resources such as efficient irrigation and effective fertilization. Increased agronomic production can be achieved by utilizing sustainable cultivation practices such as conservation agriculture, integrated nutrient management, intercropping livestock management, etc. (Shahid and Al-Shankiti. 2013).

Eco-intensification addresses the challenges of soil degradation caused by maximizing the production of available land, including marginal land that were declared unproductive simply through increased soil organic matter (SOM) content. Deforestation for cultivation purposes and conversion of pasturelands to agriculture lands have been recognized as another threat to the rapidly declining levels of SOM (Giller *et al.,* 2009). In addition, drought and conventional agricultural methods plays a key role in the loss of SOM more especially dry areas such as semi-arid parts of Southern Africa (Thierfelder *et al.,* 2018). In South Africa alone, the changes in soil organic matter levels and overall soil quality for the past thirty years are alarming, mostly due to soil erosion which affected more than 70% of the countries land surface (Barnard and du Preez, 2004; Le Roux *et al*., 2007). According to Swanepoel *et al*. (2018), South African soils have very low OM by nature and approximately 60% of countries soils' have less than 0.05% SOM. In addition, South Africa receives an annual average rainfall of about 500 mm and is therefore classified as a semi-arid region or water scare country (Sithole *et al.,* 2016).

Justification of the study

The primary goal of sustainable agriculture is to meet the increasing food demands of the rapidly growing world population by producing economically viable and environmentally friendly foods, with fewer inputs in a sustainable manner (Bley *et al.,* 2017; Maurya *et al.,* 2016). Chemical or synthetic fertilizers improve soil fertility and crop yields but their excessive use may lead to global warming, decline in soil quality, eutrophication in estuaries and contamination of other water bodies through leaching and runoff (Moharana *et al*., 2015). Unlike chemical fertilizers, organic amendments may offer other benefits apart from soil fertilization; these include improved soil quality, formation and stability of aggregates, soil water retention, carbon sequestration (Bird *et al*., 2010), and soil nutrient gains (Shaaban, 2001; Abbasi and Khaliq, 2016). The practice of applying organic amendments or conditioners (such as grass, algal biomass, crop and/or forestry residues etc) on soil could play a significant role in improving soil organic matter (SOM), soil quality (soil physical, chemical and biological properties) and crop productivity (Abbasi *et al*., 2007; Prakash and Nikhil, 2014). According to Barnard and du Preez, (2004), increasing SOM is the only way to curb and reverse soil degradation and this could be achieved by employing sustainable agronomic practices such as effective mulching techniques, crop rotation, minimum/no tillage etc more especially in South African soils which have low and still declining SOM contents. The increase and decomposition of organic matter of any given soil is determined largely by the quality and quantity organic residues retained or applied in the field as mulch (Pansu *et al.,* 2003). However, the Integrated Nutrient Management practice employs a balanced and harmonious combination of organic and inorganic amendments to rebuild degraded soils (Shahid and Al-Shankiti, 2013; Abbasi and Khaliq, 2016), improve long-term soil fertility and overall soil quality, and increase crop productivity with minimal adverse effects to the environment (Jumadi *et al*., 2014).

However, adverse weather conditions in semi-arid regions has resulted in loose organic material intended for mulching purposes in the field being non-effective (Onwona-Agyeman *et al.,* 2012). The video shared recently by No Till Club of South Africa in their Facebook page, found in this link https://fb.watch/24tFA023QV/, demonstrate the ineffective of crop residues under adverse weather condition. The caption of the video states that it's "Disappointing to see the residue blowing away like this (being blown away by strong winds). Planting cover crops in these conditions is debatable." The high-intensity storms and strong wind wash away valuable crop residues, leading to agricultural soils being prone to high evaporation rates, and erosion due to raindrop impact and therefore low productivity because of low levels of SOM. The major challenge facing smallholder farmers, especially those practicing in sub-Saharan Africa (SSA) regarding CA adoption is the use of crop residues for soil mulching purposes as required in CA. Crop residues are used to maximize profit of the farm or as feed for livestock instead of soil mulching (Giller *et al.,* 2015; Sithole *et al.,* 2016). However, the findings in the current research study indicate that agri-mats could be used as an alternative by smallholder farmers as a better alternative for them instead of using valuable crop resides for mulching purposes (Mgolozeli *et al.,* 2020). Agri-mats are a novel, innovative and sustainable mulching technology that can be used to eliminate crop residue competition in the mixed crop-livestock systems since they are manufactured from freely available biological materials [municipal sewage sludge, grass, algae residues, bagasse, weed biomass and forestry waste (thinned logs, woodchips, sawdust etc)]. Onwona-Agyeman et al. (2012) conducted a study in Japan that compared agri-mats and loose organic residue in their effectiveness in combating soil erosion on a gentle and steep slope. The authors found that agri-mats could reduce soil erosion by 94.4% and 92.3% on steep (30°) and gentle (5°) slopes respectively. In addition, agri-mats have the capacity to absorb and retain more moisture (about 67–77%) for up to 48 hours when soaked in water. In South Africa, there is scanty of information that investigates or thoroughly evaluates the effects of agri-mats on soil properties, erosion, mineralization, crop growth and yield biomass. Moreover, the information regarding the mineralization process of agri-mats alone and in combination with inorganic fertilizers under different soil types is not available in the literature. The main objective of chapter one is to provide a general introduction and background of the soil degradation problems in semi-arid South Africa which are associated with low soil organic matter content. Secondly, to provide solutions to the problem stated as a justification for the current study with general aims and specific objectives as stated below.

Aims:

Generally, the aim of this study is to promote agri-mat as a sustainable alternative mulch in South African smallholder agricultural systems and to evaluate agri-mats as a complementary practice to Conservation Agriculture especially concerning residue management, in order to feed the rapidly growing world population while preserving the environment for future generations.

Objectives

1. To determine the effects of nitrogen-mineralization of different mulching materials and their combined effects with lime-ammonium nitrate on spinach growth and yield

2. To determine the effects of agri-mat and grass mulch on soil water regime, temperature and crop yield
3. To assess the effect of agri-mat and grass mulch on aggregate size distribution and stability of two different soil types
4. To investigate the effectiveness of utilizing different mulching materials on water infiltration and runoff

Hypothesis:

H1: The combination of organic amendments and inorganic fertilizers can improve nitrogen-mineralization and increase spinach yield on loamy sand and loam soils better than sole applications organic amendments or inorganic fertilizers. H1 was tested through chapter three which has the following title.

Chapter three: Effects of micro-algal biomass, agri-mat, grass much and their combined effects with lime-ammonium nitrate on nitrogen mineralization and spinach yield in loamy sand and loam soils. The objective of chapter three is stated as objective 1 above.

H2: Agri-mat mulch technology could improve soil water regime, temperature and crop yields of spinach and maize in sandy loam and loam soils better than grass mulch and bare surfaces. H2 was tested through chapter four with has the following title.

Chapter four: Effect of agri-mat and grass mulch on soil water regime, temperature and crop yield in sandy loam and loam soils. The objective of chapter four is stated as objective 2 above.

H3: Agri-mat mulch technology has a better ability to improve aggregate stability and form better soil structure than grass mulch and bare surfaces at any soil type. H3 was tested through chapter five with has the following title.

Chapter five: Effect of agri-mat and grass mulch on aggregate stability and porosity of loam and sandy loam using X-ray computed tomography. The objective of chapter five is stated as objective 3 above.

H4: The use agri-mats technology can reduce runoff more effectively than grass much and bare surfaces at any given soil type, slope and rainfall intensity. H4 was tested through chapter six with has the following title.

Chapter six: Influence of different types of agri-mats on runoff using rainfall simulator. The objective of chapter six is stated as objective 4 above.

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CHAPTER TWO: LITERATURE REVIEW

Chapter two of this thesis was published as a literature review paper in Agronomy Journal as the following reference. The publication is appended to this manuscript as Appendix B.

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ABSTRACT

The use of crop residues in agricultural systems has been practiced for a long time especially in arid and semi-arid regions of the world. Mulches are any material that covers the soil surface. Their benefits include, *inter alia*, prevention of soil loss by erosion, moderating soil temperature thereby conserving soil moisture and contributing to soil organic matter and hence soil aggregate stability. Mulches contribute to plant nutrients through organic matter mineralization process. Due to the current drive in sustainable agricultural systems such as conservation agriculture (CA), the use of mulches is growing even stronger than before. However, the application of crop residue as mulches in agricultural fields has not been popular amongst smallholder farmers. The reason is two-folds: (a) due to low productivity of the smallholder farming systems, the amount of crop residues left over after crop harvest are never enough and (b) crop residues are used as livestock feed due to the nature of mixed farming in smallholder agricultural systems. Crop residues are also traded to other farmers to generate extra income. Therefore, the competing use of crop residues makes them unviable as mulches in agricultural fields.

However, the current study examined the use of a novel mulching material called agri-mat as a viable alternative to crop residues. Agri-mats are an effective and innovative pro-smallholder farming mulch technology that promises to be a cheaper alternative approach to prevent sediment loss and conserve soil moisture. Agri-mats are fabricated using forestry waste, grasses, etc., thus allowing smallholder farmers to sell crop residues

after harvest for profit generation whilst the soils remain covered up to two years with agri-mats. The study was carried out on two sites, namely Pretoria (Gauteng) with loamy sand soil texture and Durban (KZN) with loam soil texture. The aim of the study was to evaluate the potential of agri-mat-mat as a sustainable alternative mulch in South African smallholder agricultural systems. The study was accomplished through laboratory, glasshouse and field experiments. However, further research and extensive studies on several aspects of the agri-mats technology needs to be conducted to ascertain their roles for agricultural use efficiency and cost viability.

2.1. INTRODUCTION

The current global projections indicate that land degradation affects natural resources conservation strategies, food security, and thus national economic development (Wessels *et al*., 2007). Soil erosion through runoff is the major indicator of land degradation in all terrestrial ecosystems worldwide, more especially in agro-ecosystems. (Pimentel and Burgess, 2013). The scientific literature contains sufficient evidence on the perils of soil erosion as a global threat to agricultural production and food security more especially in arid and semi-arid regions (Lalljee, 2013; Gomiero, 2016). Thus, there is an urgent need for national land degradation monitoring programs that will help to combat food security and promote crop production and food security. Permanent soil cover, as practiced in conservation agriculture, have been identified and adopted in many parts of the world as sustainable land management strategies to, improve soil quality and health, conserve and maintain soil moisture, and other natural resources by combatting soil erosion but most importantly, to match food production with the rapidly growing global population (Munoz *et al.,* 2007; Dube *et al.,* 2012; Busari *et al.*, 2015).

The practice of applying or retaining crop residues in the field as mulch after grain harvest is crucial for soil quality improvement and sustainability as well as crop production (Dube *et al.,* 2012). In addition, run-off and sediment loss due caused by the kinetic energy of erosive rainfall can be reduced significantly by employing permanent soil cover through mulching practices in agricultural land, thereby reducing soil erosion. The adoption of permanent soil cover through mulching in sub-Saharan Africa has been poor because the majority of smallholder farmers practicing in sub-Saharan Africa (SSA) prioritize removing crop residues as feed for livestock and as source of income in order to maximize farm profit (Giller *et al.,* 2015; Sithole *et al.,* 2016; Thierfelder and Wall, 2012). Onwona-Agyeman et al. (2012) provides a solution for the challenge of unstable biological waste material such as loose crop residues being swept away from agricultural lands by unfavourable weather conditions. The authors fabricated stable permanent mulching material called agri-mats from a pressurized steam and compression technology by utilizing various forms of organic material mainly from forestry residues. Agri-mats are a novel and innovative pro-smallholder farming permanent mulch technology that promises to be a cheaper alternative approach to prevent sediment loss and conserve soil moisture. In a study conducted in Japan, Onwona-Agyeman et al. (2012) placed agri-mats in a gentle and steep slope to investigate their effectiveness for erosion control. The authors reported agri-mats reduced soil erosion by 94.4% on a steep slope which was an angle of 30^{o}. Due to the soil degradation problems which has led to low organic content in South African soils, more especially as experienced by poor-resourced smallholder farmers, the objective of chapter two is to give a literature review on various mulching materials and promote agri-mat technology as a sustainable and effective mulching solution for improved soil quality, sustainable crop production and better food security. Agri-mats, as a novel technology will be tested under South African context as indicated in the materials and methods of the seceding chapters of this manuscript.

2.2. Soil Degradation: The Greatest Threat in Agro-ecosystems

Soil degradation, mostly through soil erosion, is a greatest challenge that threatens crop production and global food security more especially in semi-arid regions (Gomiero, 2016). In semi-arid region and other dry areas, soil degradation is triggered mostly by soil erosion (runoff) due to lack of vegetation cover and unstable soil structure, leading to soil moisture and sediments loss (Mrabet *et al*., 2012; Onwona-Agyeman *et al.,* 2012; Vaezi *et al.,* 2017). According to Pimentel and Burgess. (2013), global estimates indicate that soil erosion in croplands is approximately 30 tons/ha/year on average, and ranges from 0.5

to 400 tons/ha/year. The soil erosion challenges are triggering bare surface cover, topographical position of slope but are mostly intensified by erosive and erratic rainfall distribution, which results in different wetting and drying periods (Uwah and Iwo, 2011; Khan *et al.,* 2016). The kinetic energy of raindrops is the main factor in erosive rainfall that lead to soil erosion mostly through runoff (Mohamadi and Kavian, 2015). The raindrop energy detaches soil particles from the soil surface and transport them away from the area of raindrop impact through runoff, leading to moisture and sediment (Lalljee, 2013; Pimentel and Burgess, 2013).

Runoff is the principal erosive agent in water erosion processes that is responsible for the loss of valuable plant nutrients necessary for food production in the top fertile soil (Zuazo and Pleguezuelo, 2008). The decline in SOM content due to loss of top soil through soil erosion, drought and conventional agricultural practices employed by smallholder farmers has been the leading cause of soil degradation in semi-arid parts of Southern Africa (Thierfelder *et al.,* 2018). South Africa receives, on average, less than 500 mm of rainfall per year on average and therefore classified as semi-arid country (Sithole *et al.,* 2016). In the past three decades, the changes in fertility status and quality of South African soils, due to different types of erosion at varying intensities (Le Roux et al. (2017) has led to significant declines in SOM (Barnard and du Preez, 2004). This further exacerbated quality problems of the countries' soils that are, by nature, very low in SOM content (Swanepoel *et al.,* 2018).

2.3. The Role of CA in Soil quality, Crop Production and Food Security

Conservation Agriculture (CA) has been defined as a method of managing ecosystems for improved and sustained productivity, increased profits and food security while preserving and enhancing the resource base and the environment (Busari *et al*., 2015). Soil quality, on the other hand, is the capacity of a soil to function within ecosystem boundaries, sustain biological productivity, maintain environmental quality, and promote plant and animal health (Munoz *et al.,* 2007). The beneficial effects of CA in terms of soil quality are reflected through improvements in soil organic carbon in the top 10 cm soil depth (Dube *et al.,* 2012, Moussadek *et al*., 2014), enhanced water infiltration rate (He *et al*., 2010, Mrabet *et al*., 2012), enhanced water holding capacity (Mrabet *et al*., 2012, Yadav *et al*., 2017), lower bulk density (Castellini *et al*., 2013, Yadav *et al*., 2017), higher aggregates stability (Dube *et al.,* 2012, Castellini *et al*., 2013) and better soil structure (Castellini *et al*., 2013). Soil aggregate stability and structure is maintained and improved by improving SOM content through no till or minimum tillage practice and application of organic residues as mulch on soil surfaces, leading to better soil quality with better water capture and infiltration rate.

Conservation agriculture (CA) is a sustainable land management technology that has been proven through various research studies (Dube *et al.,* 2012, Moussaddek *et al*., 2014, Busari *et al*., 2015) to increase soil quality and crop production. Thus, improve global food security and nutrition with less or no adverse effects in the environment (Shahid and Al-Shankiti. 2013; Malobane *et al.,* 2018). Naab et al. (2017) reiterates that all three CA principles must be employed simultaneously and harmoniously with the site prevailing conditions in order the technology to work effectively in achieving food security. However, the utilization of crop residues for mulching purposes as required in CA has discouraged many smallholder farmers and other food producers to adopt CA due to their economic value. Consequently, the adoption rate of CA in Sub-Saharan region of Africa has been and still very low, hence the continent suffers from challenges of food security.

2.4. The Role of Agri-mats in the Adoption of CA

The scarcity of water for agricultural purposes in semi-arid parts of Sub-Saharan African (SAA) have been, for a long time the greatest cause of poor yields in crop lands. Tillage and the lack of vegetation due to rainfall shortage and high summer temperatures threatens the agricultural productivity by degrading SOM content. SOM is the key component of soil quality (physical, chemical and biological soil characteristics) which help to improve crop production and food security if sufficient quantities are available in the soil. Soil scientists and other researchers in the agricultural sector, as a sustainable farming practices to maintain and improving SOM content, are advocating conservation

Agriculture (CA) globally. However, the adoption rate of CA in SAA remains very low because of two reasons. On the one hand, the labour burden induced by no-tillage (as required in CA) practice especially when herbicides are not used is unbearable for smallholder farmers. Rather, they believe that traditional tillage is a cost effective practice for weed control with minimal or no use of herbicides (Giller *et al.,* 2015). Furthermore, the erratic and erosive hail storms accompanied by strong heavy winds associated with some parts of semi-arid regions has discouraged smallholders farmers for adopting CA because these adverse weather condition sweep crop residues away from cultivated lands.

Agri-mats are a novel and innovative pro-smallholder farming effective mulch technology that promises to be a cheaper alternative approach that will not only prevent soil erosion but increase soil organic matter content. Agri-mats are fabricated using forestry residues and other organic waste materials such as algae, bagasse, grasses, etc., thus allowing smallholder farmers to sell crop residues after harvest for profit generation whilst the soils remain covered and protected from the raindrop impact by agri-mats (Onwona-Agyeman *et al.,* 2012). However, the agri-mats are not currently accessible to both smallholder and commercial farmers because they are a new technology and a pricing model which will determine how much each agri-mat cost or price per square meter they occupy is still being developed. Agri-mats are laid out on top of the soil surface as organic mats to serve as permanent soil cover that combat soil erosion, preserve and increase soil moisture, moderate soil temperature regimes, improve soil quality and crop productivity by increasing the organic matter status of the soil as they decompose over time. In a laboratory study conducted in Japan, Onwona-Agyeman et al. (2015) soaked urea-impregnated agri-mats and compost-manufactured agri-mats in water for 24 h and later found that urea-impregnated agri-mats absorbed more water (77%) than the compost-manufactured agri-mats (67%). In addition, the authors state that agri-mats may reduce weed growth from 0.5 ton/ha/month to 0.05 ton/ha/month. Therefore, agri-mats can also be used as a nitrogen use efficiency strategy, which may provide a solution for nitrogen fertilizer-loss challenges often experienced by farmers and other food growers in semi-arid regions due unreliable, erratic and erosive rainfall. Moreover, agri-mats can serve as a tool to not only eliminate the need to control weeds or reduce herbicide use but also be used as a strategy to reduce the cost of irrigation in semi-arid regions and other dry areas where rainfall is scarce. However, extensive research studies with the involvement of farmers especially smallholder farmers' still needs to be conducted at various sites with different climatic conditions and soil types. The future research studies must also focus developing pricing models for various types of agri-mats in order to ascertain economic viability of this novel technology thus allowing farmers the liberty of choosing agri-mats that suit their preferences based on site prevailing conditions.

2.5. CONCLUSIONS

The challenges of soil degradation through soil erosion can be addressed by employing sustainable agronomic practices such as Conservation Agriculture. The adoption of CA in Sub-Saharan Africa can be promoted by adopting agri-mat technology more especially by smallholder farmers practicing in semi-arid regions. Agri-mats are a novel, innovative and sustainable soil cover mulching technology that promises to be a cost-effective option for smallholder famers since they are manufactured from freely available organic materials. Moreover, agri-mats are made from free available organic residue and they can eliminate competing interests for smallholder farmers in the mixed crop-livestock systems by allowing the use of crop residue either as livestock feed or to sell them to other farmers for profit maximization. In addition, agri-mats can reduce the heavy burden of weed control and herbicide use when no tillage is employed. Therefore, agri-mats can play a significant role in achieving global food security through its role in soil organic matter improvement and restoration of soil quality.

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CHAPTER THREE:

EFFECTS OF MICRO-ALGAL BIOMASS, AGRI-MAT, GRASS MULCH AND THEIR COMBINED EFFECTS WITH LIME-AMMONIUM NITRATE ON NITROGEN-MINERALIZATION AND SPINACH YIELD IN LOAMY SAND AND LOAM SOILS

ABSTRACT

The rate at which organic materials decompose, mineralize and become available for plant uptake depends on many factors such as temperatures, soil type, moisture content, etc. A 2-month incubation study was carried out using sandy loam and loam soil from semi-arid (Pretoria) and humid (Durban) agroecological zones respectively. The following seven treatments were established for each soil; T1 = control, T2 = 5g of dry algae per 100g of soil, T3 = 5g of ground agri-mat per 100g of soil, T4 = 5g of ground grass per 100g of soil, T5 = 2.5g of dry algae + 75kgN.ha^{-1} (Compound Fertilizer - CF) using Lime Ammonium Nitrate (LAN) per 100g of soil (50%DA +50%CF), T6 = 2.5g of ground agri-mat + 75kgN.ha^{-1} using LAN per 100g of soil (50%GA+ 50%CF), T7 = 50%GG + 50%CF. Three experimental units per treatment were drawn at 0, 3, 7, 15, 30, 45, and 60 days for mineral-N (NH_4^+ -N and NO_3^- -N) content determination. After the incubation study, a 2-month glasshouse experiment was conducted to study effect the following five treatments in spinach growth and yield using the same two soil types. T1 = control, T2 = 50%DA + 50%CF, T3 = 50%GA + 50%CF, T4 = 50%GG + 50%CF, T5 = 150 kgN.ha^{-1} using LAN (100%CF). Each of the treatment in both incubation study and glasshouse experiment was replicated three times and both experiments were laid out in a completely randomized design. The results from the incubation study indicates that all the treatments where organic amendments were combined with nitrogen fertilizer had higher mineralization rates compared to the treatments where organic amendments were applied singularly. The highest amounts of Nitrate-N (619 mg.kg^{-1}) and Ammonium-N (507.9 mg.kg^{-1}) were both recorded the 50% dry algae (DA) and 50% compound fertilizer treatment at day 15 under sandy loam soils. Similarly, the findings from the glasshouse experiment indicates that the (50%DA + 75 kgN.ha^{-1} 50%CF) produced higher values for plant height [34.3 cm (PTA soil) and 41.3 cm (DBN soil)], leaf length [25 cm (both DBN and PTA soils)], number of leaves [14.7 cm (PTA soil) and spinach yield [202.06 $g.pot^{-1}$ (PTA soils) and 72.19 $g.pot^{-1}$ compared to other treatments. Although the sandy loam soils had higher mineralization rate, higher crop growth and biomass yield was recorded in the loam soil. In conclusion, the inorganic+organic treatment combinations release more nutrients compared to their singular forms because nitrogen enhances multiplication of soil microorganisms that increases the decomposition rate of organic matter. In addition, the results from this study show that addition of algae increase fertility status of the soil. This was attributed to low C/N ratio (6.6) in algae compared to agri-mat and grass mulch, which both had higher C/N ratios (>70). Therefore, agri-mats can partially substitute the chemical nitrogen fertilizer without affecting the yield and quality of Spinach provided algae is included as one of the organic materials during the fabrication process.

Keywords: *Dried Algae, Ground Agri-mat, Ground Grass, Lime Ammonium Nitrate, Loamy sand soil, Loam soil, Incubation study, Glasshouse experiment, Spinach yield*

3.1. INTRODUCTION

The primary goal of sustainable agriculture is to meet the increasing food demands of the rapidly growing world population by producing economically viable and environmentally healthy foods, with fewer inputs in a sustainable manner (Bley *et al.,* 2017; Maurya *et al.,* 2016). Chemical or synthetic fertilizers improve soil fertility and crop yields but their excessive use may lead to global warming, decline in soil quality, eutrophication in estuaries and contamination of other water bodies through leaching and runoff (Moharana *et al*., 2015). Unlike chemical fertilizers, organic amendments may offer other benefits apart from soil fertilization; these include improved soil quality, formation and stability of aggregates, soil water retention, carbon sequestration (Bird *et al*., 2010), and soil nutrient gains (Shaaban, 2001; Abbasi and Khaliq, 2016). The practice of applying organic amendments or conditioners (such as grasses, algal biomass, crop and/or forestry residues etc) in soil could play a significant role in improving soil quality (soil physical, chemical and biological properties) and crop productivity (Abbasi *et al*., 2007; Prakash and Nikhil, 2014). Largely, the quality and quantity of organic residues retained or applied in the field as mulch (Pansu *et al.,* 2003) determines the decomposition and increase of organic matter of any given soil. However, the Integrated Nutrient Management practice employ a balanced and harmonious combination of organic and inorganic amendments to rebuild degraded soils (Shahid and Al-Shankiti, 2013; Abbasi and Khaliq, 2016), improve long-term soil fertility and overall soil quality, and increase crop productivity with minimal adverse effects to the environment (Jumadi *et al*., 2014). According to Shahid and Al-Shankiti. (2013), organic amendments increase the efficiency of inorganic fertilizers through positive interactions on soil biological, chemical and physical properties.

The quantitative information on nutrient mineralization in soil under different management strategies is essential for better assessment of nutrient availability and their loss from soil (Moharana *et al*., 2015). Abbasi and Khaliq (2016), states, "the quantification of N supplying capacity of organic amendments applied to a soil is of immense importance to examine N release capacity and fertilizer values of these added materials." The use of algae biomass as a bio fertilizer has been recommended as an efficient technique to increase crop growth parameters and total yields of many plants due to its high nutrient content, especially Nitrogen (Prakash and Nikhil, 2014; Maurya *et al.,* 2016). Generally, the rate of decomposition and Nitrogen mineralization rate of any organic material is controlled by soil moisture (Mulbry *et al*., 2005), microbial activity (Munoz *et al*., 2007), temperature (Moharana *et al*., 2015) and C-to-N ratio (Abbasi *et al*., 2007), lignin-to-N ratio as well as Polyphenols-to-N ratio (Abbasi *et al*., 2007; Valenzuela-Solano and Crohn, 2007).

However, there is dearth of information available in South Africa regarding the combined effects of agri-mats, grass or algae and inorganic fertilizer as an effective integrated nutrient management (INM) practice to increase crop growth and development under different soil textural classes. Agri-mats are novel and innovative mulching materials that are fabricated using forestry waste, bagasse, algae, grasses, etc., thus allowing smallholder farmers to sell crop residues after harvest for profit generation whilst the soils remain permanently covered with agri-mats. Agri-mats can last on the field for up to two years or more, depending on the climatic factors (rainfall and temperatures), soil type and quality of the organic material used during the fabrication process, before they completely decompose. According to Abbasi *et al*. (2007), "particle size plays an important role in N mineralization as it affects the surface of the N source and contact with microorganisms. Organic N sources with finer particle size may contribute more rapidly to N release than the larger or coarser particles." On the other hand, N mineralization rates are often lower in fine textured (clay) soils compared to coarse-textured soils (Pare and Gregorich, 1999). Generally, Soil particle size (texture) has a major influence on soil carbon and nitrogen dynamics (Matus *et al.,* 2007). Forestry based agri-mats were ground and utilized as an organic treatment for the current incubation and glasshouse experiment and compared with other ground organic (grass and algae) waste residues for mineralization and crop nutrients uptake determinations under two soil types. Algae biomass is a nutrient dense soil conditioner that has the potential to increase soil microbial population and enzyme activity, which elevate inorganic forms of nitrogen levels in the soil such as ammonium-N and nitrate nitrate-N through mineralization (El-Gamal, 2011). The current study aims to determine the effects of nitrogen-mineralization of different mulching materials and their combined effects with lime-ammonium nitrate on spinach growth and yield.

3.2. MATERIALS AND METHODS

3.2.1. Incubation study

A 2-month incubation study was conducted to investigate the nutrient release characteristics of organic-inorganic and organic amendments alone, in a laboratory at Agricultural Research Council – Soil, Climate and Water in Pretoria. The soil samples were collected from two sites (Durban and Pretoria) at a depth of 0 – 0.15 m using a spade. The detailed soil initial characterization and textural analyses of the soils from each site is shown in Table 3.1 and 3.2 respectively. The soils were air-dried for at least a week and passed through a 2-mm sieve (Figure 3.2). A 100g sample of soil samples were transferred into 250 mL transparent plastic containers with lids and treated with required quantities of dry algae (DA), ground agri-mat (GA), ground grass (GG) and combined with LAN as a Nitrogen fertilizer (NF) using the following treatments;

- T1 = control,

- T2 = 5g of dry algae per 100g of soil,
- T3 = 5g of ground agri-mat per 100g of soil,
- T4 = 5g of ground grass per 100g of soil,
- T5 = 75kgN.ha^{-1} using Lime Ammonium Nitrate (LAN) + 2.5g of dry algae per 100g of soil (50%NF + 50%DA),
- T6 = 75kgN.ha^{-1} using LAN + 2.5g of ground agri-mat per 100g of soil (50%NF + 50%GA),
- T7 = 50%NF + 50%GG.

The 5g and 2.5g of organic amendment treatments per 100 gram of soil were used to emulate the full (150kgN) and half (75kgN) per hectare recommended rate for spinach. Three experimental units per treatment were drawn at 0, 3, 7, 15, 30, 45, and 60 days for mineral-N (NH_4^+ **-**N and NO_3^- **-**N) content determination. Therefore, the incubation study consisted of seven treatments, seven sampling dates (at 0, 3, 7, 15, 30, 45, and 60) and three replications per sampling date, to make 147 experimental units (250mL plastic containers) per sampling site (294 in total) at the beginning of the experiment.

The experiment was laid out in a complete randomized design in an incubator set at 25 ^{o}C for 60 days (8 weeks). Soil water content was monitored throughout the incubation days according to Abbasi and Khaliq, (2016) as follows; every second day the soil moisture content was checked and adjusted back to field capacity by weighing the mass of each plastic container when the water loss was greater than 0.05g. Field capacity of both loam and sandy loam soils was estimated using a model by Zotarelli et al, (2010). The deficit was added using deionized water to maintain the initial soil moisture content at field capacity. During this process, precautionary measures were taken to avoid soil disturbance, through either stirring or shaking. Nitrate-N and Ammonium-N was determined using a method described by Mulbry et al. (2005). Briefly, a 10 g sample was extracted with 100 ml 2 M KCL on a rotary shaker for 30 minutes. Extracts were filtered using 0.45 µm membrane and the pH of the filtrates was adjusted to 3-5 with H_2SO_4 as needed for preservation. Filtrates were stored frozen until further analysis. Amminium-N and nitrate-N were determined calorimetrically by flow injection analysis (Lachat Instruments, Milwaukee, WI).

3.2.2. Glasshouse experiment

The glasshouse experiment was conducted for 2-months (8 weeks) at Agricultural Research Council – Vegetable and Ornamental Plants Institute in Roodeplaat, 35km North East of Central Pretoria, to determine the effect of organic-inorganic amendments on growth and biomass yield. Five kg of soils collected from each site, as described for the incubation study were transferred into plastic pots with a height of 25 cm, top diameter and bottom diameter of 20 cm and 15 cm respectively. Each pot (with openings at the bottom at the bottom to allow drainage) was treated with required quantities of algae (AL), Agri-mat (AG), grass (GS) and Nitrogen fertilizer (NF) using the following treatments for each site;

T1 = control,

T2 = 2.5g of dry algae (DA) per 100g of soil + 75kgN.ha^{-1} using LAN (50%DA + 50%CF),

T3 = 2.5g of ground agri-mat (GA) per 100g of soil + 75kgN.ha^{-1} using LAN (50%GA + 50%CF),

T4 = 2.5g of ground grass (GG) per 100g of soil + 75kgN.ha^{-1} using LAN (50%GG + 50%CF),

T5 = 150 kgN.ha^{-1} using LAN (100%CF).

Each treatment was replicated three times in a complete randomized design. Therefore, 15 (5 treatments x 3 replication) plots per site (two sites - DBN and PTA) were established to make a total of 30 experimental units (pots).

Spinach was used as the test crop for the glasshouse experiment due to the nature of pot experiments and role of spinach in general in food and nutritional security. Three spinach seeds were planted per pot and all the pots were irrigated immediately after planting and soil moisture was monitored every third day. In each case, seedlings were thinned to one seedling per pot two weeks after sowing. The pots were weighed (assuming the weight of the growing plant as negligible) to determine the deficit and distilled water was used to irrigate the soil to field capacity. The soils were weighed every other day for the first two weeks and the average deficit was applied every other day until the end of the experiment. Similarly, with the Incubation study, the field capacity of both loam and sandy loam soils was estimated using a model by Zotarelli et al, (2010). The temperature in the glasshouse was set at 28 and 25 ^{o}C for day and night respectively. Growth parameters (plant height, leaf length and number of leaves) were measured and recorded at every week until harvest on the eighth week. At harvest, composite leave samples were collected for nutrient content analysis after total biomass yield was recorded. Table 3.3 shows the initial characterization of the three organic material used. The name of the ground grass used is guinea grass (*Panicum maximum*)

3.2.3. Statistical analysis

Analysis of variance (ANOVA) was carried out to test the effects of nitrogen mineralization and spinach crop growth parameters and yield (Gomez and Gomez, 1984) using JMP 14.0 statistical software (SAS Institute, Inc., Cary, NC, USA). Mean comparison was performed using the least significant difference test (LSD) at $\alpha = 0.05$.

Table 3.1. Physico-chemical properties of top soils (0 – 30 cm) for Durban and Pretoria sites prior to planting.

Soil Properties	Pretoria	Durban
Physical characterization		
Textural class	Sandy loam	Loam
Clay %	9.3%	24.3%
Chemical characterization		
pH in $H_2$0 (1:2.5)	6.2	6.5
Available P (mg/kg)	3.11	19.97
Total N (%)	0.064	0.200
Exchangeable bases		
Ca (mg/kg)	220	1936
Mg (mg/kg)	156.7	701
K (mg/kg)	73.4	212.7
Na (mg/kg)	74	84.4
CEC (meq/100g)	3	6

Table 3.2. Soil textural analyses of the soils from Pretoria and Durban

	Sand				Silt		Clay	Textural class
Sampling site	Coarse (mm) 2 – 0.5	Medium (mm) 0.5 – 0.25	Fine (mm) 0.25 – 0.106	Very fine(mm) 0.106 – 0.05	Coarse(mm) 0.05 – 0.02	Fine(mm) 0.02 – 0.002	Clay(mm) < 0.002	
Pretoria	6.0 %	17.2 %	37.5 %	15.6 %	5.6 %	8.7 %	9.4 %	Sandy loam
Durban	6.9 %	9.7 %	10.2 %	11.0 %	12.0 %	25.9 %	24.3 %	Loam

Table 3.3. Elemental composition of dry algae, ground agri-mat and ground grass

Treatments	**Tot C (%)**	**Tot N (%)**	**C/N ratio**	**K (g/kg)**	**Ca (g/kg)**	**Mg (mg/kg)**	**P (g/kg)**	**Na (mg/kg)**
Algae	45	6.8	6.6	5.66	14.19	8730	10 000	10 000
Agri-mat	46	0.25	184	1.58	2.73	228	309	116
Grass	42.4	0.56	75.7	1.87	1.92	1920.7	0.687	277

Treatments	**Fe (mg/kg)**	**Al (mg/kg)**	**Mn (mg/kg)**	**Zn (mg/kg)**	**B (mg/kg)**	**Cu (mg/kg)**
Algae	6270	1604	867	483	56.5	120.1
Agri-mat	830	458	30.3	234	5.1	4.87
Grass	8695	3635	240.1	54.6	5.86	7.74

3.3. RESULTS

3.3.1. Nitrogen mineralization of organic+inorganic amendment in sandy loam soils from Pretoria

The results from the current incubation study indicates that the initial levels of ammonium N were significantly (P<0.05) different at all sampling days for both soil types. Generally, the ammonium content was higher in the combined treatments (half organic and half inorganic fertilizers) compared to 100% organic amendments treatments throughout the incubation period (Figure 3.1). The highest level of nitrogen mineralization was recorded under the combined dry algae and mineral nitrogen treatment, which peaked at the value of 507.9 mg.kg^{-1} at day 15. The initial value of 130.08 mg.kg^{-1} recorded under the same treatment was the lowest compared to other treatment combinations.

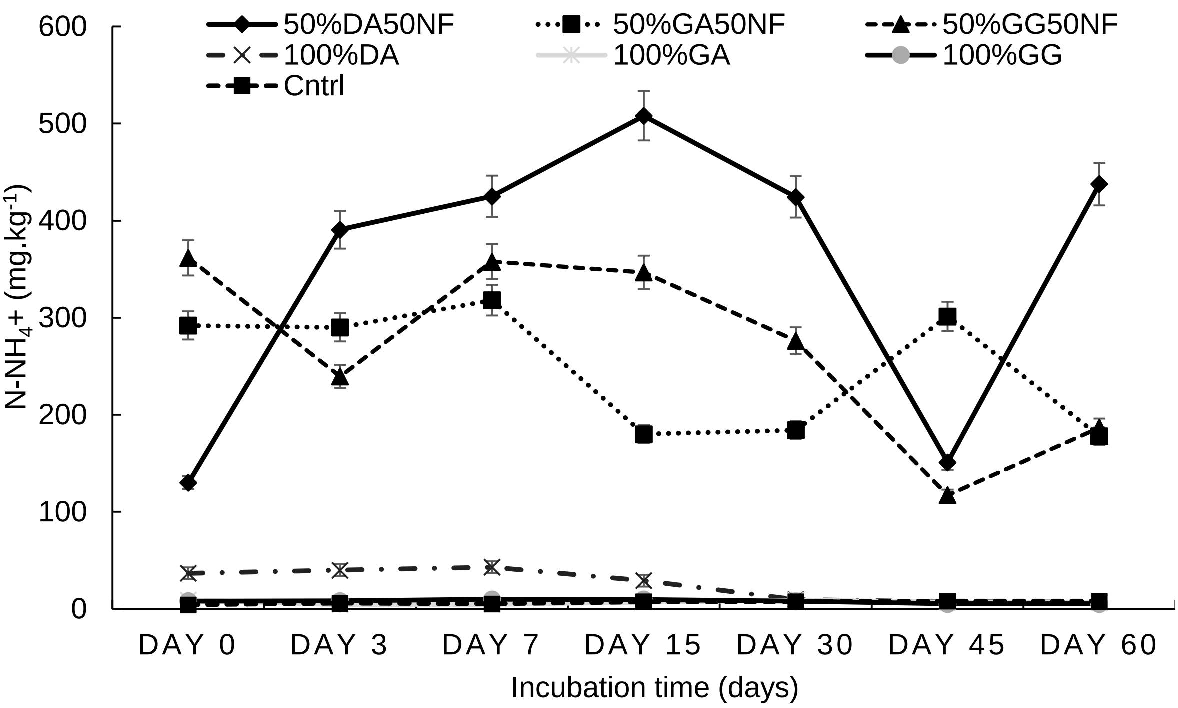

Figure 3.1. Ammonium (N-NH4^{+}) mineralization during the 2-month incubation period in a sandy loam soil from Pretoria, Gauteng. The difference in length of error bars within the same day indicates there were significant difference between treatment means.

The amount of ammonium N, which was released from all organic amendment treatments without a nitrogen fertilizer remained constant throughout the incubation study, except for the 100% dry algae which decreased in mineralization rate at day 7 and continued to drop until day 30. The lowest value of ammonium N was recorded under the control treatment for all sampling days.

The highest amount of Nitrate-N (619 $mg.kg^{-1}$) was recorded the 50% dry algae (DA) and 50% nitrogen fertilizer treatment at day 15. For the first seven days, all the three combined treatments (50%DA+50%NF; 50%GA+50%NF and 50%GG+50%NF) remained constant with an average value of 100 $mg.kg^{-1}$. Similarly, the other three organic amendments without a compound fertilizer remained constant with an average value of 11 $mg.kg^{-1}$ for the first seven days. The mineralization of nitrate was fluctuating for all treatments from day seven until the final day of the incubation (Figure 3.2). Generally, the lowest nitrate values were recorded under the control treatment while the highest values were recorded in 50%DA+50%NF treatment combination.

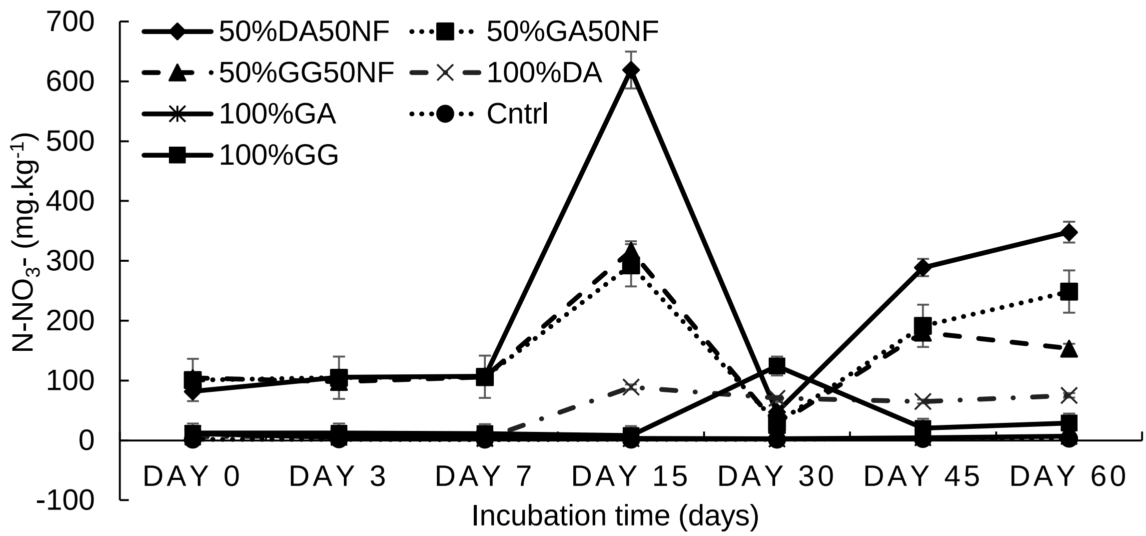

Figure 3.2. Nitrate (N-N0$_3^-$) mineralization during the 2-month incubation period in a sandy loam soil from Pretoria, Gauteng. The difference in length of error bars (or absence thereof) within the same day indicates there were significant difference between treatment means.

3.3.2. Nitrogen mineralization of organic+inorganic amendment in loam soils from Durban

The result from Durban soils indicate that ammonium initially higher in the combined treatment for the first three days of the incubation study. The highest ammonium value of 237.53 mg.kg^{-1} was recorded under the 50%DA+50%NF treatment combination at day 0 but dropped sharply after two days to 122.65 mg.kg^{-1} and dropped further to about 9.88 mg.kg^{-1} (Figure 3.3). From day seven until the day 60, there were no significant changes and/differences among all the treatments including the control.

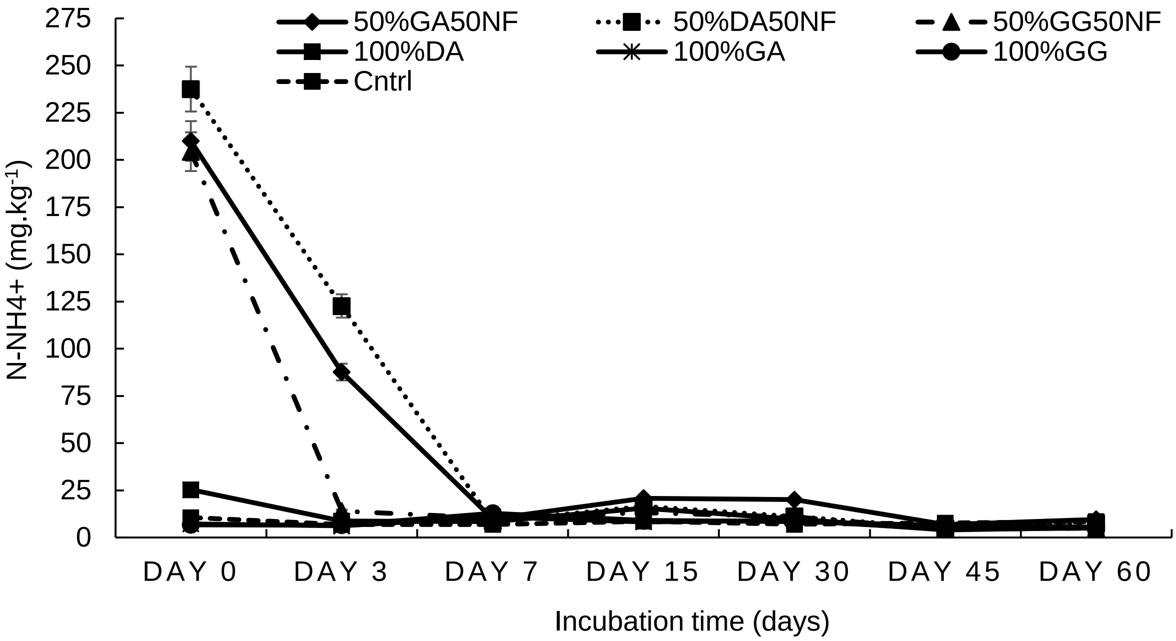

Figure 3.3. Ammonium (N-NH_4^+) mineralization during the 2-month incubation period in a loam soil from Durban, Kwa-Zulu Natal. The difference in length of error bars (or absence thereof) within the same day indicates there were significant difference between treatment means.

The results indicate that nitrate content was generally higher in the combined treatments (half-organic and half-inorganic fertilizers) compared to 100% organic amendments treatments throughout the incubation period (Figure 3.4). The highest amount of nitrate (511 mg.kg^{-1}) was recorded under the 50%DA+50%NF treatment combination during the final day of the incubation study. Meanwhile, the lowest value in the 41.4 $mg.kg^{-1}$ on the last day was recorded under the control treatment. The significant changes for nitrate addition into the soil due to the mineralization process were only observed in the organic amendment treatments that were combined with a compound fertilizer.

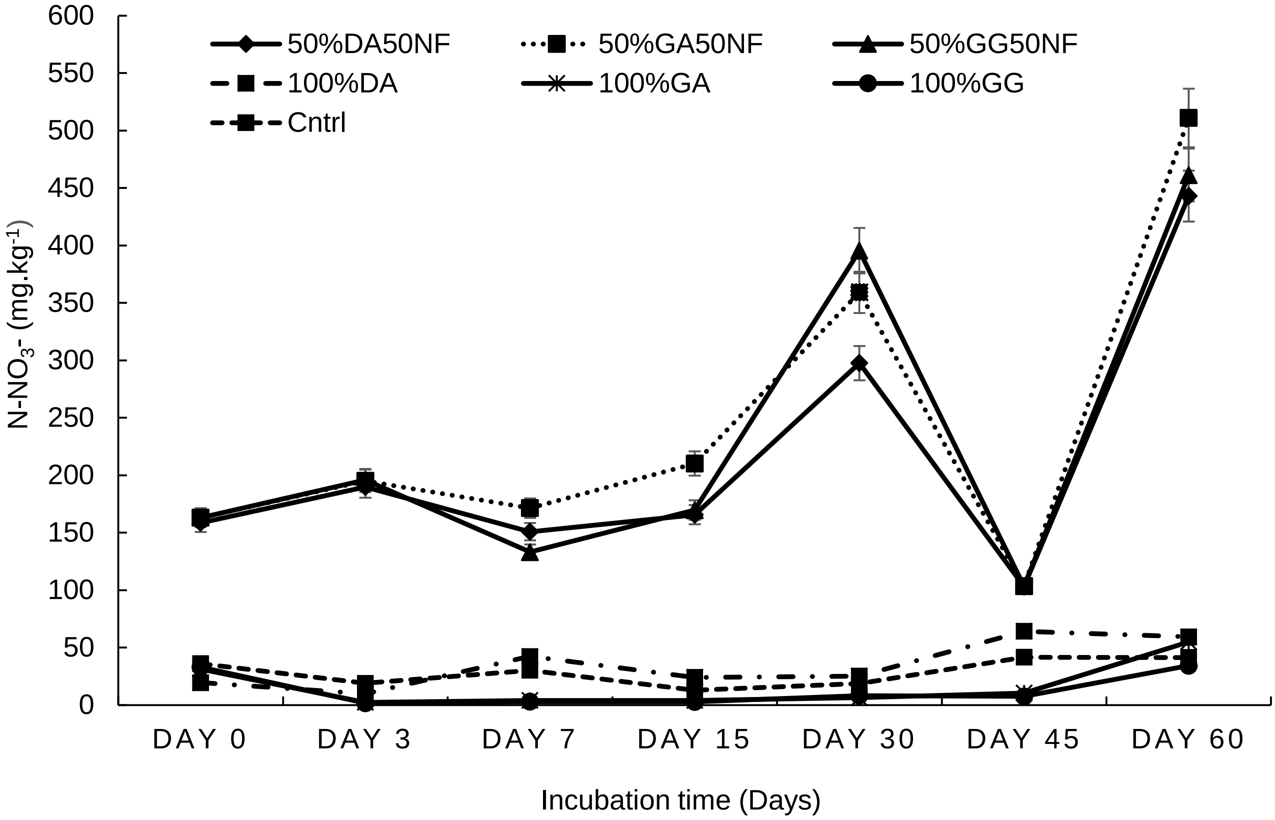

Figure 3.4. Ammonium (N-N0$_3^-$) mineralization during the 2-month incubation period in a loam soil from Durban, Kwa-Zulu Natal. The difference in length of error bars (or absence thereof) within the same day indicates there were significant difference between treatment means.

3.3.3. Effect of organic+inorganic amendments on spinach growth and yield

Organic-inorganic amendments and inorganic fertilizer alone had a significant ($P < 0.05$) effect on all measured Spinach crop growth parameters in both soil types. Generally, the plant height values of Spinach measured in the loam soil (Durban) were higher compared with values measured in a loamy sand soil (Pretoria) at all measuring times (Figure 3.5).

Figure 3.5. Effect of various organic amendments combined with lime ammonium nitrate in spinach growth planted in loam and sandy loam soil

The lowest values for plant height were recorded under the control treatment in both soil types and the highest values were produced at the combined treatment of 50% dry algae and 50kgN.ha^{-1}. At the beginning of the measurements (two weeks after planting), the lowest value of 6.3 cm (Figure 3.6a) was recorded under the loamy sand; for the loam soil, the lowest value was 17.7 cm (Figure 3.6b). The highest values of 34.3 cm and 41.3 cm were recorded under loamy sand and loam soil respectively, both when the soils were treated with 2.5 g dry algae per 100 gram of soil (50%DA) + 75 kgN.ha^{-1} (50%NF).

For the loamy sand (Figure 3.6a), 50%DA+50%NF treatment consistently produced the highest significant values for plant height compared to other treatments at all periods when measurements were taken, except during the eighth-week after planting (8WAP). The difference between 50%DA+50%NF and 150kgN.ha^{-1} (100%NF) treatment at 8WAP was insignificant, with the former producing 2 cm taller plants compared to the latter. Although the control treatment produced the lowest values compared to other treatments during the four measuring times (2, 4, 6 and 8WAP), they were not significantly different with the values recorded under the 2.5 grams per 100-gram soil + 75kgN.ha^{-1} (50%GG+50%NF) treatment except at 8WAP. At harvest (8WAP), the plant height value recorded under 50%GG+50%NF (21.5cm) was significantly higher than that recorded under the control treatment (14.5cm). Similar to the loamy sand soil, the results recorded under the loam soil, indicates that the control treatment produced the lowest plant height values compared to other treatments during the four measuring times. However, the values were not significantly different compared to the 2.5 grams per 100kg of soil + 75kgN.ha^{-1} (50%GA+50%NF) treatment except during 6th week after planting (6WAP) where the former recorded 26 cm and the latter recorded 28.5 cm. The highest significant values were recorded under 50%DA+50%NF treatment combination at all four measuring periods.

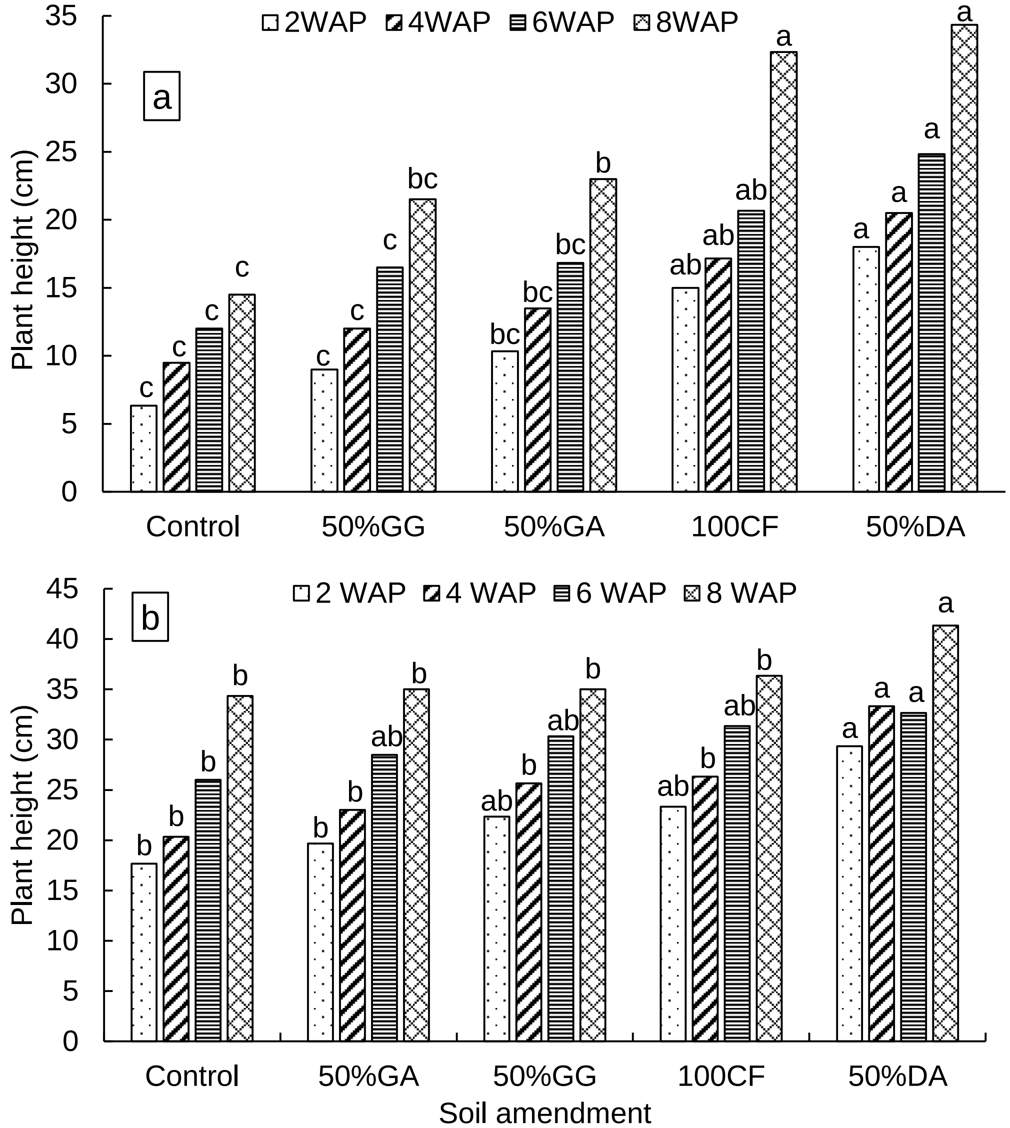

Figure 3.6. Effect of organic-inorganic amendments on loamy sand (a) from Pretoria and loam soil (b) from Durban on spinach height. Means with the same letter within the same measuring period (WAP) are not significantly (P<0.05) different from each other.

The effect of organic-inorganic amendments and inorganic fertilizer alone was more pronounced on Spinach leaf length during the last month (6WAP and 8WAP) in both soil types. The leaves of Spinach were generally longer in pots containing loam soils compared with leaves in pots filled with loamy sand soil (Figure 3.7). For the loamy sand soil, the control treatment produced the lowest significant values compared to all other treatments both during 6WAP (8 cm) and 8WAP (10.2 cm). The highest significant values of Spinach leaf length were produced under the 50%DA+50%CF treatment during both 6WAP (18 cm) and 8WAP (25 cm). At 6WAP, there were no significant differences between 50%GG+50%CF (13 cm), 50%GA+50%CF (13 cm) and 100%CF (13.2 cm) treatments. The differences were again not significant between aforementioned three treatments during 8WAP. The leaf length values were 16.7 cm, 17.3 cm and 21.2 cm for (50%GG+50%CF), (50%GA+50%CF) and (100%CF) treatments respectively.

The results indicate that there were no significant (P<0.05) differences at harvest (8WAP) between all treatments of soil amendments under loam soil including the control treatment. However, the lowest (21.6 cm) and the highest values (25 cm) were recorded under the control and 50%DA+50%CF treatment respectively. The differences were more pronounced and significant when the measurements were taken during 6WAP, where the highest significant value of 23.7 cm was recorded under 50%DA+50%CF treatment. The lowest value of 16.6 cm was recorded under the control treatments. In all treatments, the length of Spinach leaves longer in loam soils compared with loamy sand soils at both 6WAP and 8WAP, with the exception of the 50%DA+50%CF treatment where both loam soil and loamy sand soil recorded the same value of 25 cm. For the control treatments, the leaf length values in loam soil was twice the size during both 6WAP and 8WAP compared to values recorded under loamy sand soil.

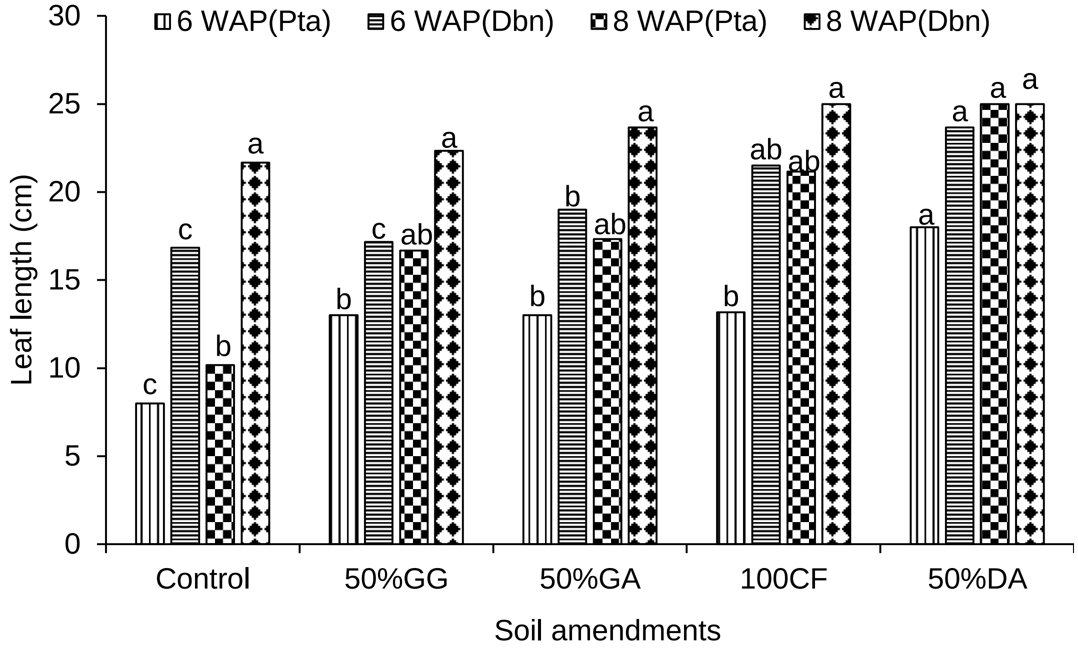

Figure 3.7. Effect of organic-inorganic amendments on loamy sand (Pretoria) and loam soil (Durban) on spinach leaf length. Means with the same letter within the same measuring time (WAP) are not significantly (P<0.05) different from each other.

The results indicate that different organic-inorganic soil amendments had a significant effect on the number of Spinach leaves counted during two-month growing period planted in loamy sand soils from Pretoria. Generally, the number of leaves increased with the increase in the number of days after planting for all treatment including the control (Figure 3.8). The control produced the lowest number of leaves per pot and were significant different compared to other treatments during all measuring times (2WAP, 4WAP, 6WAP, and 8WAP). The values recorded per pot on average were 3.0, 4.3, 5.6 and 7.7 during 2WAP, 4WAP, 6WAP and 8WAP respectively. The highest significant values of 7.0, 10.7, 12.3 and 14.7 were recorded under the 50%DA+50%CF treatment when the counts were conducted at 2WAP, 4WAP, 6WAP and 8WAP respectively.

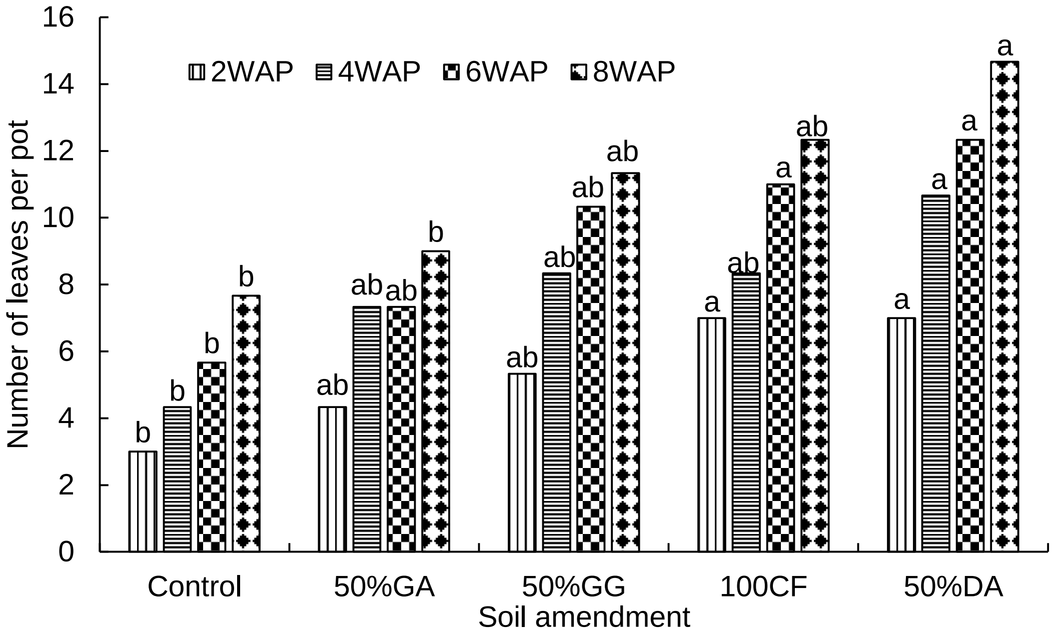

Figure 3.8. Effect of organic-inorganic amendments on the number of leaves for Spinach planted under loamy sand soil from Pretoria. Means with the same letter within the same measuring time (WAP) are not significantly (P<0.05) different from each other.

The effect of inorganic-organic amendments and compound fertilizer alone on loam soil and loamy sandy soil was more pronounced on Spinach yield biomass. The yield biomass of Spinach was generally higher in pots that were filled loamy soils from Durban compared with the loamy sand soils from Pretoria (Figure 3.9). For both soils, the lowest values were recorded under the control, 22.4 grams per pot for loamy sand and 70.3 grams per pot for loam soil. Spinach yield was more than three times higher in loam soil compared to loamy sand under the control treatment. The highest significant values were recorded under the 50%DA+50%CF treatment in both soil types, which were 72.2 grams per pot for the loamy sand and 202.1 grams per pot for the loam soil. The yield biomass of Spinach was 129.9 grams per pot higher in loam soils from Durban compared to the loamy sand soils from Pretoria. For the loam soil, there were no significant differences between 50%GA+50%CF (136.2 grams per pot), 50%GG+50%CF (136.6 grams per pot) and 100%CF (139.7 grams per pot). However, there were significant differences between 50%GA+50%CF (22.9 grams per pot), 50%GG+50%CF (40.0 grams per pot) and 100%CF (58.7 grams per pot) in Spinach biomass yield recorded under the loamy sand soils.

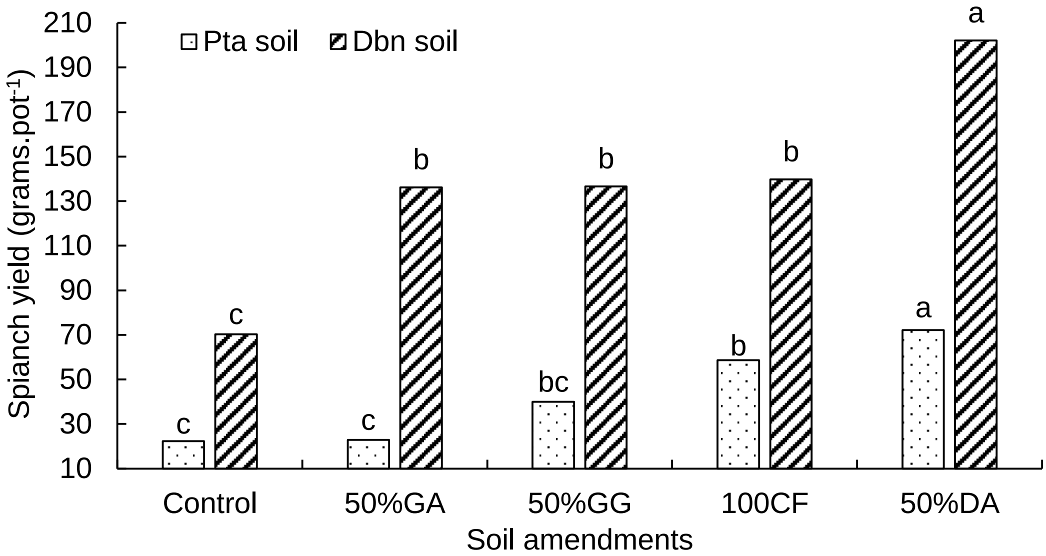

Figure 3.9. Yield biomass of spinach planted in loamy sand (Pretoria) and loam (Durban) soils treated with different soil amendments. Treatment means with the same letter under soil type are not significantly (P<0.05) different from each other.

3.4. DISCUSSION

3.4.1. Mineral N (NH_4^+ and NO_3^-) dynamics during the incubation period

Mineralization is a process where inorganic substances are transformed into inorganic or mineral N components such as ammonium N (N-NH_4^+) and Nitrate N (N-NO_3^-). The current study aims to study N mineralization dynamics through an incubation experiment over a period of two months. The results indicated that both ammonium N and nitrate N in both soil types was increased due to the application of different organic-inorganic amendments. Generally, the findings of this study indicated that inorganic amendments increase the efficiency of organic fertilizers and vice versa, through some positive interactions on soil nitrogen mineralization (Shahid and Al-Shankiti. 2013). The mineralization rate in all the treatments where the organic and inorganic fertilizer was significantly higher compared to treatments where only organic amendments were applied in both soil types. This is attributed to the tendency of inorganic fertilizers to increase the efficiency of organic amendments through positive interaction on soil biological, chemical and physical properties (Shahid and Al-Shankiti. (2013). Consequently, this positive interaction which causes accelerated mineralization rate allows for nutrients to be available in the soil within a short period of time compared to when organic amendments are applied singularly. It is not clear why these Figures 3.2 and 3.4 differ but the difference is attributed partly the variation in textural class and also to other external factors since the experiments were conducted in two sites with different agro ecological zones. Although initial characterization of both soils indicate that the loamy soil was more fertile compared with the sandy loam soil, nitrogen mineralization rate, both N-NH_4^+ and N-NO_3^- was higher in a sandy loam soil (Table 3.1). This could be attributed to lower N mineralization rates that are often observed to be lower in fine textured (clay) soils compared to coarse-textured soils (Pare and Gregorich, 1999; Matus *et al*., 2007). According to Pare and Gregorich (1999), the lower N mineralization in clay soils is assumed to be caused by the physical protection of organic matter and microbial biomass by clay layers, and by aggregate formation, which reduces microorganism activities. However, there are various components, which could contribute to the differences in mineral N dynamics between the two soil types and overall fertility status. According to Malobane. (2015), soil fertility is a complex term and encompasses a combination of components such as soil texture, soil reaction, soil depth, nutrient content, soil microbial activity, organic matter content and composition, content or absence of potentially toxic substances, etc. The gradual decline in the NH_4^+-N mineralization observed between day 0 and day 7 in the loam soil from Durban (Figure 3) could be attributed to N immobilization (Mawonga, 2016). Immobilization is the opposite of mineralization and the difference between the two is referred to as net mineralization (Malobane, 2015). The present study used the combination of organic amendments and nitrogen fertilizer to investigate the effectiveness of inorganic fertilizer in the nutrient release capacity of ground organic materials through an incubation study. The results indicate that when compound fertilizer is applied together organic amendments, the nutrient release rate or mineralization capacity is higher compared to when the organic amendments are solely applied in the soil. The same trend was observed in a glasshouse experiment where spinach was plant using the same treatments in different soil types. This could be attributed to the ability of inorganic amendments to increase the efficiency of organic fertilizers and vice versa, through positive interactions on soil biological, chemical and physical properties (Shahid and Al-Shankiti. 2013).

3.4.2. The effect of organic-inorganic amendment in plant growth

The effect of organic-inorganic soil amendments on Spinach growth and yield was evaluated on two different soil types for eight weeks. The results from this study indicated that soil amendments had a significant ($P < 0.05$) effects on all measured Spinach crop growth parameters and yield in both soil types. The present study used the combination of organic amendments and nitrogen fertilizer to investigate the effectiveness of inorganic fertilizer in the nutrient release capacity of ground organic materials through an incubation study. The preliminary results indicate that when compound fertilizer is applied together organic amendments, the nutrient release rate or mineralization capacity is higher compared to when the organic amendments are solely applied in the soil. This was attributed to nitrogen capacity to enhances multiplication of soil microorganisms that increases the decomposition rate of organic materials. Organic and inorganic fertilizers have a positive working relationships. One the one hand, “organic amendments increase the efficiency of inorganic fertilizers through positive interactions on soil biological, chemical and physical properties (Shahid and Al-Shankiti, 2013). On the other hand, inorganic fertilizer also increases the mineralization efficiency in organic fertilizer.

Among all organic inorganic-amendments, the combination of 2.5 grams of dried algae per 100 gram of soil and 75kgN per hectare (50%DA + 50%NF) was found to produce higher values for plant height, leaf length, number of leaves and biomass yield compared to other treatments. This is attributed to low C/N ratio in the algae (6.6) compared to grass and agri-mat treatments which both had high C/N ratios (Table 3.3). According to Truong and Marschner, (2018), the addition of organic materials with high N concentration (C/N < 20) results in net mineralization whereas amendments with low N concentration (high C/N) induce net immobilization. Moreover, this could also be ascribed to minimal or no-loss of Nitrogen in the 50%DA + 50%NF treatment since ammonium volatilization does not occur in soils treated with dried algal biomass (Mulbry *et al.,* 2005). In addition, the initial characterization results indicate that dried algae contained the highest content of essential crop nutrients (NPK) and most of other elements compared to other organic amendments (Table 3.1). Although the 150kgN per hectare (100%NF) produced the highest significant yield value (58.7 grams.pot^{-1}) compared to 50%GG+50%NF (40.0 grams.pot^{-1}) and 50%GA+50NF (22.9 grams.pot^{-1}) under loamy sand, the differences in biomass yield values recorded under the loam soil were not significant between the three treatments. Generally, inorganic fertilizers get lost easily through leaching in coarse textured soil under field conditions. However, since the current results were obtained in a pot experiments with monitored irrigation, the net loss of N through leaching was minimized. In spite of higher biomass yield under the 100%NF treatment compared to other two organic-inorganic amendments, the differences in leaf length measured among them in a loamy sand soil were less pronounced. The low yield under inorganic-organic soil amendments could be attributed to less N-mineralization as in the first thirty days of the experiment as indicated by the incubation study results. The quantification of N supplying capacity of organic amendments applied to a soil is of immense importance to examine N release capacity and fertilizer values of organic amendments (Abbasi and Khaliq, 2016). The trends observed under all different inorganic amendments compared to the control indicates that they have a potential to improved crop production. However, further research needs to be conducted for longer periods under incubation study and glasshouse experiments to determine the point at which all organic N become mineralized. This will help to predict the time at which they could be applied in the soil under field conditions prior to planting.

3.5. CONCLUSIONS

The aim of this study was to test the suitability of agri-mats as a soil conditioner and mulching material. Based on the findings of the incubation study, adding fertilizer and/or algal biomass in agri-mats may increase nutrient availability and improve the nutrient release rate, thus making algae a suitable soil conditioner for incorporation in the agri-mat fabrication process. The inorganic+organic treatment combinations release more nutrients compared to their singular forms because nitrogen enhances multiplication of soil microorganisms that increases the decomposition rate of organic matter. In addition, the results from this study show that addition of algae increase fertility status of the soil. This was attributed to low C/N ratio (6.6) in algae compared to agri-mat and grass mulch, which both had higher C/N ratios (>70). Therefore, agri-mats can partially substitute the chemical nitrogen fertilizer without affecting the yield and quality of Spinach provided algae is included as one of the organic materials during the fabrication process. However, it is recommended that field trials should be conducted to corroborate these findings since the current trials were run in a glasshouse through pot experiments.

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CHAPTER FOUR:

EFFECT OF AGRI-MAT AND GRASS MULCH ON SOIL WATER REGIME, TEMPERATURE AND CROP YIELD IN SANDY LOAM AND LOAM SOILS

ABSTRACT

South Africa is a water scarce country that receives an average annual rainfall of 492 mm and is therefore - classified as a semi-arid region. Two-season (winter and summer) field experiments were conducted concurrently at two different agro-ecological zones of South Africa for two consecutive years. The aim of the study was to investigate the effects of agri-mats and grass mulch on soil moisture, soil temperature regimes and crop yield of maize (in summer) and spinach (in winter) under semi-arid (Pretoria) and humid (Durban) conditions. Spinach and maize were used as test crops because they are among the most important food crops in South Africa and globally, and they thrive in a wide range of agro-ecological zones with different soil types. The following five mulch treatments were established in each site: i) Full Agri-mat mulch cover (100%AG), ii) Half agri-mat mulch cover (50%AG), iii) Bare (Control), iv) 6 tons.ha^{-1} of grass mulch (6t.GM), and v) 3 tons.ha^{-1} grass mulch (3t.GM). Each treatment was replicated three times to make 15 plots per site and both sites were arranged in randomized complete block design. The findings from this study indicates that the soil moisture content and crop biomass yield (both spinach and maize) was higher under 100% agri-mat treatment compared to other mulching treatments followed by 6t.GM in the Pretoria site which had a sandy loam soil. For the Durban site, although soil moisture content was higher under the 6t.GM treatment, the highest crop growth parameters and biomass yield for both spinach and maize was recorded under the 100%AG treatment. In addition, the 100%AG treatment moderated soil temperatures at both sites with higher soil temperatures compared to other mulching treatments during the cold winter season while lower

temperatures were observed during the hot summer season compared some mulching treatments. As hypothesized in this study, agri-mats can effectively improve crop yields, conserve soil moisture and moderate soil temperatures in semi-arid and humid agro-ecological zones with different soil types.

Keywords: *Soil moisture regime; temperature; agri-mat mulch; crop yield, agro-ecological zones*

4.1. INTRODUCTION

Mulching is a sustainable agricultural practice used to conserve soil fertility and moisture by modifying physical, chemical and biological properties of the soil (Wu *et al.,* 2011; Lalljee, 2013; Kakaire *et al.,* 2015). Organic mulching materials such as crop residues, grass, sawdust, etc., improve physical, chemical and biological characteristics of soil by adding organic matter into the soil during the decomposition process. Temperature, soil moisture, microbial activity, aeration status and soil type affect the extent and speed of mulch decomposition (Cettanio *et al*., 2008; Lalljee, 2013). Increase in soil organic matter improves soil fertility, aggregation, pore geometry and stability of soil structure as it also acts as a binding/cementing agent (Lal, 2015). The capacity of the soil to store and transport water and gases will be enhanced following the resultant relative volume (of solids and voids) and pore size distribution due to improved soil aggregation (Grigal and Vince, 2000). Soil air and moisture are important factors necessary for soil health. They each constitute 25% of the soil body and without either; soil cannot perform its ecosystem functions. For example, oxygen in the soil promotes a well-developed root system required for adsorption of moisture and nutrients by plants (Bulmer and Simpson, 2005).

In addition, adequate oxygen in the soil improves root respiration and microbial activity (Abuarab *et al*., 2013; Xiao *et al*., 2015). Hanson et al. (2000) reiterates that root/rhizosphere respiration can account for as little as 10% to greater than 90% on total in situ soil respiration depending on vegetation type and season of the year. Maintaining the balance between soil moisture and aeration is critical to avoid soil degradation problems such as poor root respiration, less microbial population and activity, which are associated with decline in soil productivity (Muggard *et al*., 2012; Alliaume *et al*., 2017). Soil water is a solvent utilized by plants to carry essential nutrients and a principal constituent of the growing plant, which also regulates soil temperatures (Hatfield and Prueger, 2015). Microorganisms also require water and favourable soil temperatures for metabolism and other activities such as decomposition of organic matter (Ussiri and Lal, 2013). Soil temperature, moisture and aeration are all essential for a healthy soil; they are the main edaphic factors controlling soil respiration (Chen *et al*., 2011). According to Vara-Prasad et al. (2000), the optimum mean soil temperature range for seed germination is between 29 and 30°C. In addition, at temperatures below 10°C, water and nutrient (especially phosphorus) uptake is limited (Gavito *et al.,* 2001). Therefore, organic mulch plays a crucial role in soil productivity by reducing soil temperatures especially in the wake of global warming (Sinkeviciene *et al.,* 2009).

In addition to the benefits mentioned above, Siczek et al, (2015) found out that the effect of mulch favourably prevented crust formation due to dissipating energy of raindrops before they hit the soil surface. Despite all these benefits of mulching, which also include modification of the soil environment especially at the surface or near surface hydrological processes and aeration (Scopel *et al.,* 2004); smallholder farmers in developing countries especially in sub-Saharan Africa are still reluctant to leave crop residues as mulch in the field. In South Africa, the declines in SOM levels for the past thirty years are alarming, mostly due to soil erosion which affected more than 70% of the countries land surface (Barnard and du Preez, 2004; Le Roux *et al*., 2007). According to Swanepoel *et al*. (2018), South African soils have very low OM by nature and approximately 60% of countries soils’ have less than 0.05% SOM. Maize or wheat straw and other crop residues are sold and/or used as livestock feed in sub-Saharan Africa by smallholder farmers to maximize profit (Thierfelder and Wall, 2012). Alternative organic waste materials such as algae residues, bagasse and forestry waste etc.; have been identified and proposed to replace crop residues for mulching purposes (Onwona-Agyeman *et al*., 2012). However, adverse weather conditions (high wind speed and intensity rainfall) in arid and semiarid regions can easily wash away organic waste material used as mulch in the field (Onwona-Agyeman *et al*., 2015).

To effectively utilize biological waste materials, reduce soil erosion, conserve soil moisture, regulate soil temperatures and suppress weed, Onwona-Agyeman et al. (2012) used a pressurized steam and compression technology to produce mulching materials called agri-mats or bio-boards from forestry residues and placed them in gentle and steep slopes in the field. The results from the study by Onwona-Agyeman et al. (2012) indicated that agri-mats could reduce soil erosion by 94.4% and 92.3% on steep (30°) and gentle (5°) slopes respectively. Moreover, the agri-mats absorb and retain more moisture (67-77%) for up to two days compared to rice straw and wood chips. The agri-mats are designed to withstand runoff water and blowing away from heavy storms and strong winds respectively (Onwona-Agyeman *et al*., 2012). However, there is a lack of information documented in South Africa about the use of agri-mat mulches for improvement of soil hydrological and thermal properties. In addition, the decomposition and nutrient release characteristics of agri-mats can be influenced by weather/climate; hence, there is a need for extensive research. The current study hypothesizes that agri-mats can effectively improve crop yields, conserve soil moisture and moderate soil temperatures in semi-arid and humid agro-ecological zones of South Africa. Therefore, the aim of this study was to investigate the effects of agri-mats and grass mulch on maize and spinach yield, soil moisture and soil temperature under semi-arid and humid conditions.

4.2. MATERIALS AND METHODS

4.2.1 Description of the study sites

Two sites, Pretoria and Durban, were selected to represent semi-arid and humid agro-ecological zones respectively. Maize and Spinach were used as test crops for the experiment in summer (between November and March) and winter (between April and August) respectively. The experimental site in Pretoria was located in the Agricultural Research Council–Vegetable and Ornamental Plant Institute (ARC–VOPI) in Roodeplaat (25°35'33.3"S; 28°20'12.8"E, altitude 1165 m), which is about 35 km north east of central Pretoria. Textural analyses results indicate that the soil has 76.3% sand, 9.3% clay and 14.3% silt at a depth of 0 – 40 cm. The area receives an average annual precipitation of 573 mm, mostly between November and March. The experimental site in Durban was located in Newlands Agro-Ecological Hub in Newlands East (29°46'25.0"S; 30°58'30.6"E, altitude 97 m), about 15 km North of Durban, Kwa-Zulu Natal (KZN). The soil textural analysis results of the top 40 cm depth indicate that the soil has 37.8% sand, 24.3% clay and 37.9% silt. The area receives rainfall almost throughout the year with an average annual precipitation of 828 mm.

4.2.2 Experimental layout and treatments

A two-year field study (2017/18 and 2018/19 seasons) was conducted in both experimental sites, Pretoria and Durban, using a randomized complete block design (RCBD) replicated three times. The following five treatments were established;

1. Full cover agri-mat (100%AG),

2. Half agri-mat cover (50%AG),

3. Bare or no cover (control),

4. Three tons of grass per hectare (3t.GR) and,

5. Six tons of grass per hectare (6t.GR).

Each plot had an area of 6 m^2 (4 m x 1.5 m) with 0.5 m spacing between plots and 1 m apart in each block. Land preparation was conducted with spades as means to minimize soil disturbance and rakes were used to level the soil surfaces and remove plant debris as well as stones. Prior to planting, moisture and temperature sensors (Decagon 5TM VWC + Temp) were calibrated and installed at each sited, and in each plot at depth of 0.4 m to compensate the effective rooting depths of both spinach and maize in sandy soils, whose root system can grow beyond 1 m soil depth under favourable conditions (Nyakudya and Stroosnijder, 2014). The sensors were connected to a three Em50-series data loggers, which accommodate five sensors each. All the sensors in both sites were programmed to record soil moisture and temperature regime every 60 minutes for the duration of the experiments.

4.2.3. Maize planting season (November to March)

Maize (*Zea mays* L) was planted during summer season in November at both sites beginning with the Durban site followed by Pretoria a week after planting was finished in Durban. Maize was planted at a spacing of 0.5 m between plants and 0.3 m between rows. The inter-row spacing (0.3 m) was informed by agri-mat dimensions i.e 1 m × 0.3 m. For both planting seasons (2017/2018 and 2018/2019), fertilizer recommendation of 100kg N. ha^{-1} (LAN) was applied uniformly at all treatments based on soil analysis results and in splits (20% at planting, 40% four weeks after planting, 30% eight weeks after planting and the remaining 10% was applied four weeks before harvest. 150 kg compound fertilizer (2:3:4) was applied as a base fertilizer uniformly at all treatments. The plots were irrigated to field capacity after planting and every other two days when necessary. Pests and diseases were controlled using Methamidofos 585 SL (with organo phosphate as active ingredient) in a mixture of 18ml per 15L of water at planting, then after each harvest except after the last harvest. Weeds were controlled manually by uprooting every two-weeks or when necessary. Crop growth parameters (plant height, leaf length, leaf width, and later - number of ears) were measured three weeks after planting and every other week thereafter, using a tape measure. Figure 4.1. show maize crop at different stages of growth during the 2017/2018 season in Durban. However, maize total yield and cob yield were not recorded in Durban due to destruction by animals at maturity stage. Maize was harvested in March of the following year, beginning in Durban and a week later in Pretoria after harvesting was finished in Durban. Total biomass, number of cobs (marketable and non-marketable) were weighed using a scale and recorded for crop yield determination.

Figure 4.1. Maize crop at different stages of growth during the 2017/2018 season in Durban, KZN.

Unlike the Durban site, animals or other external factors did not disturb the maize trial in Pretoria during maturity stage. Figure 4.2 and Figure 4.3 show the maize with cobs at maturity during the 2017/2018 and 2018/2019 growing seasons respectively.

Figure 4.2. Maize growth at maturity stage in Pretoria, Gauteng

Figure 4.3. Maize cobs at maturity stage from 50%AG and 3t.GM treatments in Pretoria, Gauteng

4.2.4. Spinach planting season (April to August)

Spinach (*Spinacia oleracea*) was planted in April, a month after maize was harvested for both 2018 and 2019 planting seasons (April - August). Similarly, with the maize planting season, spinach was first planted in Durban and then a week later, planting was conducted in the Pretoria site. Spinach seeds were planted in seedling trays using hygro-mix and slightly covered with vermiculite for easy germination. The seedlings were transplanted after a week when they reach an average height of 0.1 m. The seedlings were spaced at 0.3 m between rows and 0.3 m between plants and there were five rows of spinach per plot. Each plot was irrigated immediately after transplanting. The recommended fertilizer application rate of 100 $kgN.ha^{-1}$ (LAN), (which was based on spinach planting guidelines) was applied uniformly at all treatments in splits as follows – 30% at planting, 40% after first harvest (conducted four weeks after planting) and the remaining 40% after second harvest (conducted after eight weeks from transplanting). 100 kg compound fertilizer (2:3:4) was applied as a base fertilizer uniformly at all treatments (Also based on spinach planting guidelines rather than soil analysis). Crop growth parameters such as plant height, leaf length, and leaf width were measured every two-weeks after transplanting and at each harvest using a tape measure. During harvesting, only the three rows inside each plot were used for total biomass yield while the rows on the edges of the plots were considered as border rows as indicated in Figure 4.4. After each harvest, fresh biomass yield was weighed using a scale and dried afterwards at 70˚C for 24 hours in an oven. Composite samples of spinach leaves were taken during each second harvest for leaf content (quality) determination. The last (third) harvest for spinach in each season was conducted on the third month (12 weeks after transplanting). Figure 4.5. Show the leaves of spinach that were harvested from the plots treated with 100% agri-mat mulch during the second harvest,

Figure 4.4. Harvesting of spinach during the second season in Durban, KZN.

Figure 4.5. Leaves of spinach harvested form the 100%AG plot in Durban, KZN.

4.2.5. Weather data collection

The weather data parameters were automatically collected from the programmed weather stations located within the premises of each experimental site. The automated weather stations (in Durban and Pretoria) consisted of the following instruments:

i) An electronic rain-gauge (RIMCO, R/TBR tipping bucket rain gauge, Rauchfuss instruments division, Australia) to measure rainfall;

ii) An evaporation pan and electronic cup anemometer (MET ONE, Inc. USA) to estimate crop evapotranspiration and wind speed respectively and

iii) An electronic relative humidity and temperature sensor (083E) to measure relative humidity as well as minimum and maximum temperatures. The weather stations also consisted of an LI 200X pyranometer (LiCor, LiCor, Lincoln, Nebraska, USA) for measuring solar radiation, and a CR 10X data-logger (Campbell Scientific inc, USA) to store daily data generated by various components of the weather stations.

4.2.5.1. Weather data in Durban, KZN.

The mean weekly minimum air temperature ranged from the lowest temperature of 14.8^{o}C recorded in the third week after planting to the highest of 20.9 ^{o}C in week 15 during the 2017/2018 growing season. For the second growing season (2018/2019), the mean weekly minimum temperature varied from the lowest value of 14.7 ^{o}C in week 1 to the highest value of 24.1 ^{o}C in week 19 (Figure 4.6c). The highest mean maximum weekly temperatures of 30.2 ^{o}C (week 12) and 32.1 ^{o}C (week 5) were recorded in the first (2017/2018) and second (2018/2019) growing seasons respectively. The lowest maximum temperature of 25.3 ^{o}C (week 4) was recorded during the 2017/2018 and 23.3 ^{o}C (week 1) in the 2018/2019 growing season. The highest mean weekly solar radiation of 22.8 $MJ.m^{-2}$ was recorded during week 9 of the first (2017/2018) growing season, while a lowest value of 14.1 $MJ.m^{-2}$ was recorded in week 5. For the 2018/2019 growing season, mean weekly solar radiation was lowest (12.4 $MJ.m^{-2}$) in week 18 and higher at week 2 with a value of 24.8 $MJ.m^{-2}$ (Figure 4.6d).

In addition, total fort-nightly rainfall distribution (a), mean weekly evapotranspiration (b), mean weekly maximum and minimum temperatures (c) and mean weekly solar radiation (d) during the 2017/2018 and 2018/2019 growing season were recorded from the nearby weather station in in Durban, KZN. The total weekly rainfall data indicated that rainfall was generally well distributed in both seasons during the Maize planting season for the Durban site. The total rainfall received during the first (2017/2018) growing season was 724 mm, 132 mm higher than the total amount of 592 mm recorded the second (2018/2019) growing season (Figure 4.6a). The mean highest weekly evapotranspiration of 5.6 mm was recorded during the 2017/2018 growing season in week 10, with the lowest value of 3.4 mm recorded during the third week (Figure 4.6b). For the 2018/2019 growing season, the highest (5.4 mm) and lowest (3.2 mm) mean weekly evapotranspiration were recorded during the week 9 and week 20 respectively.

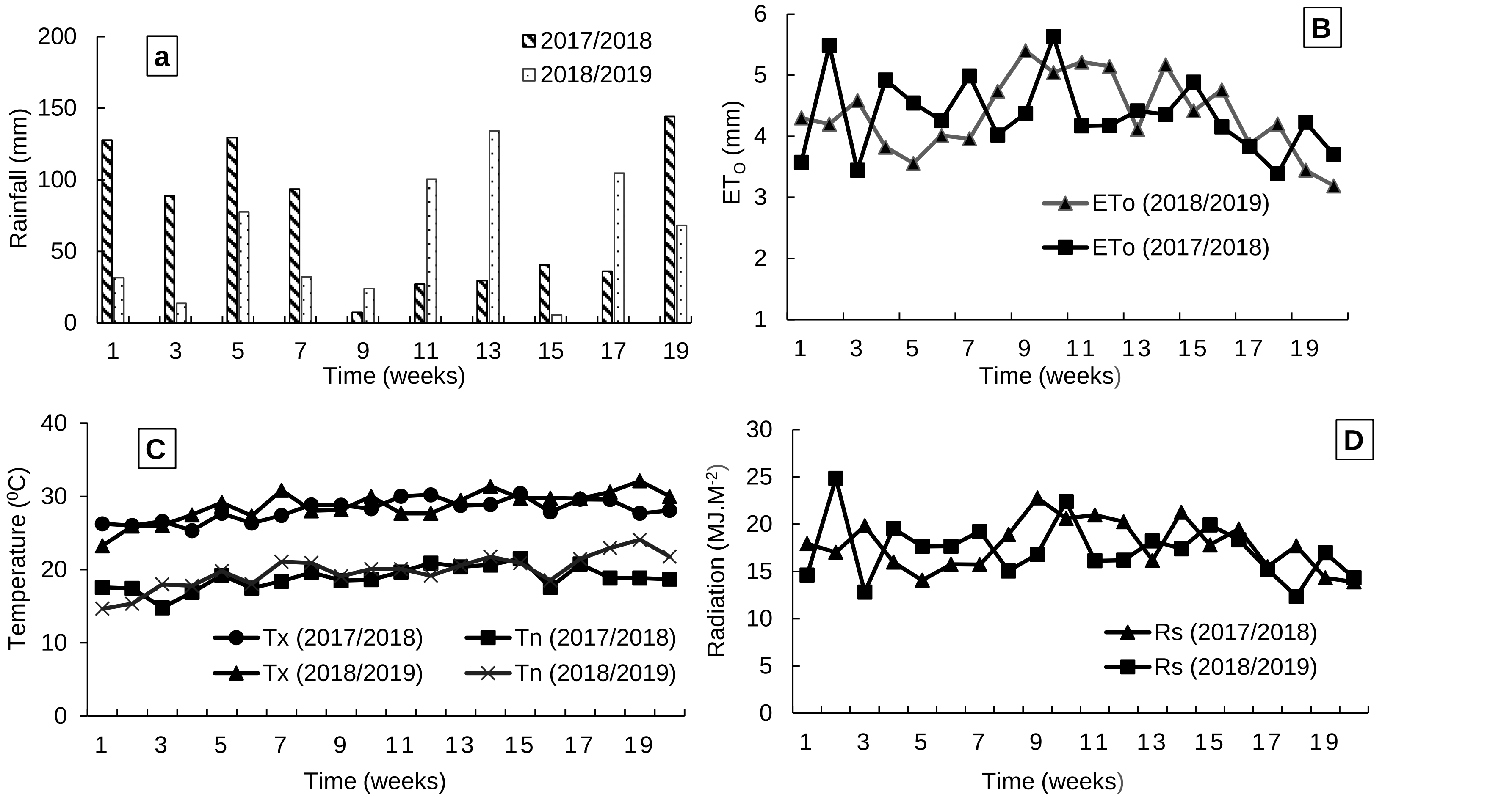

Figure 4.6. Total fort-nightly rainfall distribution (a), mean weekly evapotranspiration (b), mean weekly maximum and minimum temperatures (c) and mean weekly solar radiation (d) during the 2017/2018 and 2018/2019 growing season for Maize in Durban, KZN.

The data loggers were connected to soil moiture and temperature sensors to record moisture and tempeturature every sixty minutes. Soil temperature and soil moisture recorded hourly was downloaded from data loggers monthly using a portable computed (HP 15 i5 notebook) as indicated in Figure 4.7.

Figure 4.7. Soil temperature and soil moisture content download from data loggers monthly using a portable computed in Durban, KZN.

4.2.5.2. Weather data in Pretoria, Gauteng.

The total weekly rainfall data indicates the Pretoria site received rainfall only during the first eight weeks after planting for the first (2018) growing seasons. From the 9th week onwards until the final harvest, there was almost no rainfall as this was the winter growing season (Figure 4.8a). In the second (2019) season, rainfall was received in the first four weeks after planting and afterwards, no rain was received until the final harvest except only 1.01mm in the 14th week. The second (2019) growing season had a higher total rainfall of 84.8 mm compared with first the season (2018), which received 70.1 mm. The mean weekly evapotranspiration (ETo) was higher during week 20 in both growing winters seasons (3.76mm in 2019 and 3.65mm in 2018). The lowest ETo values of 2.01 mm (week 14) and 2.43 mm (week 11 and 12) were recorded during the 2018 and 2019 growing seasons respectively (Figure 4.8b). The lowest mean weekly minimum temperature of 0.18 ^{o}C was recorded in week 13 in both growing seasons.

Similarly, the highest mean minimum temperature of 14.2 ^{o}C was recorded in the first week for both growing seasons (Figure 4.8c). Mean maximum weekly temperatures were higher (28.04 ^{o}C) in week 19 and week 20 (28.62 ^{o}C) during the 2018 and 2019 winter growing seasons respectively. The lowest maximum mean temperature of 19.19 ^{o}C (week 15) and 22.92 ^{o}C (week 13) was recorded during the 2018 and in the 2019 growing season respectively. The mean weekly solar radiation was higher (17.6 MJ.m^{-2}) was during week 4 of the 2018 growing season, while a lowest value of 10.91 MJ.m^{-2} was recorded in week 15 (Figure 4.8d). The weather data for 2019 growing season indicates that mean weekly solar radiation was lowest (12.24 MJ.m^{-2}) in week 1 and higher at week 20 with a value of 17.51 MJ.m^{-2}. Generally, the trends in Figure 4.9 indicates that air temperatures (mean maximum and mean minimum), evapotranspiration and solar radiation were all higher in the first week after planting, started to decrease steadily until week 11 and then increase again after week 15 until the end of the experiment in week 20.

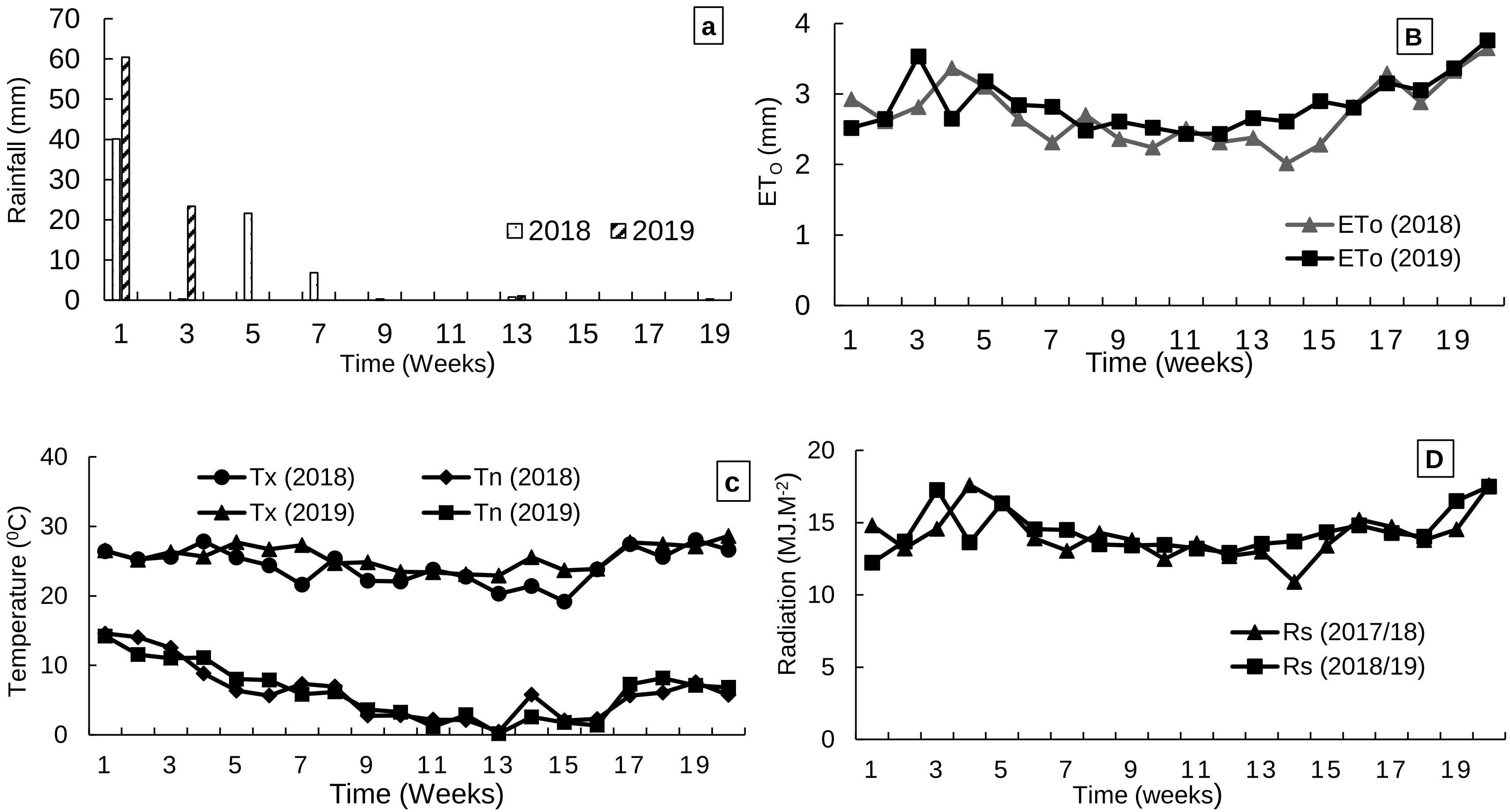

Figure 4.8. Total fort-nightly rainfall (a), mean weekly evaporation (b), mean weekly maximum and minimum temperatures (c) and mean weekly solar radiation (d) during 2018 and 2019 spinach growing season in Pretoria, Gauteng

4.2.6. Laboratory analyses

Soil samples were collected with a spade from both experimental sites at top 30 cm soil depth, then air-dried for a week and ground to pass through a 2 mm sieve. The dried and sieved soil samples were analysed in the laboratory as described by Carter and Gregorich, (2006). Briefly, Total N content was determined by Kjeldahl digestion and distillation method. The total organic carbon was determined using the Walkley and Black procedure by dichromate wet oxidation method. Available P was extracted using Bray-1 solution and determined by molebdenum blue calorimetry. Soil pH was measured in a 1:2.5 (w/v) soil/water mixture using a combination of digital electrode. Cation exchange capacity (CEC) was measured using Mehlic method. Exchangeable K, Na, Ca, and Mg were extracted with 1M ammonium acetate (NH_4OAc) at pH-7, and assayed by atomic absorption spectrophotometry. Thereafter, K was determined using a flame photometer and Ca by EDTA titration method. Soil particle size distribution was determined using the hydrometer method after oxidizing SOM with hydrogen peroxide as described by Gee and Or (2002). The initial characterization of the soil nutrient content including detailed particle size distribution from both sites is shown in Table 3.1.

4.2.7. In situ data

Soil water content and temperature regime data was downloaded monthly from the EM50 data loggers. The data loggers were connected to soil moisture and temperature sensors, which were calibrated prior to installation at a 0.4 m soil depth.

4.2.8. Statistical analysis

Statistical analysis was performed using SAS institute, JMP® (Carry, 2016). Data was subjected to analysis of variance (ANOVA) at 5% probability level to assess statistical significance of mulching on soil water regime and soil temperature as well as crop yield of Maize and Spinach. Student t-test was used to indicate statistical differences between treatment means.

4.3. RESULTS

4.3.1. Effect of mulching on Soil Water Content and Temperature in Durban

The results from the current study indicates that mulching either with agri-mat or grass had an effect on soil moisture regime and temperature. The 6 $tons.ha^{-1}$ grass mulch treatment resulted in the highest moisture content value of 0.223 $m^3.m^{-3}$ compared to other treatment combinations (Figure 4.9). The lowest soil moisture content of 0.154 $m^3.m^{-3}$ was recorded under the bare (control) treatments at 0.4 m soil depth. Generally, the results indicate that between the five mulching treatments, the soil moisture ranged, on average from highest to lowest in the following order 6t.GM > 3t.GM > 100%AG > 50%AG > Bare during the hourly within a day and days in a week (Figure 4.9a and b). However, the fluctuating spikes for the trend on average daily soil moisture within a month (Figure 4.9c) were more visible compared to hourly trends within a day (Figure 4.9a) and daily trends within a week (Figure 4.9b. Morever, the trends in Figure 4.9c indicates that for the first seven days, the highest order for the five mulching treatments in soil moisture was 6t.GM > 3t.GM > 100%AG > 50%AG > Bare. However, the trend from the eight day onwards with the control treatment remaining lower compared to other treatments until day 30.

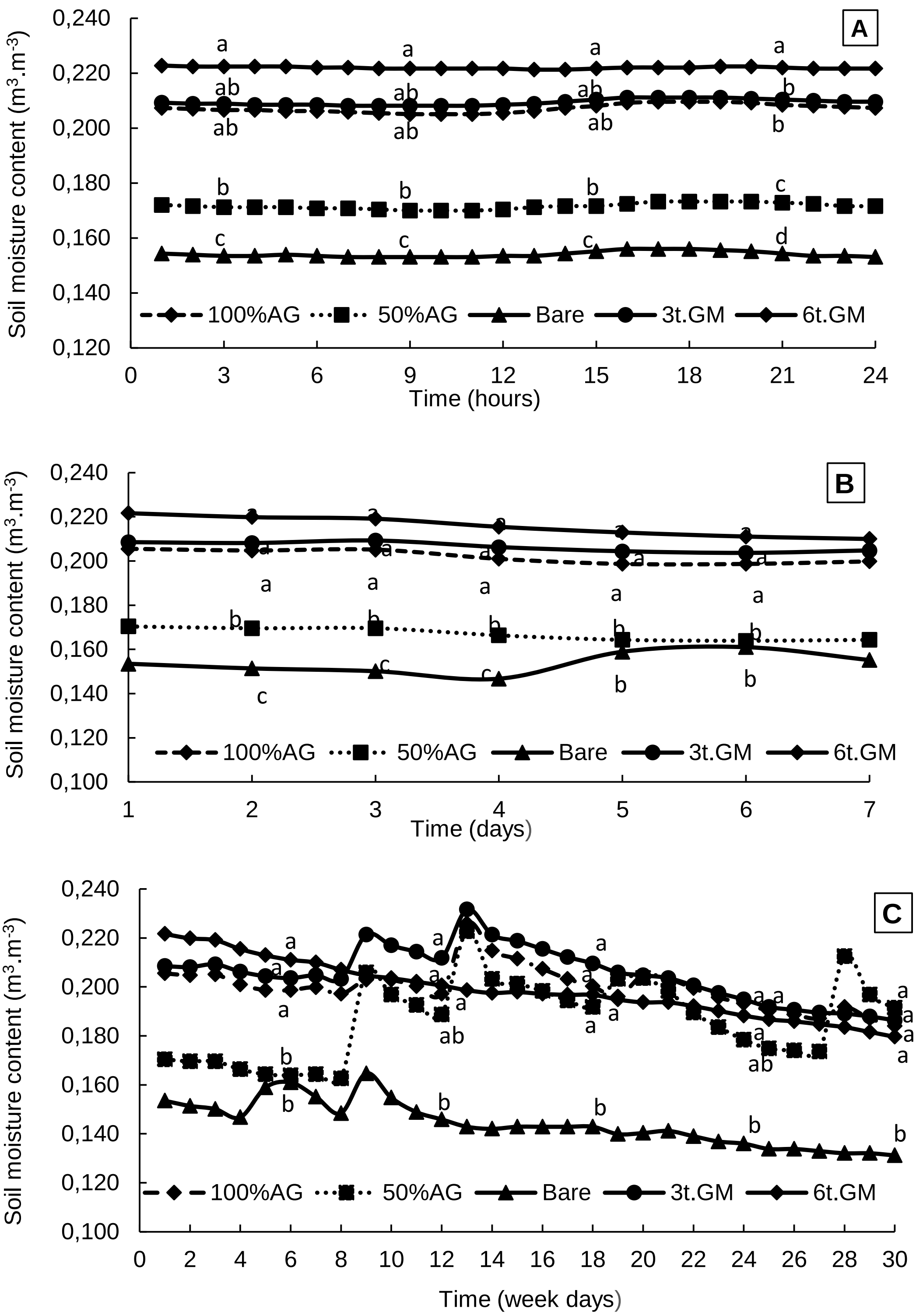

Figure 4.9. Effect of mulch on soil hourly (a), days in week (b) and days in month (c) moisture content trends measured at 40cm soil depth during second (2019) spinach growing season in Durban, Kwa-Zulu Natal. Means with the same letter within the same time inteval are not significantly different.

The results from soil data loggers installed at 0.4 cm soil depth indicated that soil temperatures consitently formed a forward tilted S-shape trend in all five mulching treatments for the three time caterogies; average changes in a day (Figure 4.10a), average daily changes in a week (Figure 4.10b) average daily changes in a month (Figure 4.10c). Although the trends were similar in the three categories (average changes in a day, week and month), the highest peak was reached at a different time for each category (after 18hours for figure 4.10a, around 18hours for 4.10b and before 18hours for 4.10c). Soil temperature in winter dropped steadily from 1 am until the about noon and started to increase again due to higher air temperatures during the day. The increase in soil temperaure reach their peak around 6pm in the afternoon and began to decrease again at night time until they pick up again the following day. The control treatments had lower soil temperaure between 21h00 at nigth and 12h00 midday compared to all other mulching treatments. However, the soil temperature under the control treatment increased after 12pm and remained equal or even higher than other soil temperatures recorded under other mulching treatments until 21h00 at night.

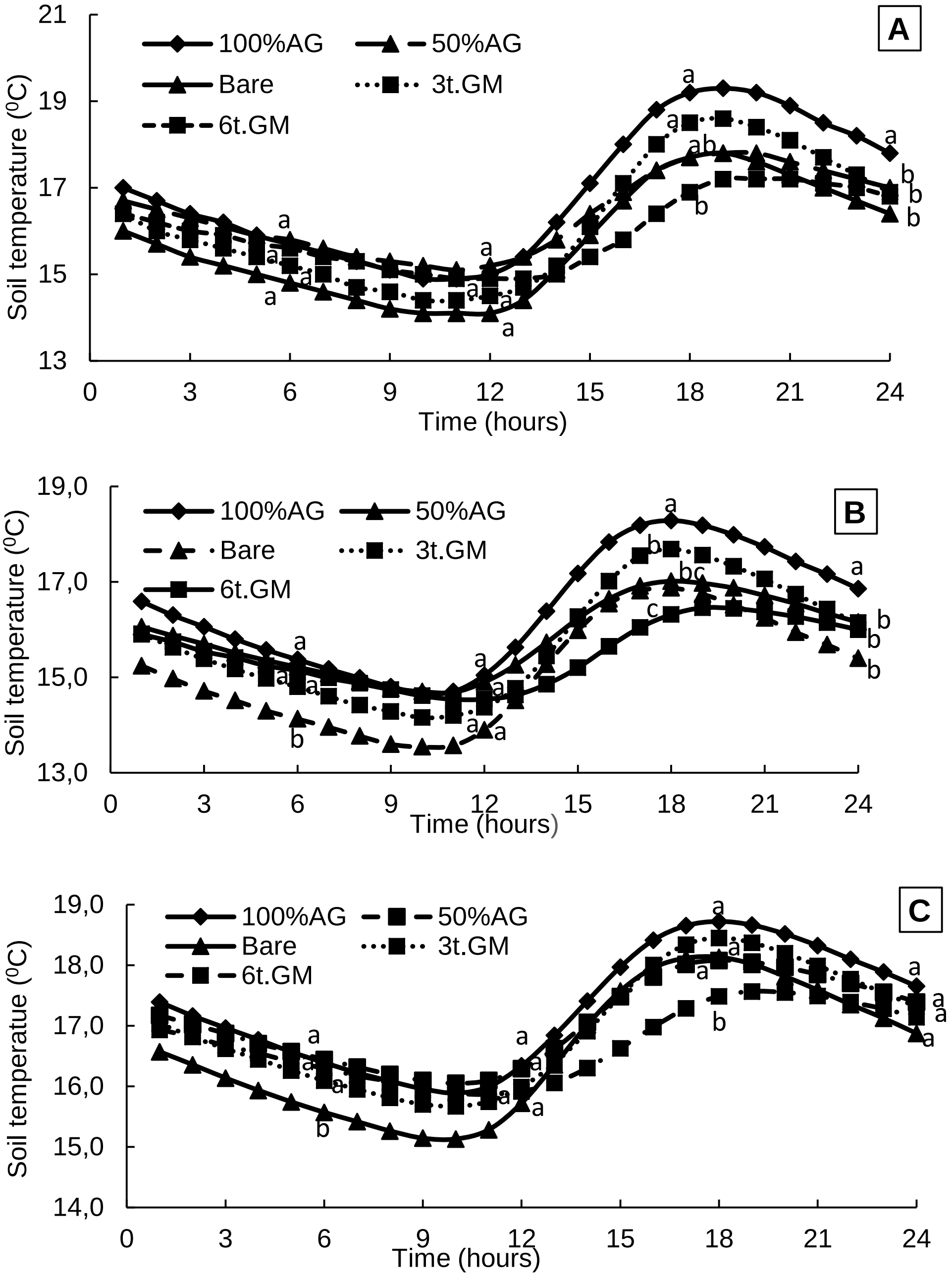

Figure 4.10. Effect of mulching on soil temperature trends in hourly average, on a day (a), in a week (b) and in a month (c) during second (2019) spinach growing season in Durban, Kwa-Zulu Natal at 40cm soil depth. Means with the same letter under the same time interval are not significantly different from each other.

4.3.2. Effect of mulching on Soil Water Content and Temperature in Pretoria

Similar with the trends observed in the Durban site, the results obtained soil data logger in Pretoria indicated that mulching had significant effects on soil moisture regimes and temperature. The 100%AG mulch treatment resulted in the high soil moistue content compared to other treatment combinations at all three time frame categories; hourly average trends in a day (Figure 4.11a), daily average in a week (Figure 4.11b) and daily average in a month (Figure 4.11c). Accordingly, the lowest soil moisture content was recorded under the bare (control) treatments at all three time categories. Generally, the soil moisture ranged from highest to lowest in the following order 100%AG > 6t.GM > 3t.GM > 50%AG > Bare.

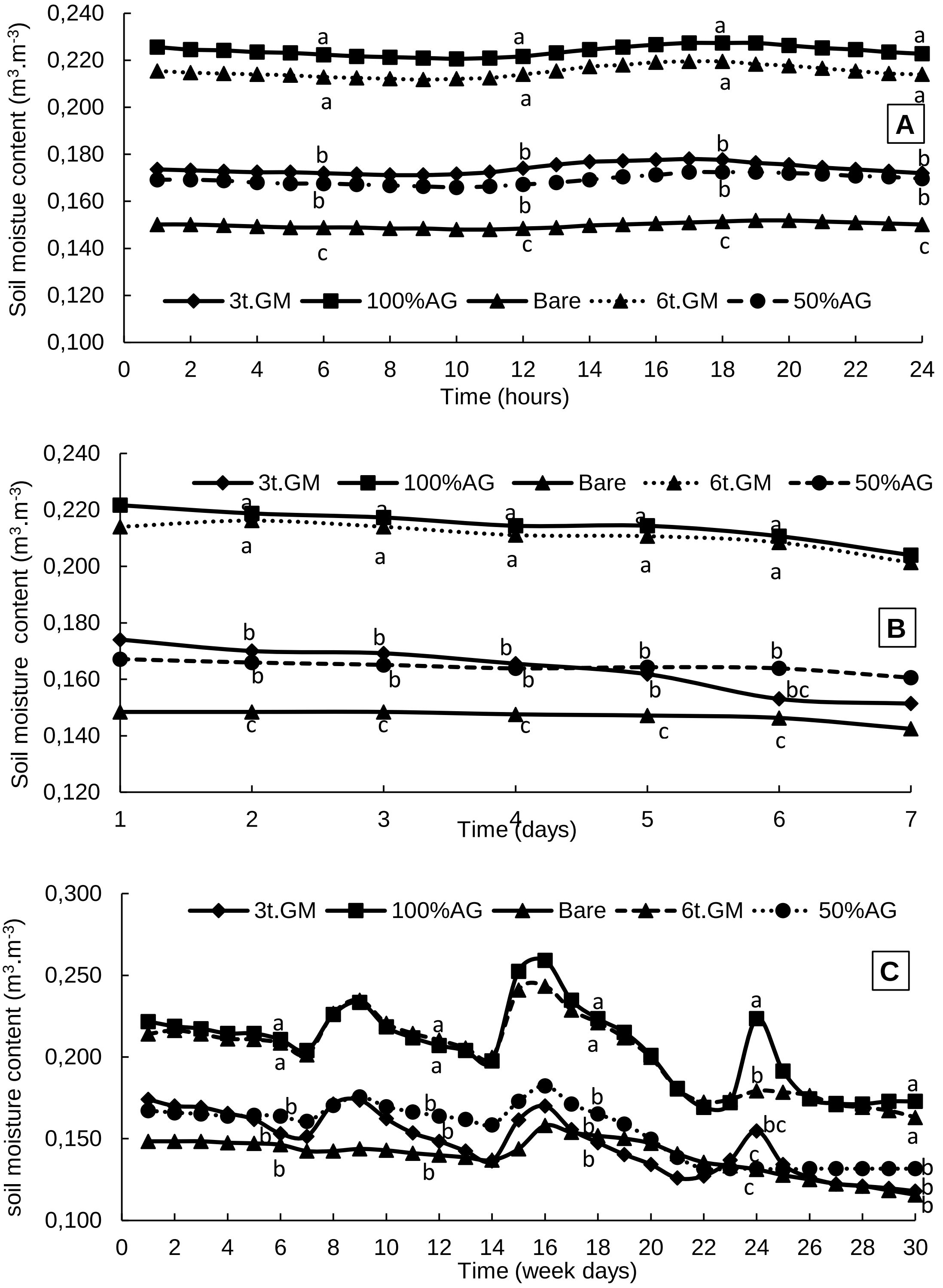

Figure 4.11. Effect of mulch on soil moisture in hourly bases in a day (a), days in a week (b) and days in month (c) trends measured at 40cm soil depth during first (2017/2018) maize growing season in Pretoria, Gauteng. Means with the same letter under the same time interval are not significantly different from each other.

Similar with the observations in Durban, the soil temperatures in Pretoria formed a forward tilted S-shape trend in all five mulching treatments for the three time caterogies; hourly changes (in a day), average daily changes in a week and average daily changes in a month. Unlike during the winter season, the soil temperature in summer dropped steadily from 1am until about 9am and started to increase again due to higher air temperatures during the day. The increase in soil temperaure reached their peak betwee 4 and 6 pm in summer and begin to decrease again at night time until they pick up again the following day (Figure 4.12). Generally, the highest peak in all time categories was reached before or around 18 hours on average.

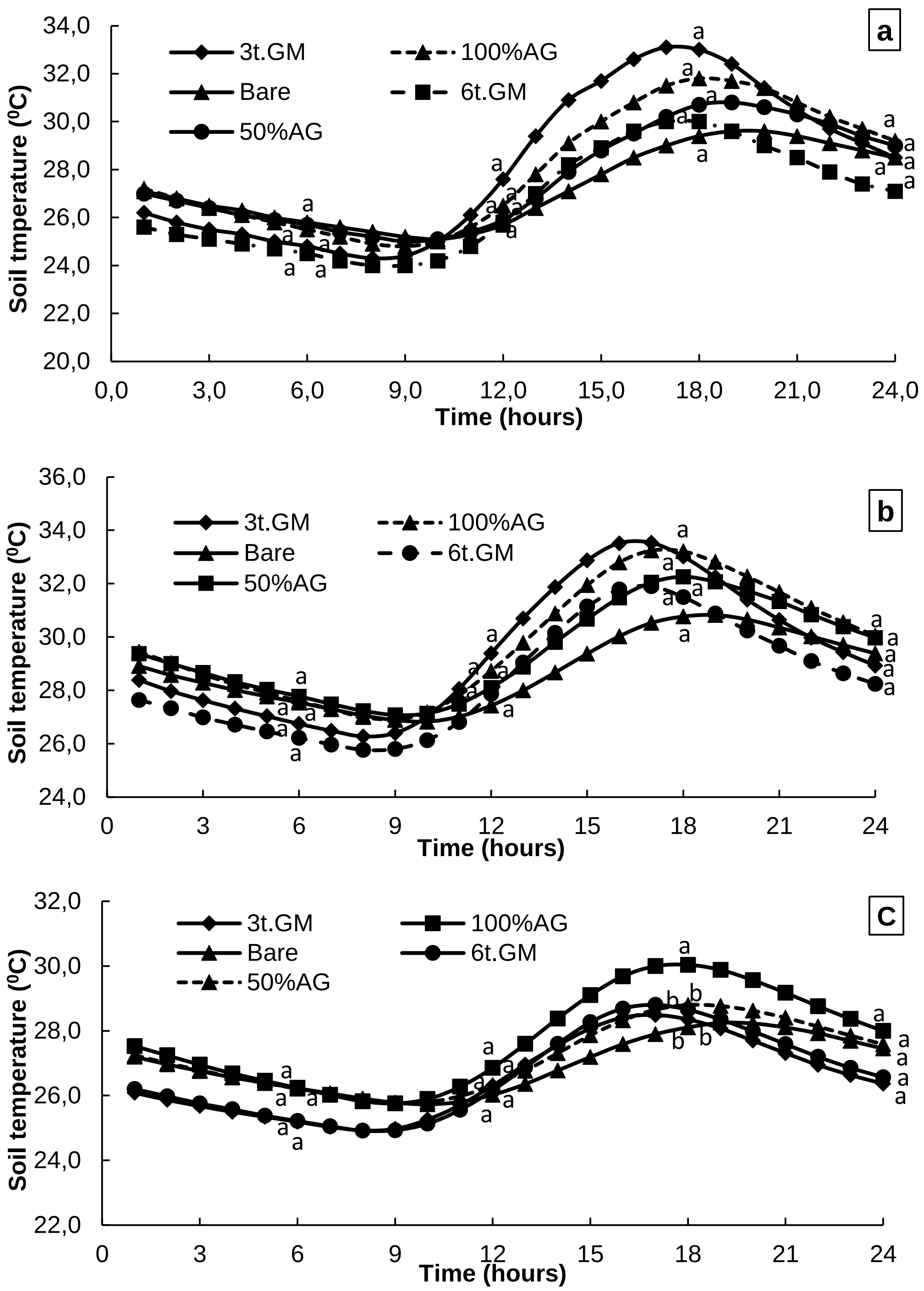

Figure 4.12. Effect of mulching on daily (a), weekly average (b) and monthly average soil temperature trends during first (2017/2018) maize growing season in Pretoria at 40cm soil depth. Means with the same letter under the same time interval are not significantly different from each other.

4.3.3. Effect of mulching on maize crop growth parameters

The results from the Durban site show that mulch treatments had significant ($P < 0.05$) effects on maize plant height from the third week after planting and every other second week until the last measurement in week 15. The 100%AG mulch treatment consistently resulted in the highest plant height at all times when the measurements were made except during week 2 (Figure 4.13). The differences for plant height during the first measurements in the second week after planting were only marginal. However, the 100%AG treatment produced the highest plant height of 24.1 cm while the lowest plant height of 20.3 cm was recorded under the control treatment.

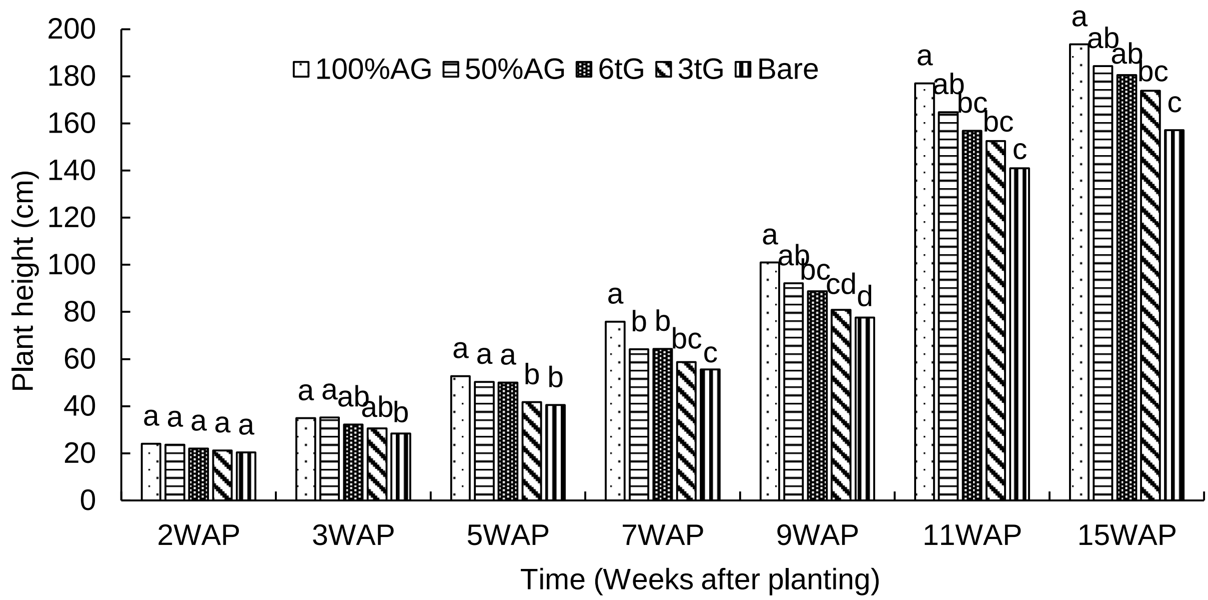

Figure 4.13. Plant height for Maize during the 2017/2018 growing season in Durban, Kwa-Zulu Natal. Means within the same measuring period (WAP) with the same letter are not significantly different ($P < 0.05$). LSD_{2WAP} = 0.4277, LSD_{3WAP} = 0.625, LSD_{5WAP} = 0.0077, LSD_{7WAP} = 0.0031. LSD_{9WAP} = 0.0048, LSD_{11WAP} = 0.0137, LSD_{15WAP} = 0.0162

Mulching had no significant ($P < 0.05$) effects on maize growth parameters during the 2018/2019 growing season in Durban except in week ninth after planting. During week nine after planting there were significant ($P < 0.05$) differences between treatment means but only for measured leaf length and leaf width. The differences in treatments means under plant height were only marginal. From week 10 to 15, the differences again were marginal for all measured maize growth parameters. Despite the good vegetative growth as reflected in the crop growth parameters, animals in Durban damaged and ate the cobs of maize during grain filling stage at both growing seasons.

The results from the Pretoria site indicates that mulching had a significant ($P < 0.05$) effects on all measured maize crop growth parameters as noted in plant height, leaf length and leaf width beginning from week 5 until week 12 (Table 4.1). The 100% agri-mat mulch treatment (100%AG) resulted in the highest plant height, leaf length and width at all weeks except for leaf width at week 8 and 12. The control (bare) treatment resulted in lowest plant height, leaf length and leaf width values compared to other mulch treatments regardless of the time of measurements. In the fifth week, plant height, leaf length and leaf width values of 46.0 cm, 34.1 cm and 3.5 cm were recorded under the control treatment respectively. In contrast, the 100% agri-mat treatment resulted in the highest values for plant height, leaf length and leaf width i.e. 125.7 cm, 56.4 cm and 5.9 cm respectively in week five. Additionally, the 100%AG treatments resulted in the highest plant height of 202.7 cm during week 12 whilst the lowest plant height of 60.3 cm was recorded under the control treatment. Similar with plant height at week 12, the 100%AG treatment produced the highest leaf length (117.9 cm) and leaf width (10.4cm) whilst the control treatment produced the lowest leaf length (68.3 cm) and leaf width (3.9 cm).

Table 4.1. Crop growth parameters of Maize from week 5 to week 12 after planting during the second (2018/2019) summer trial in Pretoria, GP. H stands for height, L = length, W = width, WAP = weeks after planting and LSD for least significant difference. Mean values under the same column within the same measuring period with the same letter are not significantly from each other

	5WAP			6WAP			7WAP			8WAP		
Trtments	**Plant H (cm)**	**Leaf L (cm)**	**Leaf W (cm)**	**Plant H (cm)**	**Leaf L (cm)**	**Leaf W (cm)**	**Plant H (cm)**	**Leaf L (cm)**	**Leaf W (cm)**	**Plant H (cm)**	**Leaf L (cm)**	**Leaf W (cm)**
100%AG	125.67a	56.44a	5.99a	135.67a	64.89a	6.69a	148.89a	73.56a	7.46a	157.44a	80.33a	8.84ab
50%AG	100.78a	56.11a	4.76ab	108.22a	62.44a	5.27a	109.22b	71.11a	5.93a	116.33b	77.44a	6.16c
Bare	46.00b	34.11b	3.46b	51.67b	40.78b	3.53b	57.67c	45.67b	3.91a	63.22c	52.56b	4.42c
6t.GM	102.56a	43ab	5.62a	113.44a	54.22ab	6.5a	124.78ab	63.89ab	7.37a	136.44ab	73.78a	9.19a
3t.GM	106.33a	50.55a	4.99ab	113.88a	67.89a	5.4a	122.22ab	75.78a	6.12a	131.00ab	83.67a	6.58bc
LSD$_{(p<0.05)}$	0.0047	0.0375	0.0409	0.0042	0.378	0.0077	0.0011	0.0374	0.0062	0.0008	0.0264	0.005
	9WAP			**10WAP**			**11WAP**			**12WAP**		
Trtments	**Plant H (cm)**	**Leaf L (cm)**	**Leaf W (cm)**	**Plant H (cm)**	**Leaf L (cm)**	**Leaf W (cm)**	**Plant H (cm)**	**Leaf L (cm)**	**Leaf W (cm)**	**Plant H (cm)**	**Leaf L (cm)**	**Leaf W (cm)**
100%AG	168.78a	90.22a	7.34a	178.22a	98.67a	8.255a	189.44a	107.11a	9.06a	202.67a	117.89a	10.44a
50%AG	122.89b	84.44a	6.48a	132.67b	93.22a	6.82a	140.89b	96.89b	7.18b	157.22b	108b	8.35a
Bare	49.44c	59.65c	3.4b	54.22c	60.22c	3.07b	56.56c	63.11c	3.58c	60.33c	68.33c	3.88b
6t.GM	168.89a	69.56b	6.97a	179.78a	78.22b	8.00a	188.56a	101.67a	8.88ab	193.67a	92.56b	10.9a
3t.GM	138.78a	66.89bc	6.97b	145.3b	69.44b	7.3a	153.78b	74.11b	7.69ab	161.222b	87.89b	8.2a
LSD$_{(p<0.05)}$	<.0001	0.0005	0.0023	0.0001	0.0003	0.0002	<.0001	0.0002	0.0002	<.0001	0.0004	0.4416

4.3.4. Effect of mulching on maize biomass yield

Unlike the Durban site, animals or other external factors did not disturb the maize trial in Pretoria during maturity stage. Mulching had a significantly ($P<0.05$) effects on maize biomass yield during both planting seasons. The application of 100% agri-mat mulch resulted in the highest biomass yield of 9.4 tons.ha^{-1} during the first (2017/2018) growing season and 9.3 tons.ha^{-1} during the (2018/2019). During first season, the 50% agri-mat treatment had the second highest biomass yield with a value of 8.5 tons.ha^{-1}. However, the biomass yield values produced under 100%AG and 50%AG treatments were not significantly different from each other (Figure 4.14a). The bare (control) treatment resulted in the lowest biomass yield value of 5.7 tons.ha^{-1}. For the second season (2018/2019), the 100% agri-mat treatment resulted in the highest total yield (9.3 tons.ha^{-1}) whilst the control treatment had the lowest biomass yield of 4.6 tons.ha^{-1} (Figure 4.14b).

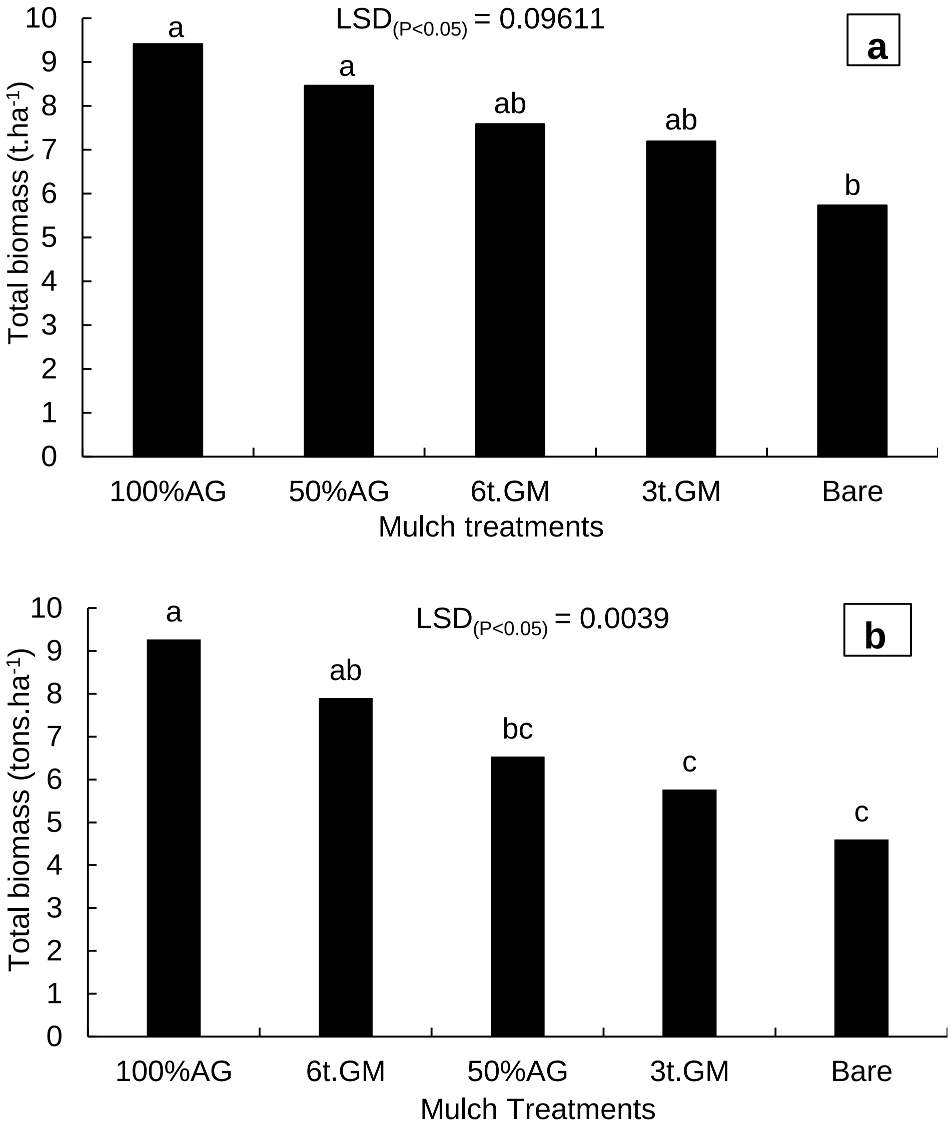

Figure 4.14. Effects of mulching on maize total biomass yield during (a) first season (2017/18) and (b) second season (2018/19) in Pretoria, Gauteng. Treatment means with the same letter within the same growing season are not significantly different from each other.

4.3.5. Effect of mulching on maize cobs fresh yield

Mulching had a significant ($P < 0.05$) effect on maize cob yield in both growing seasons (Figure 4.15). The application of 100% agri-mat mulch resulted in the highest cob mass in both seasons compared to all other treatments, while the control resulted in the lowest cob mass. The highest cob mass was 5.0 $tons.ha^{-1}$ and 5.6 $tons.ha^{-1}$ for 2017/2018 and 2018/2019 growing seasons respectively. Meanwhile, the lowest cob mass values of 2.8 $tons.ha^{-1}$ and 2.5 $tons.ha^{-1}$ were recorded under the bare (control) treatment during the 2017/2018 and 2018/2019 growing seasons respectively.

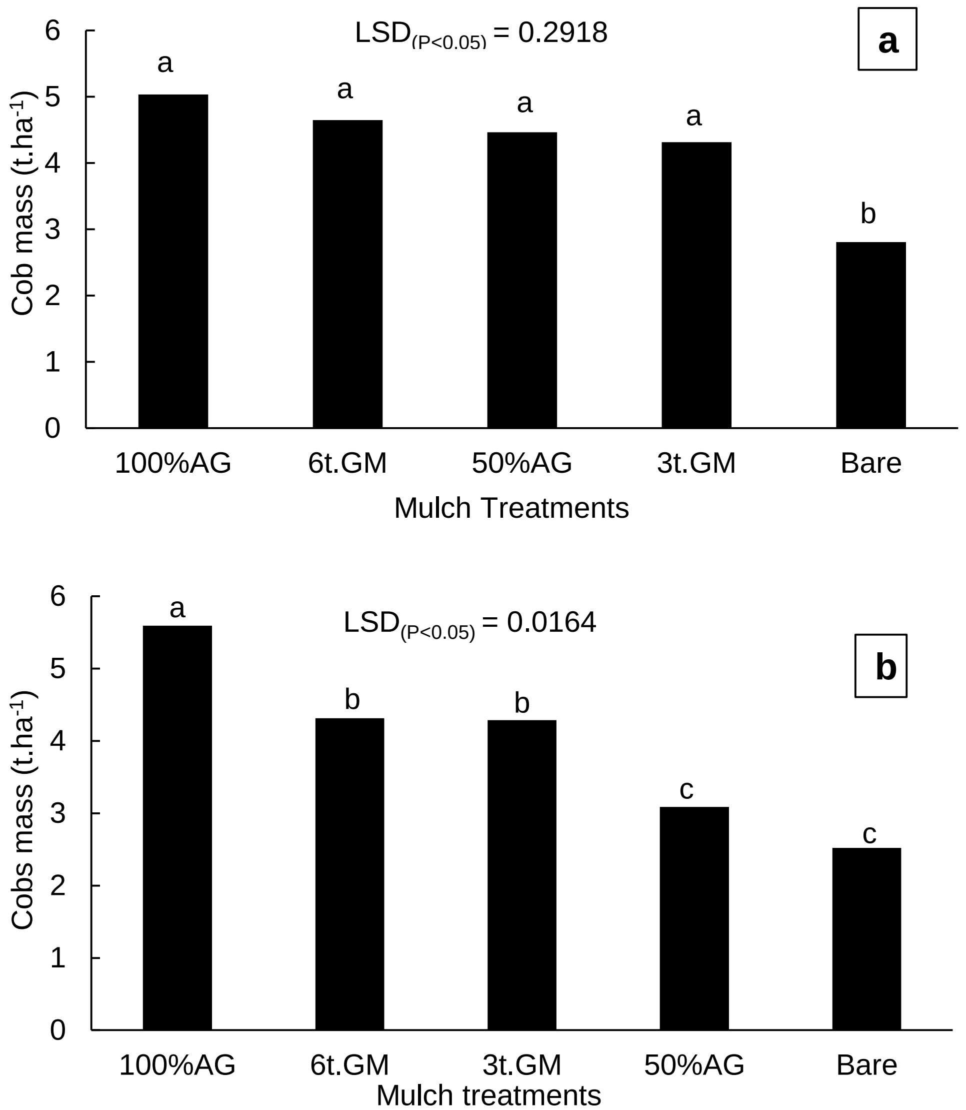

Figure 4.15. Effects of mulching on maize fresh cob yield during the (a) first season (2017/18) and (b) second season (2018/19) in Pretoria, Gauteng. Treatment means with the same letter under the same growing season are not significantly different from each other.

4.3.6. Effects of mulching on spinach crop growth parameters

The results from the Durban site show that mulching had a significant ($P < 0.05$) effect on all measured spinach crop growth parameters at all three harvests for both growing seasons except for leaf width during the second harvest. The 100% agri-mat mulch treatment (100%AG) produced the highest plant height, leaf length and leaf width during the first (2018) growing season at all three harvesting periods except for leaf width during the second harvest (Table 4.2). The highest spinach plant height of 69 cm for was recorded during the second harvest in 2018 winter season under 100%AG mulch treatment, while the lowest plant height of 23.3 cm was recorded during the first harvest of the second (2019) growing season under bare (control) treatment.

Generally, the measured spinach growth parameters were higher during the 2018 growing season compared with the 2019 growing season at all three harvesting times. The control treatment produced the lowest plant height, leaf length and leaf width values during both growing seasons. For the 2018 growing season, plant height, leaf length and leaf width values under the control treatments were 34.9 cm, 22.8 cm, and 13.3 cm at first harvest; 57.11 cm, 32.11 cm, and 17.56 cm at second harvest; 27.33 cm, 15.89 cm, and 9.56 cm at third harvest respectively. Similarly, for the 2019 growing season, the lowest plant height, leaf length and leaf width values of 23.3 cm, 12.3 cm, and 9.2 cm at first harvest; 31.2 cm, 19.4 cm, and 12.8 cm at second harvest; 31.8 cm, 18.3 cm and 10.2 cm at third harvest respectively, were all under the control treatment.

Table 4.2. Crop growth parameters of Spinach from during first, second and third harvest in 2018 and 2019 winter season. PH stands for Plant height, LL = Leaf length, and LW = Leaf width. Treatments with the same letter under the same column (i.e. PH) are not significantly different from each other.

2018		**Harvest 1**			**Harvest 2**			**Harvest 3**	
Treatments	**PH (cm)**	**LL (cm)**	**LW (cm)**	**PH (cm)**	**LL (cm)**	**LW (cm)**	**PH (cm)**	**LL (cm)**	**LW (cm)**
100%AG	49.33a	29.0a	17.89a	69.0a	39.0a	19.22a	59.11a	32.33a	15.89a
50%AG	42.11ab	25.11bc	15.56ab	60.22b	33.89ab	19.56a	37.55c	21.0b	12.67b
Bare	34.89b	22.78c	13.33b	57.11b	32.11b	17.56a	27.33d	15.89b	9.56b
6t.GM	38.89b	23.33bc	14.78b	63.44ab	33.22b	17.44a	50.11b	28.44a	15.11a
3t.GM	42.78ab	26.77ab	15.331b	64.00ab	36.0ab	19.78a	35.44c	20.11b	12.56ab
LSD	0.0413	0.0217	0.0556	0.0269	0.0996	0.5341	<.0001	0.0007	0.0190
2019		**Harvest 1**			**Harvest 2**			**Harvest 3**	
Treatments	**PH (cm)**	**LL (cm)**	**LW (cm)**	**PH (cm)**	**LL (cm)**	**LW (cm)**	**PH (cm)**	**LL (cm)**	**LW (cm)**
100%AG	42.67a	21.76a	11.78a	58.22a	28.44a	17.0a	59.67a	31.78a	15.67a
50%AG	38.22ab	19.78ab	12.11a	44.0b	24.00ab	14.44a	48.33b	25.11ab	12.78ab
Bare	23.33c	12.33c	9.22b	31.22c	19.44b	12.78a	31.78d	18.33b	10.22b
6t.GM	37.56ab	20.22ab	11.44ab	44.67b	25.44ab	14.67a	44.33bc	24.67ab	13.0ab
3t.GM	32.11bc	15.67bc	10.0ab	42.22bc	22.56ab	14.57a	37.33cd	22.22b	13.44ab
LSD	0.0116	0.0099	.01156	0.0079	0.2786	0.5322	0.0007	0.0332	0.1911

The results observed in Pretoria indicated that mulching had a significant ($P < 0.05$) effect on spinach crop growth parameters (plant height, leaf length and leaf width) during the second and third harvest of both 2018 and 2019 winter growing seasons. Plant height was generally higher during the 2019 growing season at both second and third harvest, compared with the 2018 growing season (Figure 4.16). The 100%AG treatment resulted in the highest plant height at both growing seasons, which is 44.0 cm during the second harvest of the 2018 growing season and 48.5 cm during the third harvest of the 2019 growing season. The control treatment produced the shortest plants at both growing seasons, 23.3 cm and 26.2 cm during the 2018 and 2019 growing season respectively.

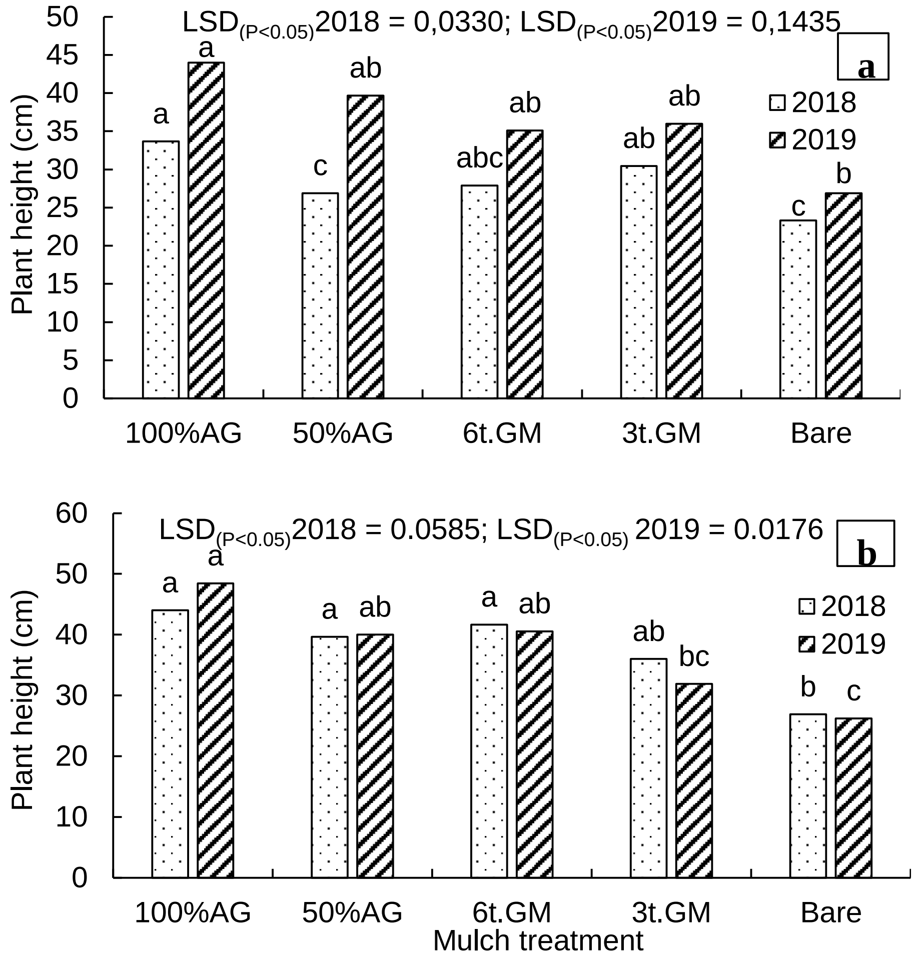

Figure 4.16. Effects of mulching on Spinach Plant height during the second (a) and third harvest (b) in 2018 and 2019 winter seasons in Pretoria, Gauteng. Means within the same growing season (i.e 2018) with the same letter are not significantly ($P < 0.05$) different from each other.

Similar to plant height, mulching treatments had significant ($P < 0.05$) effects on spinach leaf length measured during the second and third harvest of both 2018 and 2019 winter growing seasons. Although the differences were minor, spinach leaf length was generally higher during the 2019 compared with the 2018 growing season at the second harvest, except for the 3 tons.ha^{-1} grass mulch treatment. For the third harvest however, the leaf length was higher during the 2018 compared with the 2019 growing season, with the exception under 50% agri-mat mulch cover (Figure 4.17). The highest leaf length of 26.7 cm was recorded under the 100%AG mulch treatment during the third harvest for 2018 growing season and second harvest for 2018 growing season. The control treatment produced lowest leaf length for spinach leaves at all harvests for both 2018 and 2019 growing seasons. The leaf length was 15.8 cm during the second harvest of the 2018 growing season and 15.9 cm during the 2019 growing season. For the third harvest, the leaf length values under the control treatment were 16.1 cm and 14.3 cm during the 2018 and 2019 growing seasons respectively.

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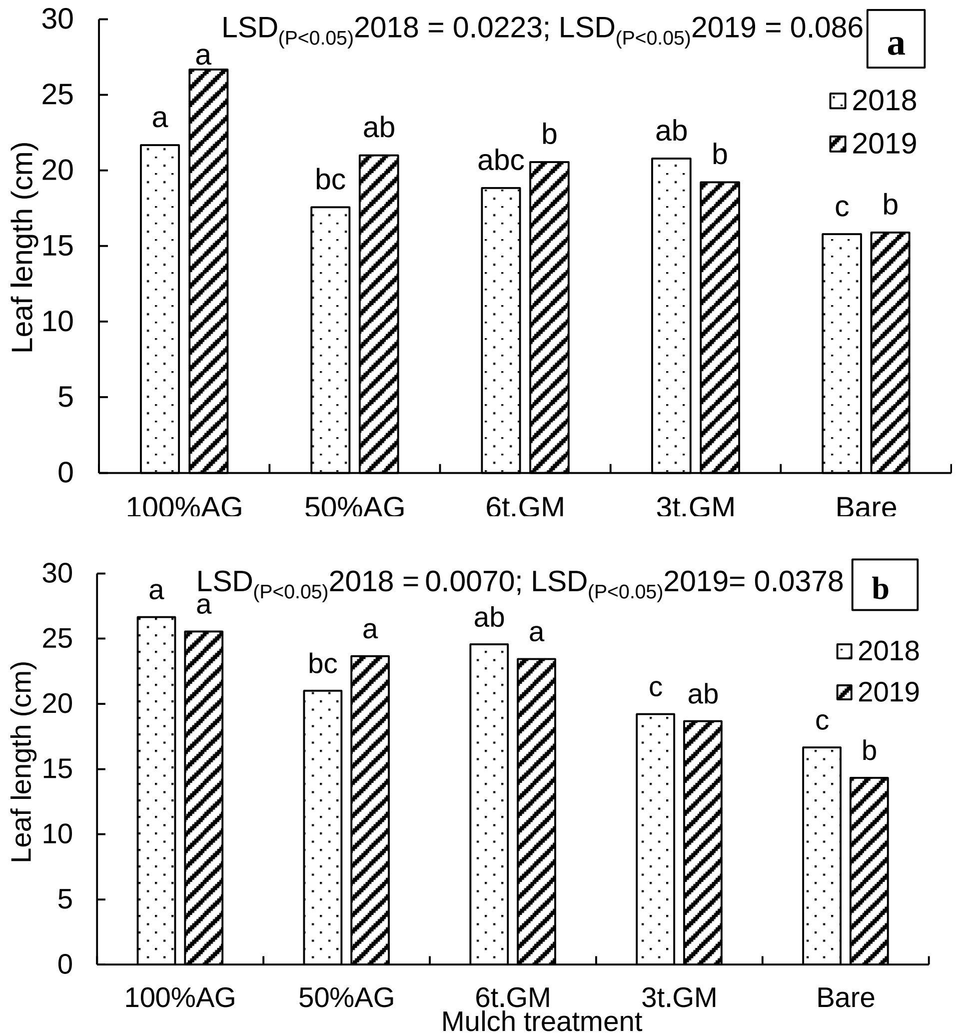

Figure 4.17. Effects of mulching on Spinach leaf length during the second (a) and third harvest (b) in 2018 and 2019 winter seasons in Pretoria, Gauteng. Means within the same growing season (i.e 2018) with the same letter are not significantly ($P < 0.05$) different from each other.

Similar to spinach plant height and leaf length, mulching treatments had a significant ($P < 0.05$) effect on spinach leaf width measured during the second and third harvest of both 2018 and 2019 winter growing seasons. The measurements recorded during the second harvest indicated that leaf width was generally higher during the 2019 compared with the 2018 growing season (Figure 4.18). For the third harvest, however, the leaf width was higher during the 2018 growing season compared with the 2019, with the exception under 50% agri-mat mulch cover.

The 100%AG treatment produced the highest leaf width of 14.7 cm and 18.4 cm during the second harvest of 2018 and 2019 growing season respectively. Similarly, for the third harvest, the 100%AG treatment resulted in the highest leaf width of 18.4 cm for 2018 growing season, and 14.9 cm for the 2019 growing season. Conversely, the lowest leaf width values for spinach were recorded under the control treatment at all harvests for both growing seasons. In the 2018 growing season, the leaf width was 11.7 cm whilst it was 10.7 cm during 2019 growing season. The control treatment resulted in the lowest leaf width values even during the third harvest, which were 12.3 cm for 2018 and 9.1 cm. for the 2019 growing season.

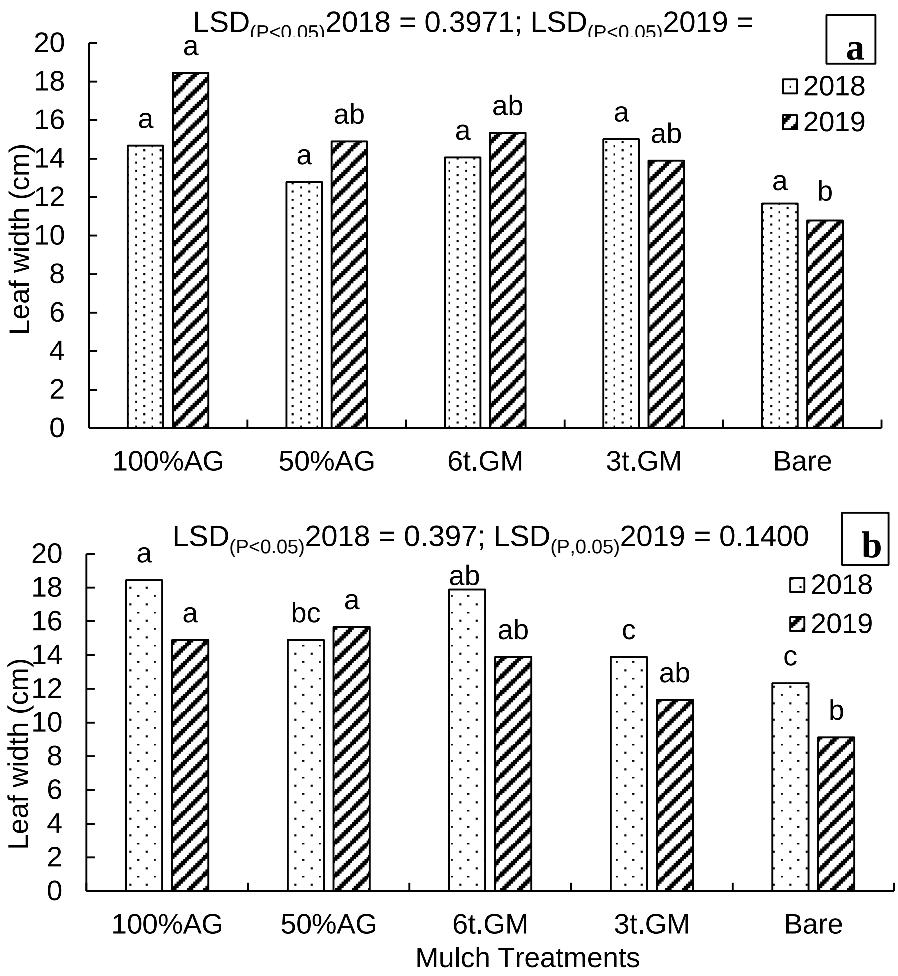

Figure 4.18. Effects of mulching on spinach leaf width during the second (a) and third harvest (b) in 2018 and 2019 winter seasons in Pretoria, Gauteng. Means within the same growing season (i.e 2018) with the same letter are not significantly ($P < 0.05$) different from each other

4.3.7. Effect of mulching on spinach biomass yield

Mulching had a significant (P < 0.05) effect on spinach fresh biomass yield in both seasons in Durban. During the first (2018) growing season, covering the surface with 100% agri-mat resulted in highest biomass yield of 35.9 tons.ha^{-1}, whilst the bare control had the lowest biomass yield of 14.9 tons.ha^{-1} (Figure 4.19). However, in the second season, there were no significant (P < 0.05) differences between 100% agri-mat, 50% agri-mat and 6 tons.ha^{-1} grass mulch treatments, but they were all significantly higher than the control and the 3 tons.ha^{-1} grass mulch treatment. The lowest value of 19.5 tons.ha^{-1} was recorded under the control (no cover) treatment.

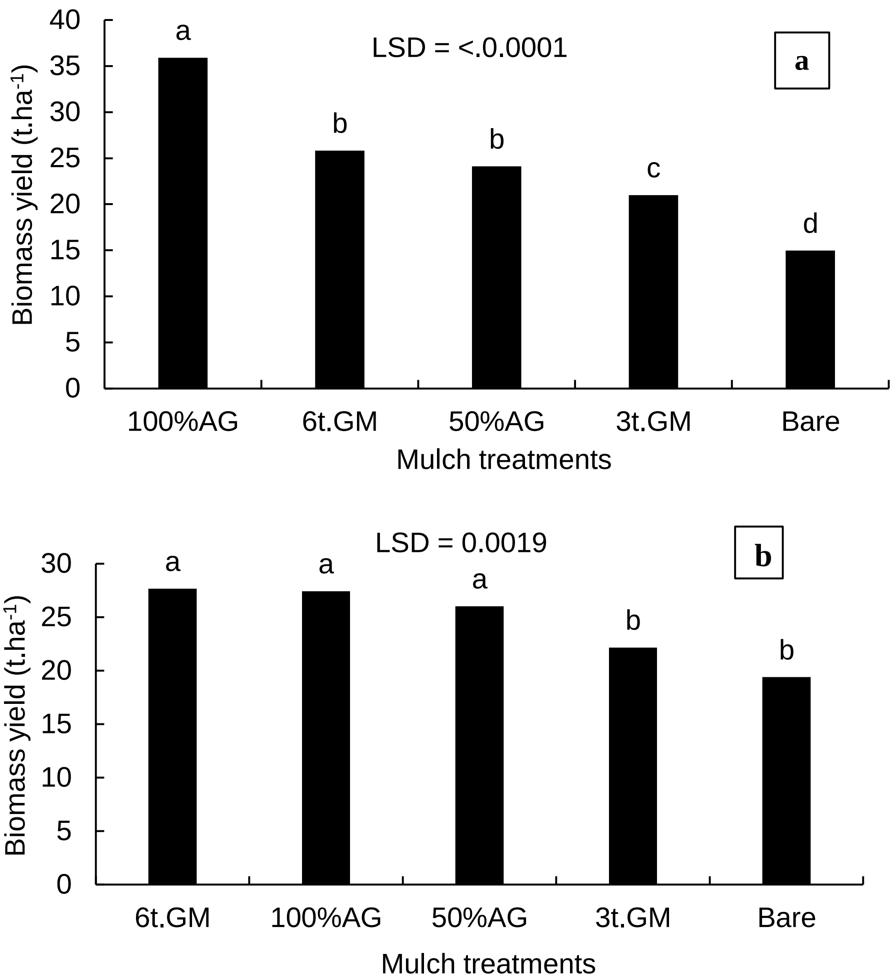

Figure 4.19. Effects of mulching on spinach biomass yield during (a) first season (2018) and (b) second season (2019). Means with the same letter under the same growing season indicates that treatment are not significantly (P<0.05) different from each other.

Similar to the Durban site, mulching had a significant (P <0.05) effect on spinach biomass yield in Pretoria. The 100%AG treatment resulted in the highest yield during both growing seasons (17.6 tons.ha^{-1} and 13.8 tons.ha^{-1} in 2018 and 2019 respectively). On the other hand, the lowest biomass yield of 7.7 tons.ha^{-1} during the 2018 and 4.7 tons.ha^{-1} during the 2019 growing season were recorded under the control treatment (Figure 4.20). Generally, the trends between treatments means were similar in both growing seasons, the biomass yield of spinach was decreasing with the decrease in the amount of mulch applied.

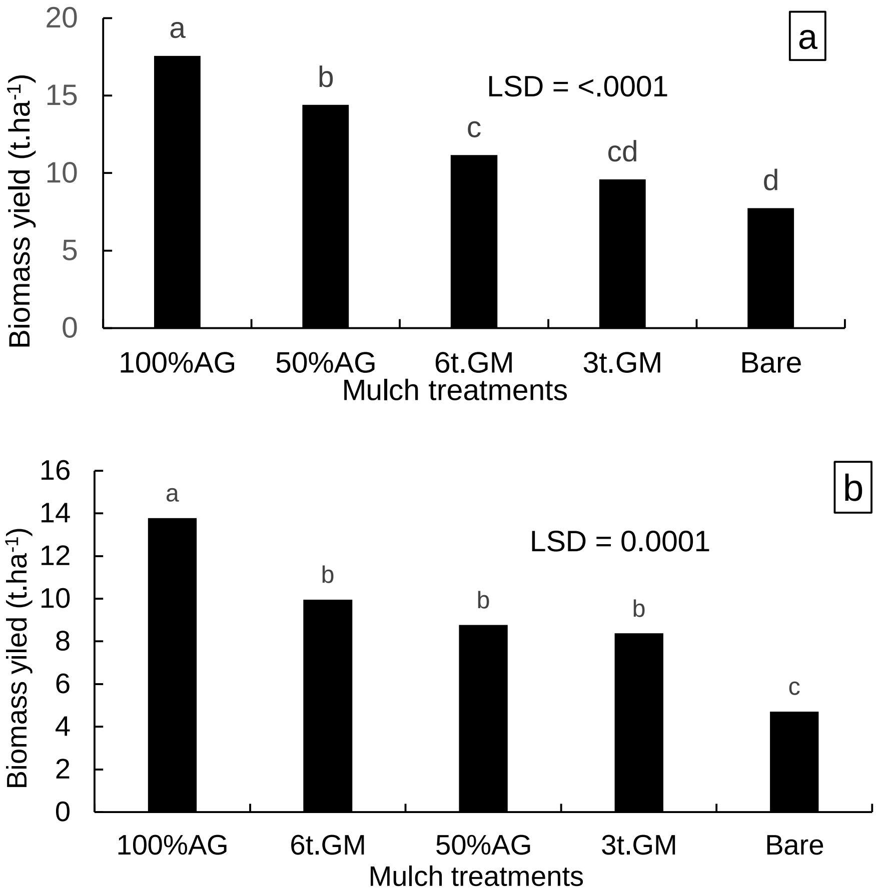

Figure 4.20. Effects of mulching on spinach biomass yield during (a) first season (2018 winter) and (b) second season (2019 winter). Means with the same letter under the same growing season indicates that treatment are not significantly (p<0.05) different from each other.

4.3.8. Effect of mulching on spinach leaf nutrient content

In Durban, mulching had no significant ($P < 0.05$) effects on spinach leaf quality (nutrient content). However, the 100% agri-mat mulch treatment (100%AG) produced the highest leaf nutrient content for potassium, calcium, magnesium, phosphorus, iron and manganese. Among all analyzed leaf elements, zinc recorded lowest value of 32.12 $mg.kg^{-1}$ under the control treatment. The 50% agri-mat mulch treatment resulted in lowest total carbon and total nitrogen, i.e 41.59% and 1.66% for respectively. The 3 $tons.ha^{-1}$ grass mulch treatment resulted in lowest total calcium value of 42.42 $mg.kg^{-1}$ (Table 4.5). Generally, the 3 $tons.ha^{-1}$ treatment produced the lowest values for most of the plant elements such as potassium, calcium, magnesium, sodium, iron, aluminum and copper. Similarly, the results from the Pretoria site indicated that mulching had no significant ($P < 0.05$) effects on spinach leaf nutrient content. The differences observed between treatment means were only marginal.

4.4. DISCUSSION

The results from the current study suggest that mulching had a significant effect on maize and spinach growth, development and yield regardless of the season at both experimental sites. The 100% agri-mat mulch treatment (100%AG) produced the highest crop growth parameters (plant height, leaf length and leaf width) at most weeks for both test crops including total biomass yield and leaf nutrient content of spinach. The measurements from soil moisture and temperature indicates that all the plots that were covered with 100% agri-mat mulch treatment had higher moisture content compared to other treatments. The 100%AG treatment resulted in higher soil temperature during with winter seasons and this suggested that agri-mat may retain more heat from radiation keep the soil warmer for longer periods compared to other mulching materials. In summer, the 100%AG treatment acts an insulation on the soil surface, preventing excess heat which may increase evaporation. The 6.tons.ha^{-1} grass treatment was the second most performing treatment after 100% agri-mat in most cases. The current results are in line with other findings by many researchers who has shown that mulching practice can result in high moisture capture and storage with minimal losses through evaporation (Wu *et al.,* 2011; Lalljee, 2013; Amooh and Bonau, 2015; Kakaire *et al.,* 2015). The spinach yield and leaf quality was generally higher in Durban compared to the Pretoria site in both growing seasons. This is partly attributed to the soil fertility status, which is higher in Durban site, compared to soils in the Pretoria site.

The initial characterization at both sites indicates that the humid region of Durban has soils that are more fertile than Pretoria soils (Table 3.1). Moreover, the rainfall amount in Durban was generally higher compared to the Pretoria site for the entire duration of the experiments. According to Amooh and Bonau. (2015), loamy soil has both sand and clay, so have macro and micro pores, giving a more balance supply balance of both air and water in the macro and micro pores respectively. However, the presence and quantity of chemical nutrients only, are not sufficient as indicators of a soil to produce high yields; soil moisture and temperature regimes are equally important suitability attributes of a soil as a medium for plant growth (Amooh and Bonau, 2015). According to Uwa and Iwo, (2011), soil moisture is known to enhance efficient use of fertilizer while excellent solar radiation during the growth seasons encourage higher photosynthetic rates which culminates in higher yields. The application of 100% agri-mat mulch resulted in the highest cob mass in both seasons compared to all other treatments, while the control resulted in the lowest cob mass. Although crop performance can be attributed to increase in organic matter content due to decomposition of mulch, the improved crop performance and yield in the current study is attributed mostly to soil moisture due to mulching since the agri-mat material were still intact even at the end of the experiment. Moreover, the soil moisture sensors indicate that soil moisture was higher in fully mulched plots compared to the control and half-mulched treatments. In line with crop performance, the soil moisture ranged from highest to lowest in the following order 100%AG > 6t.GM > 3t.GM > 50%AG > Bare for the Pretoria. The highest cob mass recorded under the 100%AG treatment was 5.0 tons.ha^{-1} and 5.6 tons.ha^{-1} for 2017/2018 and 2018/2019 growing seasons respectively. Similarly with the spinach biomass yield, the 100%AG treatment resulted in the highest yield during both growing seasons (17.6 tons.ha^{-1} and 13.8 tons.ha^{-1} in 2018 and 2019 respectively). The improved crop performance under the 100%AG treatment for maize total biomass yield and cob yield as well as spinach biomass yield during both growing seasons indicate the importance of mulching for moisture conservation in the soil.

On the other hand, it is unclear why the trends for soil moisture in the Durban site ranged from highest to lowest in the following order 6t.GM > 3t.GM > 100%AG > 50%AG > Bare. This order was not in line with crop performance as observed in the Pretoria site. Althought the maize biomass and cob yeild was not recorded in the Durban site due to damages by animals, the 100%AG mulch treatment consistently resulted in the highest plant height at all times when the measurements were made except during week 2 (Figure 4.8). In addition, the highest biomass yield of spinach (35.9 tons.ha^{-1}) was recorded under 100%AG treatment during the first growing season but the highest biomass in the second was recorded under the 6t.GM treatment. However, the difference in spinach biomass yield between 6t.GM (27.6

tons.ha^{-1}) and 100%AG (27.4 tons.ha^{-1}) treatments were not significant during the second season. Mulching has been shown to be one of the most effective practices that improves soil water status, and influence soil temperatures in favour of a crop during growing seasons as it provides a protective layer on the soil surface (Siczek *et al.,* 2015). Although maize total yield and cob yield were not recorded in Durban due to destruction by animals at maturity stage, the crop growth parameters recorded prior to the unforeseen event indicates that mulching is essential for moisture storage even in humid regions.

Generally, mulch improves soil quality, moderates soil temperatures and helps to reduce the risk of crop failure at field level through effective capture and use of rainfall water (Giller *et al*., 2009; Lalljee, 2013). Mulching essentially increases the organic matter content of the soil as it decomposes, and ultimately improves infiltration rate, porosity, moisture retention capacity and permeability (Amooh and Bonau, 2015). However, the crop performance in the current study was influenced more by moisture increase due to mulching rather than increase in soil organic matter as a result of mulch decomposition. Largely the quality and quantity organic residues retained or applied in the field as mulch (Pansu et al., 2003; Giller et al., 2009) determine the decomposition and increase of organic matter of any given soil. Naturally, South African soils have very low soil organic matter (SOM) and soil fertility, with about 60% estimated to contain less than 0.5% SOM. Conserving and increasing SOC is thus important for soil health, optimum crop production and better food security, it is therefore important to conserve and increase soil organic matter by employing the mulch practice (Swanepoel *et al*., 2018; Thierfelder *et al.,* 2018). In addition to improved soil water capture and soil organic matter, mulch can moderate soil temperatures by increasing both daily maximum and minimum temperatures in during the winter season and eventually produce better yields (Maggard *et al*., 2012). The loss of water through soil evaporation amounts to about 30% of the total precipitation in the semi-arid tropics and this explains why the yields in Durban were generally higher compared with the crop yields in Pretoria (Amooh and Bonau, 2015). According to Amooh and Bonau. (2015), the primary source of moisture loss in agricultural soils is evaporation. The general mulch application rate of 0.5 – 2.0 tons.ha^{-1} by poor resource farmers due to competition of crop residues has been shown to be inefficient to increase crop yields (Giller *et al*., 2009).

The 3 tons.ha^{-1} grass mulch treatment in the current study performed better that the control treatments except under spinach leaf nutrient analysis in Durban. Generally, leaf nutrient analysis was higher in spinach leaves harvested in Durban compared to those harvested in Pretoria. This is partly attribute to the higher soil fertility status and higher rainfall amounts in the Durban site compared with the Pretoria site. The lowest significant values for spinach yield in Pretoria were recorded under the control treatments during both growing seasons, 7.7 and 4.7 tons.ha^{-1} during the 2018 and 2019 growing season respectively. In Durban, there were no significant ($P < 0.05$) differences between 100% agri-mat, 50% agri-mat and 6t/ha grass mulch treatments during the 2019 spinach growing season, but they were all significantly higher than the control and the 3tons.ha^{-1} grass mulch treatment. However, the 100% agri-mat mulch treatment produced the highest leaf nutrient content for most measured plant elements such as potassium, calcium, magnesium, phosphorus, iron and manganese. The lower crop yields especially in semi-arid regions has prompted the search for alternative cheaper and sustainable organic materials to be used as mulch cover in order to protect and maintain soil health, increase crop productivity and improve food security without adverse effects to the environment (Lalljee, 2013). This is because of the recognition that agriculture plays a crucial role in economic growth and social wellbeing especially for smallholder farmers in Southern Africa (Thierfelder *et al.*, 2018).

4.5. CONCLUSIONS

The effects of agri-mats and grass mulch on some soil physical characteristics and crop yield was investigated in a loam and sandy loam soil. The findings from this study indicates that the soil moisture content and crop biomass yield (both spinach and maize) was higher under 100% agri-mat treatment compared to other mulching treatments followed by 6t.GM in the Pretoria site which had a sandy loam soil. For the Durban site, although soil moisture content was higher under the 6t.GM treatment, the highest crop growth parameters and biomass yield for both spinach and maize was recorded under the 100%AG treatment. In addition, the 100%AG treatment moderated soil temperatures at both sites with higher soil temperatures compared to other mulching treatments during the cold winter season while lower temperatures were observed during the hot summer season compared some mulching treatments. As hypothesized in this study, agri-mats can effectively improve crop yields, conserve soil moisture and moderate soil temperatures in semi-arid and humid agro-ecological zones with different soil types. However, further research is needed to improve the soil conditioning capacity of agri-mats including their role in microbial population and enzyme activity, decomposition rate turnover and fertilizing capacity.

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CHAPTER FIVE:

EFFECTS OF AGRIMAT AND GRASS MULCH ON AGGREGATE STABILITY AND POROSITY OF LOAM AND SANDY LOAM SOIL USING THE X-RAY COMPUTED TOMOGRAPHY

ABSTRACT

Mulching is an important practice responsible for the formation and stability of soil aggregates as well as the overall porosity needed for soil health and crop productivity. The current study adopted the fast wetting method to determine the aggregate stability of a loam soil from Durban and sandy loam soil from Pretoria which were under agri-mat and grass mulch for two years (site descriptions, experimental layout and designed are explained in Chapter four). Air-dried aggregates within a size range of three to five mm were collected from the three mm mesh sieve and oven dried at 40 ^oC for 24 hours to bring them to a constant matric potential. The aggregate size distribution was measured by dry sieving using 2000 µm, 1000 µm, 500 µm, 250 µm, and 53 µm mesh sieves to create six aggregate classes namely: < 50 µm, 50 – 100 µm, 100 – 200 µm, 200 – 300 µm, 300 – 400 µm, 400 – 500 µm, and > 500 µm. The difference between the initial mass and the sum of the mass of the five other fractions was used to estimate the mass of the < 53 µm fraction and aggregate stability was expressed as Mean Weight Diameter. In addition, X-ray Computed Tomography (CT) method was utilized to study the physical architecture (total porosity) of the two soils. Air dried soil aggregates of approximately 10 mm per treatment in triplicates were selected from both experimental sites for image scanning and analysis using a Nikon XTH 225L micro-focus CT X-ray unit. The aggregate stability test results indicate that the 100% agri-mat mulching cover has a greater stabilizing ability compared to all other mulching materials (6t.GM, 3t.GM, 50%AG and Control) in both soil types. The order of stabilizing ability among different mulching treatments for the loam soil is 100%AG > 6t.GM > 3t.GM > 50%AG > Control. For the sandy loam soil, the order is as follows: 100%AG > 6t.GM > 50%AG > 3t.GM > Control. The X-ray CT analysis

results show that, due to the higher frequency of storage pores (0.5-50 µm) and feeding root pores (100 - 200 µm) in the loam soil compared to the sandy loam soil, the loam soil has better capacity to accommodate more roots and had higher volumes of water reservoir for plants and microbes. In addition, the 100% agri-mat mulch treatment improved the water holding capacity of the loam soil by decreasing total macro-porosity, making it less porous compared to other treatments. Therefore, the loam soil has stable aggregates, with sufficient aeration and high water holding capacity compared to the sandy loam soil regardless of the mulch treatment applied after a period of two years.

Keywords: *Aggregate stability, Agri-mat, grass mulch, loam soil, sandy loam, X-Ray CT.*

5.1. INTRODUCTION

Soil texture, clay mineralogy and soil organic matter have a substantial effect on aggregate formation and stability. For example, aggregate stability increases with an increase in clay and organic matter content of the soil (Wakindiki and Ben-Hur, 2002). Soil aggregates are the basic units of soil structure, which are formed through the architectural organization of sand, silt and clay by such organic compounds as fungal hyphae, polysaccharides, aromatic compounds etc. and inorganic cementing agents such as multivalent cations and clay mineralogy (Blanco-Canqui and Lal, 2004; Zhao *et al*., 2017). According to Zhao *et al.* (2017), the formation of soil aggregates is a specific process that involves the absorption of organic matter into clay through the bridge of the multivalent metal cations. The practice of applying and maintaining organic materials as mulch in agroecosystems reduces soil degradation, improve soil porosity and overall soil structure due to its crucial role in the soil organic matter (SOM) build-up (Pigliai *et al.,* 2004). Due to the economic value of crop residues, the use of freely available organic mulching materials (i.e grass, weeds, etc) as a source of organic matter is gaining interest in arid and semi-arid regions especially in sub-Saharan Africa. In Nigeria, Adekiya et al. (2017) found that the use of grass materials

(Guinea and Elephant grass) during dry season maximized yield and increased, inter alia, soil water content, soil porosity and organic matter compared to the bare control.

Agri-mats are an innovative, sustainable and effective soil cover mulching technology that promises to be a cost-effective option for poor resource smallholder farmers farming in dry areas. Agri-mats are manufactured using freely available biological materials such as forestry waste (thinned logs, woodchips, sawdust etc.) grass or weed biomass, municipal sewage sludge, algae residues, bagasse etc. The most notable attributes of agri-mats include their ability to prevent soil erosion, suppress weeds, and conserve soil moisture, increase and sustain soil organic matter content (Onwona-Agyeman *et al*., 2012). SOM is a major binding agent responsible for the formation and stabilization of soil aggregates. Several properties of the soil such as erodibility, aeration, fertility and soil organic carbon protection as well as sequestration are influenced by soil aggregation and stability (Blanco-Canqui and Lal, 2004; Andruschkewitsch *et al*., 2014). Soil porosity (aeration) is one of the two most important properties regulating soil air and water dynamics and their availability to plants. Increase in OM plays an important role in soil aggregation by increasing soil organic carbon (SOC) content which in turn contribute to the formation and stabilization of soil structure and other soil physical properties (Eusufzai and Fujii, 2012; Zhou *et al*., 2020). This increase in soil structure formation and stability is facilitated by soil fauna and micro-fauna which feed on SOM/SOC and excrete sticky substances that bind soil particle to from larger and stable aggregates. SOM contains about 55% SOC and 45% other essential elements (Blanco-Canqui and Lal, 2004). SOC improves the formation of macro-porosity, and therefore favours high water infiltration rate and storage by the entire profile, as well as adequate aeration for root development and plant growth. The rate of water infiltration and air flow into the soil is determined by porosity and pore size distribution (So *et al*., 2009; Eusufzai and Fujii, 2012). Soil microbial population (especially mycorrhizal species) and activity such as decomposition of organic matter contribute towards the formation and stabilization of macro-aggregate (Six *et al.,* 2000).

The formation or build-up of aggregates (micro- and macro-) depends primarily on plant roots availability and quantity as well as quality of crop residues. In turn, the formation of soil structure and its stability depends on macro-aggregates and micro-aggregates, which are stabilized by microbial polysaccharides and humic compounds respectively (Blanco-Canqui and Lal, 2004). According to Pigliai et al. (2004), pore space measurements are gaining interest over traditional measurements as means to quantify structural changes following agricultural activities. Pore space measurements such as pore size distribution within the aggregates, aggregate size and stability are important characteristics of soil structure that may help to predict the behaviour of the soil when subjected to abiotic stress such as erosion (Pigliai *et al*., 2004; Malobane *et al*., 2019). Various methods to determine aggregate stability have been proposed including fast-wetting method by Le Bissonnais (2016) and the suitability of each method depend on the purpose of the study (Marquez *et al*., 2004). Soil aggregate stability is a crucial soil physical property which affects water movement and storage, porosity (aeration) and thus, crop growth (Amezketa *et al*., 2003). X-ray computed tomography (CT) is a non-destructive and more advanced image analysis technique which can be used to study the detailed insight of the special pore arrangement and microstructure of soil aggregates (Pigliai *et al*., 2004). According to Malobane et al. (2019), the micro-structure of soil aggregates governs both soil stability and soil quality. Consequently, examining the microstructure of soil aggregates may help to understand the measurements of aggregate stability. Additionally, X-ray CT offers a non-destructive way to characterize soil structure over a range of scales at high resolution. In South Africa, the use of X-ray CT can be used to discriminate soil aggregates on soils with different textural classes under grass and agri-mat mulch. The current study aims to discriminate soil aggregates of two soils with different textural classes, which were subjected to agri-mat and grass mulch treatments and to determine the resulting micro-structure using X-ray CT and tomographic image analysis. The first objective was to better under the effect of agri-mat and grass mulch on aggregate formation and stability of soils with different textural classes in South

Africa. Secondly, it was to quantify the porosity of the two different soils as affected by different mulching materials using X-ray computed tomography.

5.2. MATERIALS AND METHODS

5.2.1. Study sites description and soil sampling

Two experimental sites, one in Pretoria, Gauteng and another in Durban, Kwa-Zulu Natal (KZN) were selected to study the effects of agri-mat and grass mulch on soil aggregate formation and stability of two different soil types over a two-year period (2017 – 2019). Prior to treatment application, composite soil samples were taken from each site for soil physico-chemical properties at 0 - 30 cm soil depth using a flat spade. Soil samples were air-dried and ground to pass through a 2 mm sieve before each analyses. The soil pH was measured in a 1:2.5 (w/v) soil/water mixture using a combination of electrode. Cation exchange capacity (CEC) was measured using Mehlic method. Total N content was determined by the Kjeldhal method, available P was measured using Olsen Method, Exchangeable K, Na, Ca, and Mg were extracted with 1M NH_4OAc at pH 7, and assayed by atomic absorption spectrophotometry. At the end of the 2-year period, soil samples were collected at the top 10 cm soil depth using a flat spade. The aggregates were then gently placed into rigid boxes (to avoid aggregate breakdown), transported to the laboratory and air-dried for aggregate discrimination and stability test.

The site in Pretoria, Roodeplaat (25°35′33.3"S; 28°21′12.8"E, altitude 1165 m), is characterized by an average annual precipitation of 573 mm. Textural analyses results indicate that the soil has 76.3% sand, 9.3% clay and 14.3% silt – and is classified as sandy loam. The site in Durban, Newlands East (29°46'25.0"S; 30°58'30.6"E, altitude 97 m), receives average precipitation of 828 mm per year. The soil textural analyses results indicate that the soil has 37.8% sand, 24.3% clay and 37.9% silt – and is classified as loam soil. The detailed initial characterization of the phyisico-chemical properties from both site prior to planting is shown in Table 3.1. under chapter four.

5.2.2. Experimental design and treatment application

The experiment in both sites (Pretoria and Durban) was divided into three blocks, each containing five plots to give 15 plots. Each plot with a gross area of 6 m^2 measured 4m x 1.5m with 0.5 m spacing between plots and 1 m apart from each block. The plots were arranged in a randomized complete block design and each treatment was replicated three times. The following five treatments were established;

i). Full agri-mat cover (100%AG),

ii) Half agri-mat cover (50%AG),

iii). Bare or no cover (control),

iv). 6 tons.ha^{-1} of grass mulch (6t.GM) and

v) 3 tons.ha^{-1} grass mulch (3tGM).

The formation and/or build-up of aggregates depend primarily on both organic residues and plant roots (Blanco-Canqui and Lal, 2004). The scientific name of the used Guinea grass was (*Megathyrsus maximus*) and it was harvested from the Pretoria site. The agri-mats were made by compressing wood chips from forestry residues using steam and compression technology as described by (Onwona-Agyeman *et al*., 2012). The agri-mats that were used in the field in both Pretoria and Durban sites were made in Japan and shipped to South Africa for the purposes of the current study. Following the promising preliminary results from this study, the Japanese team decided to ship the modified agri-mat machine to South Africa. The modified agri-mat fabrication machine allows various organic materials such as bagasse, algae, grass, forestry residues etc. Consequently, agri-mats are now made in South Africa, including the ones described in Chapter six, using local organic materials.

5.2.3. Aggregate preparation and scanning using CT and 3D-image analysis

Air dried soil aggregates of approximately 10 mm per treatment in triplicates were selected from both experimental sites for image scanning and analysis. Therefore, a total number of 45 aggregates (15 treatments × 3 reps) were scanned and analysed per site using a Nikon XTH 225L micro-focus CT X-ray unit (Nikon Metrology, Leuven, Belgium) at the MIXRAD laboratory of the South African Nuclear Energy Corporation, which is located in Pelindaba, North West Province, South Africa. The scanning resolutions and parameters were set at 18.9 µm for microstructure visualisation and 90keV/90µA for maximum penetration of X-rays into the soil aggregates respectively. For homogeneity proximities in the X-ray beam spectrum, aluminum filter was used to remove lower energy photons that contribute to noise. Thus, optimize high X-ray photons in the beam spectrum. In order to calibrate the background of the required radiographs, a shading correction image is acquired by the X-ray machine first. The aggregate samples were securely mounted in a polystyrene mould to prevent any movement during the scans. The mounted specimens were then placed onto a rotating sample manipulator to facilitate scanning at 360^0 revolutions. Finally, one thousand images were obtained at 2 second exposure time for each projection (Malobane *et al*., 2019).

The image scans were reconstructed using Nikon CTPro software® (Nikon Metrology, Leuven, Belgium) and then analysed using VGStudio Max V3.0® (Volume Graphic GmbH, Heildelberg, Germany). During the analysis of the images, a region of interest (ROI) of about 52 ± 01 mm^3 volume was selected in the middle of the 3-Dimentional (3D) aggregates. Equivalent diameter was used to express pore sizes from the 3D-aggregate. The pores were classified into seven classes: < 50 µm, 50 – 100 µm, 100 – 200 µm, 200 – 300 µm, 300 – 400 µm, 400 – 500 µm, and > 500 µm. Sphericity (S) was used to classify aggregate pores into three pore shape classes: i) Elongated pores (S ≤ 0.2), ii) Irregular pores (0.2 < S < 0.5), and iii) Regular pores (S ≥ 0.5). The 3-Dimentional (3D) sphericity was defined as the ratio of surface area of a sphere having the same volume as the object to the actual surface area of the object. The 3D total porosity was defined as the total number of pore voxels divided by the total number of voxels (Zhou *et al*., 2012; Malobane *et al*., 2019).

5.2.4. Aggregate stability test

The estimation of aggregate stability was determined as described by Le Bissonnais (2016) using the fast wetting method. Air-dried aggregates were sieved using a 5-mm mesh sieve that was placed on top of another sieve with 3 mm aperture. The 3 – 5 mm aggregates were collected from the 3 mm mesh sieve and oven dried at 40 ^{o}C for 24 hours to bring them to a constant matric potential. For each treatment, 5-gram sample of aggregates was immersed into a beaker containing 50 ml deionized water for 10 minutes. A syringe was then used to carefully suck water off the beaker without disturbing the aggregates. The aggregates were carefully transferred to a 53 µm sieve, which was previously immersed into ethanol. The sieve was moved up and down gently, in and out of the ethanol five times, to separate the < 53 µm fragments from those that are > 53 µm. The remaining aggregates on top of a 53 µm mesh sieve were collected and dried in an oven at 105 ^{o}C for 24 hours. The aggregate size distribution was measured by dry sieving using 2000 µm, 1000 µm, 500 µm, 250 µm, and 53 µm mesh sieves to create six aggregate classes namely: 2000 – 5000 µm, 1000 – 2000 µm, 500 – 1000 µm, 250 – 500 µm, 53 – 250 µm, and < 53 µm. The difference between the initial mass (5 g) and the sum of the mass of the five other fractions was used to estimate the mass of the < 53 µm fraction. The aggregate stability was expressed as the Mean Weight Diameter (MWD) of the six classes using equation (1):

$$MWD = \sum_{i=1}^{7} \mathrm{XiWi}$$

Where X is diameter of the aggregate and W is the mass fraction of aggregates class size i (Le Bissonnais, 2016).

5.2.5. Statistical analysis

Statistical analysis was performed using SAS institute, JMP® (Carry, 2016) to analyse the results. Data was subjected to analysis of variance (ANOVA) at 5% probability level. Student t-test was used to indicate statistical differences between treatment means.

5.3. RESULTS

5.3.1. Effects of agri-mats and grass mulch on aggregate stability

The results from both soil types indicate that mulching with different organic materials significantly ($P<0.05$) influenced aggregate stability. All mulch treatments improved both soil types (Table 5.1 and 5.2) from unstable to medium stability after a period of two years. Although the aggregates of both soil types were classified as medium stable, the aggregates of the loam soil from Durban had higher values of mean weight diameter compared to those of sandy loam soil from Pretoria. The order of stabilizing ability among different mulching treatments for the loam soil is 100%AG > 6t.GM > 3t.GM > 50%AG > Control (Table 5.1). For the sandy loam soil (Table 5.2), the order was as follows: 100%AG > 6t.GM > 50%AG > 3t.GM > Control. The cause of the difference in the order for the stabilizing ability of half-mulching treatments is unclear for the two soils. In Durban, the 3 tons.ha^{-1} grass mulch treatment had higher stabilizing ability than the 50%AG treatment. However, the 50%AG mulch treatment had a higher stabilizing ability than the 3 tons.ha^{-1} grass mulch treatment in Pretoria.

Table 5.1. Aggregate stability of loam soil from Durban, KZN as affected by different mulching treatments.

Treatment	Mean Weight Diameter	Stability Class
100%Agri-mat mulch	1.068a	Medium
6 tons grass mulch	0.969ab	Medium
3 tons grass mulch	0.952ab	Medium
50% Agri-mat mulch	0.924b	Medium
Control	0.676c	Unstable

Treatment means followed by the same letter within the same column are not significantly ($P<0.05$) different from each other.

Table 5.2. Aggregate stability of sandy loam soil from Pretoria - Gauteng, as affected by different mulching treatments.

Treatment	Mean Weight Diameter	Stability Class
100% Agrimat mulch	0.989a	Medium
6 tons grass mulch	0.773ab	Medium
50% Agrimat mulch	0.772ab	Medium
3 tons grass mulch	0.754ab	Medium
Control	0.599c	Unstable

Treatment means followed by the same letter within the same column are not significantly ($P<0.05$) different from each other.

For the loam soil, mulching had a significant ($P<0.05$) effects on all soil aggregate classes (Table 5.3). The 100%AG mulch treatment resulted in significantly higher percentage values of the 5000-2000 µm, 2000-1000 µm, and 1000-500µm aggregate classes compared to other mulch treatments. Contrary, the 100%AG treatment produced significantly lower percentage values under 250-53 µm and <53 µm aggregate classes compared to other treatments (Table 5.3).

Table 5.3. Aggregate size distribution under different aggregate classes in a loam soil from Durban, KZN.

	Aggregate Classes (%)					
Trtmnts	5000-2000µm	2000-1000µm	1000-500µm	500-250 µm	250-53 µm	< 53 µm
100%AG	18.4a	14.0a	18.2a	26.4a	12.6b	10.4c
50%AG	14.0b	11.2ab	15.8ab	29.6a	14.8ab	14.6b
6t.GM	16.8ab	11.0ab	15.2ab	23.6b	11.8b	21.6a
3t.GM	16.4ab	9.0ab	13.8b	28.8a	17.2ab	14.4b
Cntrl	9.0c	8.8b	13.8b	27.0a	23.8a	17.6ab

Treatment means followed by the same letter within the same column are not significantly (P<0.05) different from each other.

Generally, both soil types (loam and sandy loam) were dominated by macro-aggregates (>250 µm) than by micro-aggregates (<250 µm) even under the control treatment. Contrary, the 50%AG mulch treatment produced more (89%) of macro-aggregates compared to 100%AG, which produced 77% of macro-aggregates. On the other hand, both 6t.GM and 3t.GM produced equal values of macro-aggregates (67%) and micro-aggregates (33%) under the loam soil.

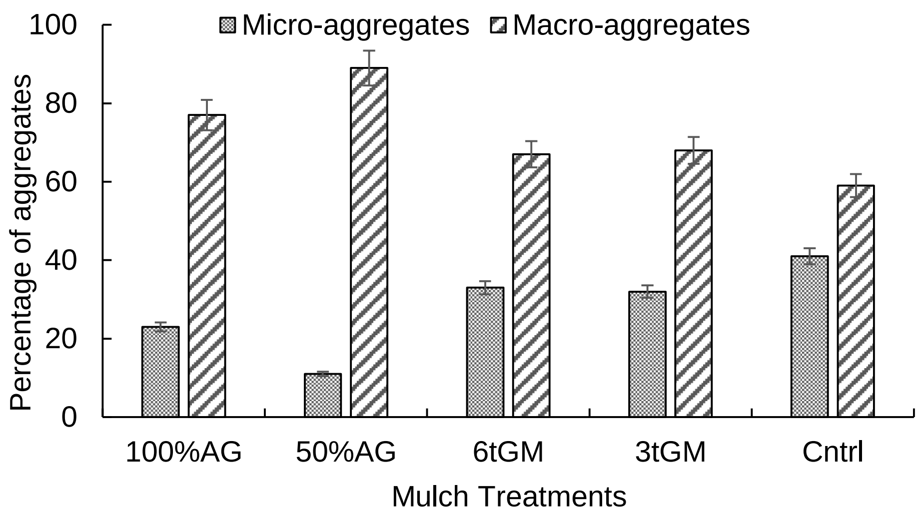

Figure 5.1. The distribution of aggregates between micro (<250 µm) and macro (>250 µm) at different mulching treatments a loam soil from Durban, KZN. The error bars indicate statistical differences in aggregate distribution within a treatment in percentage.

Results for the sandy loam soil indicated that mulching resulted in significant (P<0.05) differences in the soil aggregate classes except for 1000-500 µm, and <53 µm soil aggregate classes (Table 5.4). Similarly, with the results observed in the loam soil above (Table 5.3), the 100%AG much treatment was responsible for the formation of more macro-aggregates (>250 µm) than micro-aggregates (<250 µm).

Table 5.4. Aggregate size distribution under different aggregate classes in a sandy loam soil from Pretoria, Gauteng

	Aggregate Classes (%)					
Trtmnts	5000-2000µm	2000-1000µm	1000-500µm	500-250 µm	250-53 µm	< 53 µm
100%AG	23.8a	5.4a	9.4a	32.4b	13.0c	16.0a
50%AG	13.4b	4.4ab	9.8a	37.0ab	16.2b	19.2a
6t.GM	14.2b	3.2b	8.6a	38.8ab	18.2a	17.0a
3t.GM	13.8b	3.2b	7.6a	39.4a	17.4ab	18.6a
Cntrl	8.6c	4.0ab	10.2a	37.8ab	17.4ab	22.0a

Treatment means followed by the same letter within the same column are not significantly (P<0.05) different from each other.

The fraction of micro-aggregates (<250 µm) in the sandy loam soil was generally lower than that of macro-aggregates (>250 µm) under all mulch treatments (Figure 5.2). The soil micro-aggregate increased with the decrease in mulch thickness or percentage while soil macro-aggregates decreased with the decrease in mulch thickness or percentage.

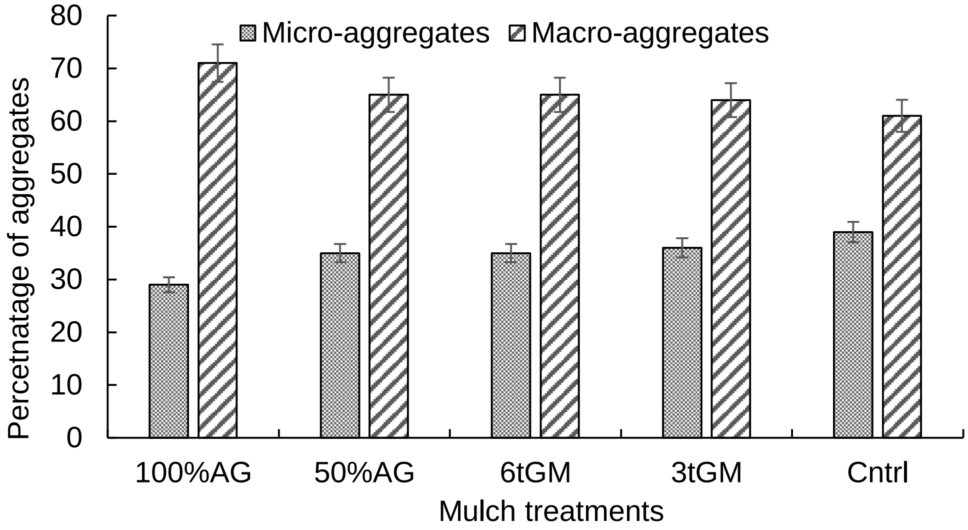

Figure 5.2. The distribution of aggregates between micro- (<250 μm) and macro-aggregates (>250 μm) at different mulching treatments in a sandy loam soil from Pretoria, Gauteng. The error bars indicate statistical differences in aggregate distribution within a treatment in percentage.

5.3.2. Soil aggregate visualization and pore size distribution in Durban, KZN

Pore size distribution indicates that the percentage of pores with a dimeter >500 μm was generally higher compared to all other effective pore diameter classes. Although there is no distinct trend showing whether mulching increases or decreases porosity (Figure 5.3), the statistical analysis results indicated that mulching with different organic materials had a significant (P<0.05) effective on soil pore diameter classes.

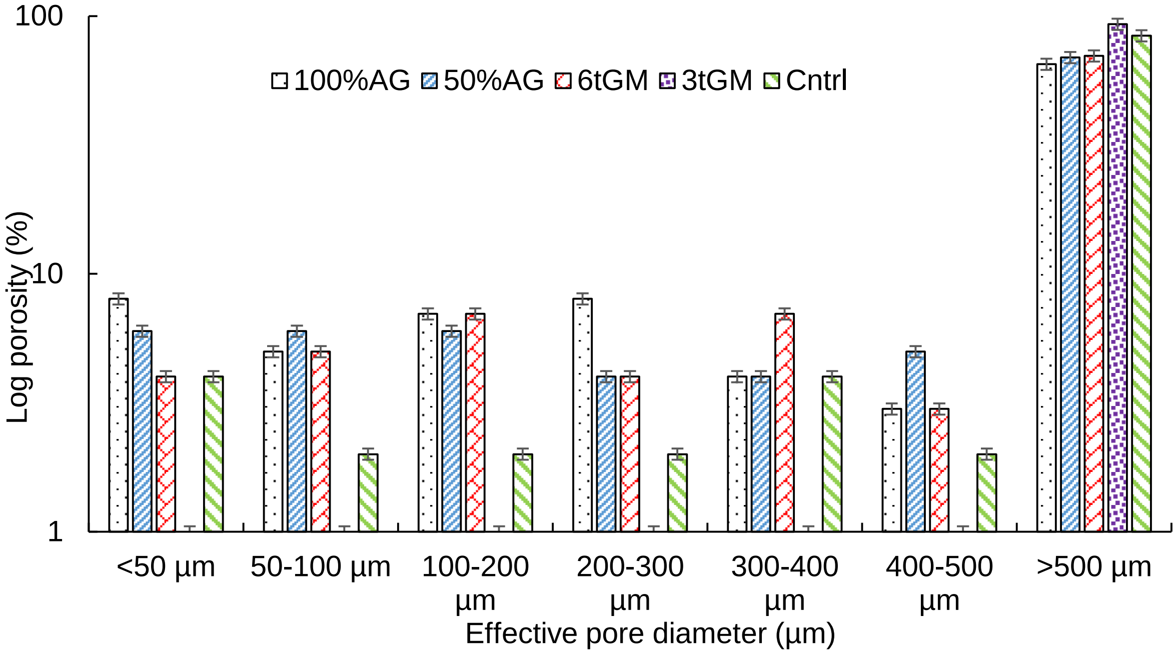

Figure 5.3. Pore-size distribution porosity of soil aggregates as influenced by different mulching treatment applied in a loam soil from Durban, KZN.

The pore size distribution frequency of pores followed a similar pattern (decreased as the effective pore diameter increased) for all treatment means. Although the loam soil contained higher percentage of >500 µm effective pores, the frequency in which they occur was significantly lower compared to other effective pore diameters, except for 200 - 300 µm and 300 - 400 µm aggregate classes (Figure 5.4).

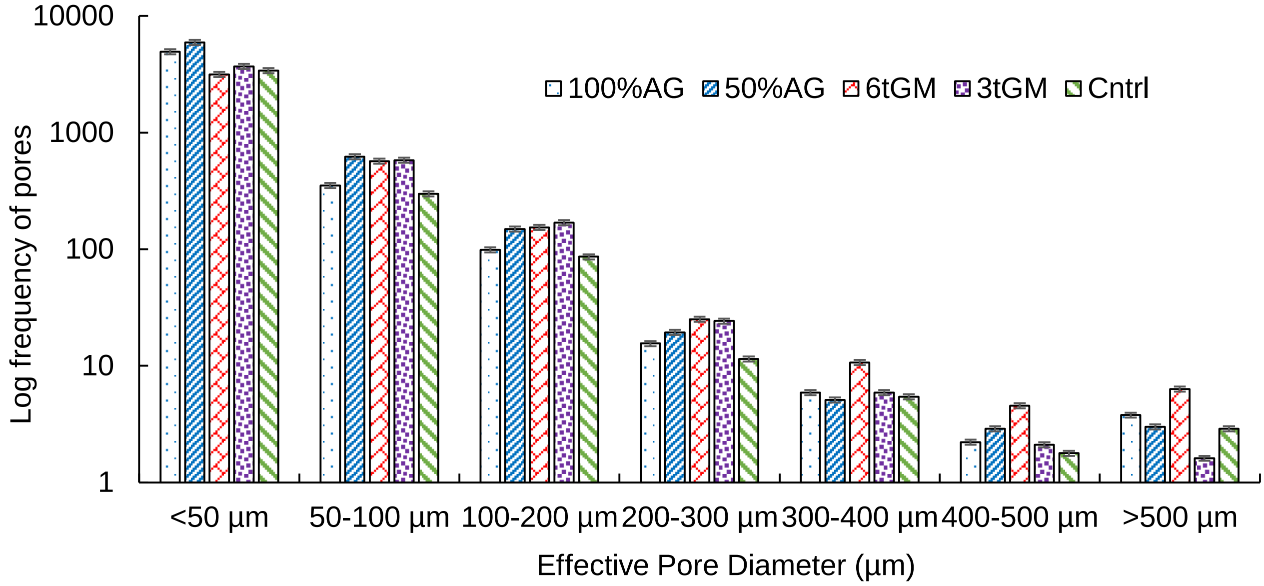

Figure 5.4. Pore-size distribution frequency of soil aggregates as influenced by different mulching treatment applied in a loam soil from Durban, KZN.

The effect of different mulching materials on fractions of various pores (regular, irregular and elongated) and total porosity was not significant (P<0.05) statistically. Generally, the total porosity ranged from 3.33 to 9.5% between the mulching treatments. The fraction of regular pores was higher than that of other pore shapes (with a range from 93.1 to 96%) followed by fraction of irregular pores (with a range from 3.6 to 6.69%). Elongated pores had the lowest percentage (with a range from 0.04 to 0.09) compared to the other two pore shapes for all mulch treatments.

5.3.3. Soil aggregate visualization and pore size distribution in Pretoria, Gauteng

Figure 5.5 show the differences in the distribution and frequency of pore visualized at 100 – 200 µm (0.1 – 0.2 mm) using X-ray CT technology under 100%AG mulch treatment. The loam soil (bottom image) had more variety of pores compared to the sandy soil (top).

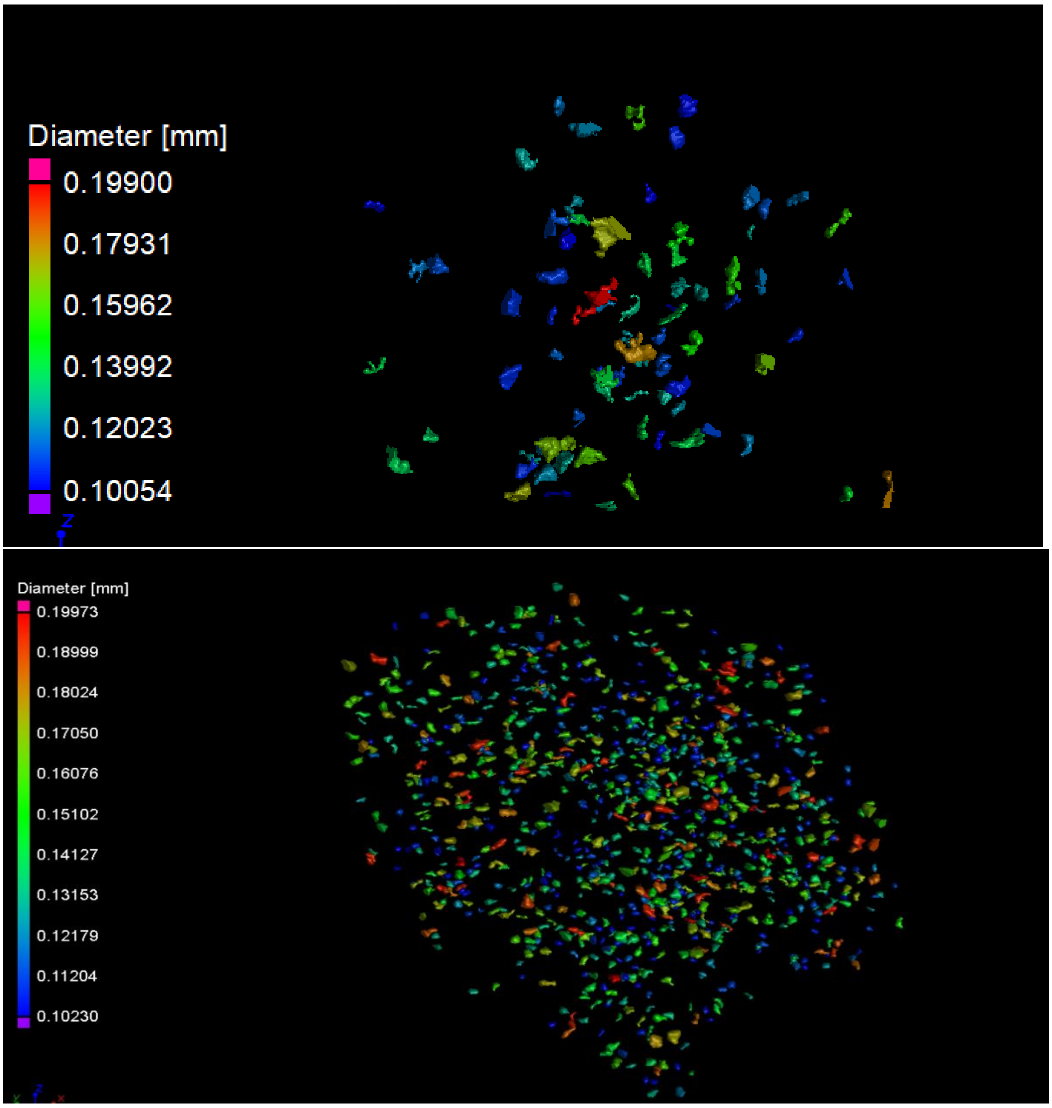

Figure 5.5. The difference in pore size and pore space of 3D images of the pore architecture in sandy loam soil (top) and loam soil (bottom) from the feeding root pores (100 - 200 µm) range.

The results indicate that there were no significant (P>0.05) differences between treatment means at various effective pore classes except under the >500 µm effective pore range. Additionally, >500 µm effective pore diameter range was statistically higher in percentage compared to all other effective pore diameter classes (Figure 5.6).

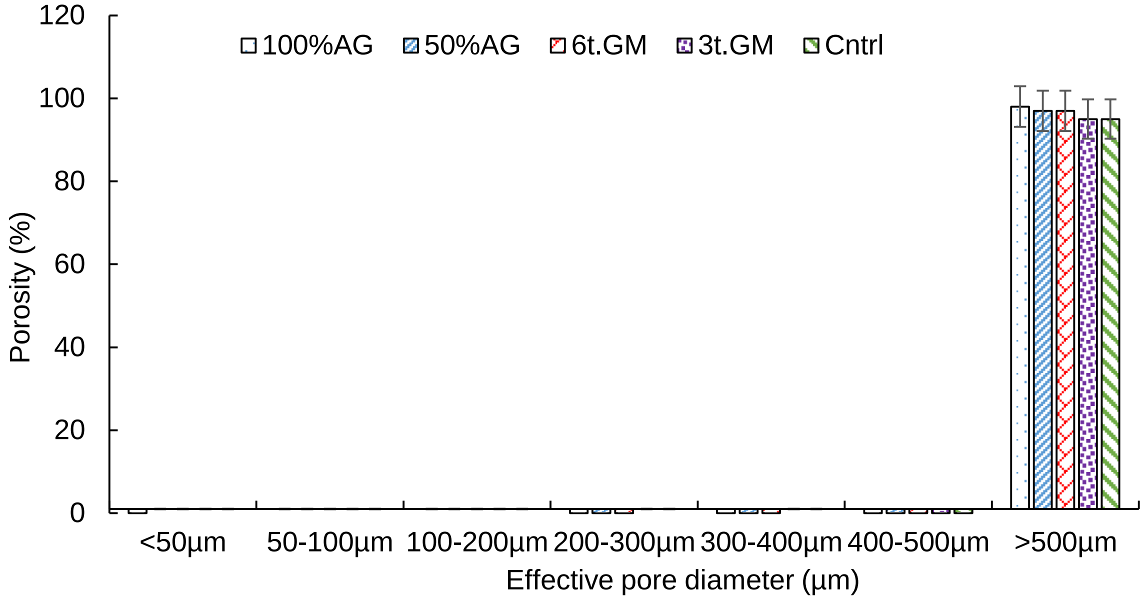

Figure 5.6. Pore-size distribution porosity (percentage) with error bars from soil aggregates from different mulching treatment applied in a loam soil from Pretoria, Gauteng.

Similar to the trends observed in the loam soil (Figure 5.7), the pore size distribution frequency of pores followed a similar pattern (decreased as the effective pore diameter increased) for all treatment means in the sandy loam soil. In addition, sandy loam soil was dominated by higher percentage of micro-pores (<50 µm) while both 400-500 µm and >500 µm aggregate classes were significantly lower compared to others.

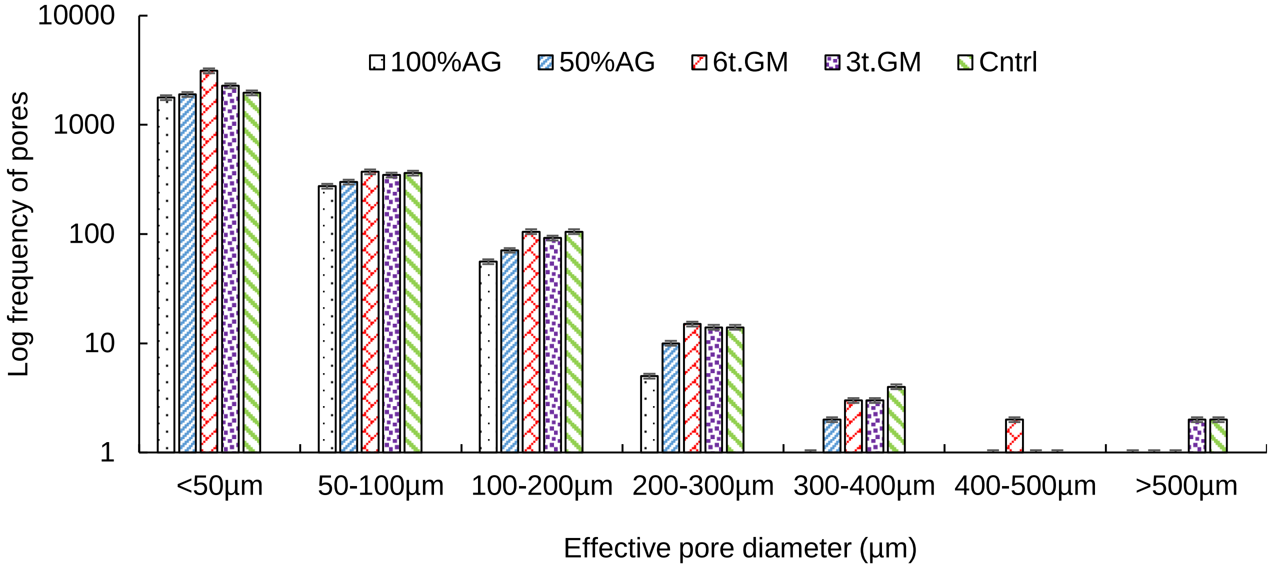

Figure 5.7. Pore-size distribution frequency with error bars from soil aggregates at different mulching treatment applied in a loam soil from Pretoria, Gauteng.

The results for the sandy loam soil indicated that fractions of various pores and total porosity were significantly (P<0.05) influenced by different mulching materials (Table 5.5). However, the fraction of regular pores ($S \geq 0.5$) was higher compared to other pore shapes, followed by fraction of irregular pores ($0.2 < S < 0.5$) as observed in the loam soil. Elongated pores ($S \leq 2$) had the lowest percentage compared to other two pore shapes in all different mulch treatments.

Table 5.5. CT measured porosity and pore shape distribution in a loam soil from Pretoria, Gauteng.

	100%AG	50%AG	6t.GM	3t.GM	Cntrl
Total Porosity (%)	15.4a	8.77b	10.09b	8.06b	10.79b
Fraction of regular pores (%)	96.23a	95.63ab	94.80ab	94.56ab	93.52b
Fraction of irregular pores (%)	3.71b	4.29ab	5.16ab	5.37ab	6.41a
Fraction of elongated pores (%)	0.06a	0.07a	0.04a	0.07a	0.07a

Treatment means followed by the same letter along the same row are not significantly (P<0.05) different from each other.

Figure 5.8 shows that both soil types are extremely porous since the total macro-porosity is greater than 40%. However, the effect of mulching in total macro-porosity (>50 µm) formation was more pronounced and significant (P<0.05) in the loam soil. The increase in mulch thickness or percentage influenced the water holding capacity of the loam soil by reducing the macro-porosity in the following order: 100%AG>50%AG>6t.GM=3t.GM. The bare (cntrl) treatment was more porous than all other mulched treatments. The results indicate that total micro-porosity of the sandy loam soil was not significantly (P<0.05) influenced by mulching treatments (Figure 5.8).

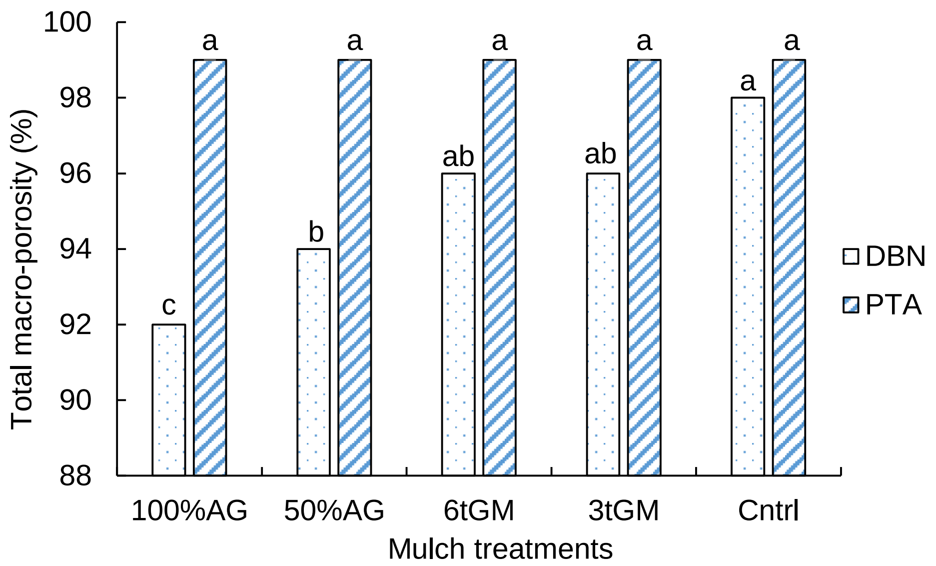

Figure 5.8. Effect of mulching treatments on macro-porosity (pore >50µm) in a loam (DBN) and sandy loam (PTA). Means with the same letter under the same soil type are not significantly (P<0.05) different from each other.

5.4. DISCUSSION

The current study investigated the effect of different mulching materials on aggregate stability and soil porosity of a loam and sandy loam soil. Aggregate stability was expressed as Mean Weight Diameter (MWD) following the procedure by Le Bissonnais (2016). The author classified aggregates as very stable if MWD is more than 2.0 mm, stable if MWD is between 1.3 and 2 mm, medium if MWD is between 0.8 and 1.3 mm, unstable if MWD is between 0.4 and 0.8 mm and very unstable if MWD is less than 0.4 mm. Accordingly, the results indicates that, in reference to the control, mulching increased the stability of soil aggregates from unstable to medium stability after a period of two years for both loam and sandy loam soil (Table 5.2 and 5.3). The practice of adding organic residues such as straw mulch, grasses, as mulch or organic amendments has been conducted in different parts of the world to improve organic matter content, aggregate stability, porosity and overall quality of the soil (Yang *et al*., 2018). The findings from this study indicated that the 100%AG mulching material has a greater stabilizing ability compared to all other mulching materials in both soil types. This can be ascribed to the agri-mats ability to conserve soil moisture, increase and maintain higher soil organic matter content compared to other loose mulching materials (Onwona-Agyeman *et al*., 2012).

The stability of soil aggregates can be improved by increasing either the percentage or thickness of mulching material. In addition, the duration of mulching period can play a significant role in improving the organic matter content of the soil. Soil organic matter promote the formation of more and larger aggregates, thereby enforcing the soil aggregate stability and water storage capacity (Yang et al. (2018). The distribution of different aggregate classes of any soil type is a function of quality and quantity of organic material applied (Table 5.3 and 5.4). According to Totsche et al. (2018), macro-aggregates comprises all soil aggregates > 250 µm, whereas soil micro-aggregates denote all compound soil structures < 250 µm. The proportion of micro-aggregates in both soil types was generally lower compared to macro-aggregates under all mulch treatment means (Figure 5.1 and 5.2). The degree and speed at which any organic material increases the proportion of macro-aggregates of a given soil type depends on other inherent soil binding agents and prevailing conditions (Totsche *et al*., 2018). The current study shows that the percentage of the number or frequency of soil macro-aggregate was lower than that of micro-aggregates in both soil types. Various aggregate classes in the macro-aggregates range (>250 µm) from both soil types show that when mulch application is increased, the stability of macro-aggregates improves. Similarly, with the results observed in the loam soil above (Table 5.4), the 100%AG much treatment was responsible for the formation of more macro-aggregates than micro-aggregates due to higher percentage (100%) or thickness (3 cm) in mulch cover which increases the organic matter content and thus macro-aggregates formation (Yang *et al*., 2018).

The formation and stability of soil aggregates, as observed in this study, is increased by addition of organic residues. Organic residues improve the population of soil microbes, which aide in the formation of soil organic matter and better soil porosity (Blanco-Canqui and Lal, 2004; Yang *et al*., 2018). Although the current study indicates some improvements in soil aggregation due to elevated levels of soil organic matter (SOM) due to mulch application, it is recommended that future studies should relate different fractions of SOM on soil aggregation such as particulate organic matter fraction. The physical architecture of soil aggregates, which refers to how porous, connected and distributed soil aggregates are (e.g. porosity, pore connectivity pore and pore size distribution,) in the soil 3D matrix is responsible for soil microbial activities (Shujie *et al*., 2009; Rabbi *et al.,* 2016). Soil porosity refers to the volume of interconnected soil pores (with various sizes and shapes) that are occupied by water and/or air (Beraldo *et al*., 2014). The findings of the current research indicated that the sandy loam and loam soil studied are extremely porous because the total macro-porosity of both soils is greater than 40%. Pigliai et al. (2004) asserted that “for better interpretation of results, it can be stressed that according to the micro-morphometric method, a soil is considered dense (compact) when the total macro-porosity (pores larger than 50 micro meters) is greater than 10%, moderately porous when porosity ranges from 10 to 25%, porous when it ranges from 25% to 40%, and extremely porous over 40%.” The total macro-porosity of the sandy loam soil was not influenced by mulching and this could be attributed to the shorter period of the experiment, which ended while larger proportions of agri-mats and grass mulch could have decomposed (Figure 5.7).

The 100%AG mulch treatment produced the highest percentage for total porosity, which was significantly higher compared to other mulching treatments (Table 5.7). Moreover, the 100%AG mulch treatment produced more transmission pores (50 – 500 µm) in both soil types (Table 5.4 and 5.5), which indicates that agri-mats can play a significant role in both soil – water – plant relations and in maintaining good soil structure quality for better soil health and improved crop productivity (Pigliai *et al*., 2004). Generally, the X-ray CT analysis results showed that, due to higher frequency of storage pores (0.5-50 µm) and feeding root pores (100 - 200) in the loam soil compared to the sandy loam soil (Figure 5.4, 5.6 and 5.8), the loam soil has better capacity to accommodate more roots as well as higher volume of water reservoir for plants and microbes (Pigliai *et al*., 2004). On the other hand, the difference in the architecture of the feeding roots (100 – 200 µm) between the two soils (Figure 5.5) indicate that the inflow and out flow of water and air is more rapid in the sandy loam soil compared to the loam soil. According to Khan et al. (2002), sandy loam soil is highly permeable in the surface layers with low water retentive capacity, but the moisture retention in the lower layer of the profile is comparatively higher because of increasing content of finer particles. In addition, the loam soil had a higher percentage of pores > 500 µm compared to sandy loam soil, which indicates better water infiltration and drainage capacity particularly as a fine-textured soil (Pigliai *et al*., 2004). The presence macro-pores for adequate water supply in the upper most few centimetres of the soil is essential for proper seed germination and crucial for early development of the emerging crop (Khan *et al*., 2002).

5.5. CONCLUSION

Various organic materials increased the aggregate stability of loam and sandy loam soil from unstable to medium, with the 100% agri-mat mulch treatment being more effective compared to other mulch treatments. The X-ray computed tomography permitted a detailed insight of the spatial pore arrangement of soil aggregates and associated water and/or air movement within them. Based on the morphological characteristics of soil aggregates (pore diameter, pore size distribution, and pore connectivity), the 100%AG treatment was superior relative to other organic mulching material in the soil pore structure formation (total macro-porosity) regardless of soil type. However, it is recommended that future research studies determine soil water retention curve (SWRC) to definitely characterize water retention properties and other soil physical qualities related to SWRC as a result of agri-mat treatment. Future studies could relate different fractions of SOM with soil aggregation such as particulate organic matter fraction. Moreover, further research is needed in order to better understanding the effect of agri-mats in the overall soil health by studying their role in microbial population and activity.

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CHAPTER SIX:

INFLUENCE OF DIFFERENT TYPES OF AGRI-MATS ON RUNOFF USING RAINFALL SIMULATOR

ABSTRACT

Soil erosion by water is a major global environmental concern due to its devastating effect on agricultural sustainability and food security. The current study investigated the effectiveness of agri-mats in soil water erosion control. Agri-mat infiltration rate and runoff rate were determined using Mini Portable Pressure Head (MPPH) Rainfall Simulator in a laboratory. The simulations were run for 60 minutes per agri-mat and the time it took to collect the first infiltration and runoff water was recorded using a stopwatch. Thereafter, infiltration and runoff water was collected every 10-minute interval until the 60th minute. A total of six agri-mat samples were subjected into a runoff and infiltration rate test for this study: three agri-mats were made with 100% dry sugarcane bagasse and the other three agri-mats were made with (10% dry algae + 90% dry sugarcane bagasse). The agri-mats that were fabricated only with 100% Bagasse (B) had lower infiltration rate compared with agri-mats made with 90% Bagasse + 10% Algae (BA). The 100% dry sugarcane bagasse B agri-mat treatment had higher runoff rate of 16.8 mm. hr^{-1} compared to a mere 1.7 mm. hr^{-1} recorded under the BA agri-mat during the first 10 minutes of rainfall simulation test. In addition, the B agri-mat released magnesium at a rate of 105.7 mg. hr^{-1} compared to 6.6 mg. hr^{-1} lost from the BA agri-mat treatment. Results shows that when algae was used as an additional organic material during the fabrication process, agri-mat delayed runoff by absorbing more moisture than it losses. Moreover, the results from this study show that algae addition in agri-mats reduce nutrient loss through runoff. Incorporation of algae in the agri-mat technology could improve the functionality and value of agri-mats for agriculture purposes. Algae has the capacity to increase water holding capacity of the agri-mats while improving nutrient status and electrical conductivity of the agri-

mats, making them more beneficial not only as the runoff combating technology but as a soil conditioner

Keywords: *Agri-mats, algae, infiltration, runoff, erosion, rainfall simulator*

6.1. INTRODUCTION

Land degradation, mainly through soil erosion directly and negatively affects global food security and agricultural sustainability in an unprecedented manner (Lu *et al*., 2016). Soil erosion is caused by wind energy and/or raindrop (water) impact mostly on bare soils with unstable aggregates (Vaezi *et al*., 2017). Soil erosion by water is more prominent relative to wind erosion and is considered a major environmental concern. This is due to its role in the eutrophication of inland and coastal water bodies through inter-rill, rill, gully and stream erosion (Pimentel and Burgess, 2013; Vaezi *et al*., 2017). The behaviour of the soil to erosion disturbances is influenced by, inter alia, vegetation cover (live or dead), soil type, topographical position of slope, precipitation, wind speed (or energy) and soil structure (Pimentel and Burgess, 2013; Mohamadi and Kavian, 2015). According to Vaezi et al. (2017), soil erosion is a three-phase process that consists of detachment of soil particles from the soil mass, transportation of detached particles by either raindrop impact or surface water flow, and deposition by overland flow. Soil sediment and water loss along with valuable soil nutrients pose the greatest threat to land productivity and may lead to unsustainable agricultural production systems in severe cases (Montenegro *et al*., 2013).

Extreme cases of soil erosion cause reduction in soil functioning through degradation of soil quality (physical, chemical and biological characteristics of the soil), which helps to maintain environmental quality, sustain biological productivity, and promote the health of plant and animals in the ecosystem (Munoz *et al*., 2007). There has been a lot of technologies put forward by researchers to try and address soil erosion such as contour bunds or banks, cellular confinement systems, embankments, mulching, etc. According to Sanders, (1986), there is a wide variety of practices and techniques that are known and available to control erosion (biological and mechanical), however, they all have their disadvantages and limitations which increase with slope. The vast majority of erosion control techniques are partly ineffective and in some cases a complete failure mainly due to extreme weather conditions (heavy rains and strong winds) and very steep slopes (Sanders, 1986; Onwona-Agyeman *et al*., 2015). However, agri-mats have been identified as sustainable and effective techniques and developed by researchers for soil and water conservation purposes (Onwona-Agyeman *et al*., 2012; Subedi *et al.,* 2012).

Generally, agri-mats serve as multi-purpose boards that could be applied on pavements, walkways, playgrounds, parks and mostly as mulch in agricultural lands (Onwona-Agyeman *et al*., 2012; Wu *et al.,* 2016). Agro-chemicals can be added into agri-mats during their fabrication process to increase their fertilizing ability and durability (Onwona-Agyeman *et al*., 2012). Agri-mats are tailor-made for poor-resource smallholder farmers because they are fabricated predominantly from freely available organic waste materials (grasses, bagasse, weeds, forestry waste, etc) than valuable crop resides. However, the agri-mats are not currently accessible to both smallholder and commercial farmers because they are a new technology and a pricing model which will determine how much each agri-mat cost or price per square meter they occupy is still being developed. The utilization or sales of crop residues after grain harvest as livestock feed is a much more economic viable option for smallholder farmers than for mulching purposes, especially for soil erosion control measures (Giller *et al.,* 2015). However, rice straws, wood chips and other lose organic mulching materials can be easily washed by overland flow and strong winds, while agri-mats can withstand extreme weather events and last over two years in the field (Onwona-Agyeman *et al.,* 2012). Overland flow and strong winds are a common phenomenon in arid and semi-arid regions due mostly to poor vegetation cover and erosive rainfall (Vaezi *et al*., 2017).

Several research studies have been conducted to investigate the effectiveness of crop residue and other organic materials using rainfall simulators under field and laboratory conditions. The advantage that laboratory experiments have over field experiments includes the ability to control the determining factors such as slope, soil moisture content, rainfall intensity and duration, surface roughness, etc (Jiraratchwaro *et al*., 2019). In South Africa, the information on the use of agri-mats for soil erosion control under laboratory scale is scanty. Moreover, there is no information in the literature which investigates water infiltration rate of agri-mats relative runoff rates under laboratory conditions. The current study aims to determine the effectiveness of agri-mats as a water conservation tool under rainfall simulation experiments. The objective of this study was to determine the infiltration and runoff rate of agri-mats using Mini Portable Pressure Head (MPPH) Rainfall Simulator.

6.2. MATERIALS AND METHODS

6.2.1. *Agri-mat fabrication process.*

The agri-mats were fabricated using a heat-press machine at the Agricultural Research Council – Agricultural Engineering, Pretoria. To make one agri-mat, 430 g of dry bagasse was thoroughly mixed in a bucket with 84 g of MgO powder (as an adhesive/binder) and 1560 ml of water by hand. Each of the material is mixed in three successive steps of three equal measure (1/3). For larger quantities, the materials are multiplied by the number of agri-mats needed, and an electrical mixer is used to ensure thorough mixing. A handheld pressure sprayer is used to distribute and carefully spray water (1/3) all over the dry bagasse placed inside the drum of an electric mixer, which is allowed to run for 10 minutes. To complete step one, 1/3 measure of MgO powder is evenly distributed onto the wet bagasse inside the electric mixer drum by hand. The electric mixer is run for another 10 minutes to ensure thorough mixing of the three materials. The second and third steps are done accordingly.

To fabricate one agri-mat, a 25 mm × 50 mm rectangular frame is placed on top of an aluminum plate. To ensure smooth surface on the bagasse, and that bagasse does not stick to the aluminum plates and frames, a Teflon sheet (50 mm length, 25 mm width and 3 mm thickness) is placed on top of an aluminum plate. Teflon side-wall plates, with equal length and width with aluminum rectangular frames are placed inside, along the aluminum frames. Approximately 2074 g of the mixture is then distributed inside the frame. A wooden push plate wrapped with plastic is used to press the bagasse mixture by hand. The wooden push plate is removed and replaced by another Teflon sheet with the same dimensions (50 mm × 25 mm × 3 mm). Convex mold C with an aluminum surface and handles is superimposed on the top of the frame. The handles in the convex mold C are removed and the frame is placed on top of a hydraulic pump inside the heat-press machine. The heat-press machine has a lower- and upper-aluminum plate and are programmed to reach a maximum of 155 ^{o}C for agri-mat fabrication purposes. The lower-aluminum plate is mounted on top of a jack, which has a pressure gauge. The hydraulic pump is then carefully removed, leaving the aluminum frame inside the heat-press machine on top of the lower-aluminum plate.

The frame is then jacked up until it is sandwiched between the lower- and upper-aluminum plates at a pressure of 60 kPa. The cold temperature on the aluminum frame and convex C mold results in slight temperature drop in the lower- and upper-aluminum plates. However, after several minutes, the temperatures start to increase again and the stop-watch is used to time the heat-press for 10 minutes as soon as the temperatures reach 155^{o}C (Figure 6.1).

Figure 6.1. Agri-mat fabrication process demonstration using a heat-press machine

The hot frame with agri-mat is removed from the heat-press machine and placed on top of the hydraulic pump after a period of 10 minutes. A smooth and intact agri-mat measuring (50 mm length, 25 mm width and 15 mm thickness) is carefully removed from the rectangular frames when all the components have cooled off (Figure 6.2).

Figure 6.2. Fresh agri-mats from the heat-press machine

6.2.2. *Agri-mat infiltration rate and runoff test*

Agri-mats infiltration and runoff test was conducted in a laboratory at Tokyo University of Agriculture and Technology, Fuchu city. A MPPH rainfall simulator was calibrated and programmed to simulate a rainfall with an intensity of 70 $mm.hr^{-1}$. Generally, the intensity of rainfall varies within semi-arid regions and is projected to worsen in the future by climatologist due to climate change. South Africa is a semi-arid country and therefore receives low rainfall of approximately 500 mm per year on average (Sithole *et al*., 2016). According to Mhaske et al, (2019), a low rainfall scenario can be simulated with about 65 $mm.hr^{-1}$ in soil water erosion laboratory studies and hence the 70 $mm.hr^{-1}$ rainfall intensity was adopted for this study.

The drop former has dimensions of 0.51 m in length and 0.51 m width. For this experiment, the simulator was adjusted to 2.28 m in height. A schematic diagram of the MPPH Rainfall simulator can be found in the study published by Jiraratchwaro *et al*., (2019). The rainfall simulator had two transparent water buckets mounted at the back, one above the raindrop generating plate and another on the surface and both were connected to a pressure pump with water pipes (Figure 6.4a). The capillaries are made of 0.4 mm steel needles that are 4 mm long and produce drops of uniform size (Figure 6.3b).

An agri-mat was cut into half to fit snugly into a square (25 mm × 25 mm) Permeability (P) and Runoff (R) tray known as PR-tray (Figure 6.3c). The PR-tray has transparent plastic frames and a steel-sieve layer at the base where the agri-mat is placed. A white clay was used to tightly seal agri-mat along the walls of the PR-tray, thus allow water to permeate or infiltrate only through the agri-mats. The PR-tray with the agri-mat was placed at an angle of 5^o under the capillaries of the rainfall simulator for all simulation runs. Under the steel-sieve layer, the PR-tray has a tightly closed base with one pipe near the left corner, which channels infiltration water out of the tray. Above the steel-sieve layer (on top of the agri-mat), one side of the PR-tray is open, to allow the movement of runoff water out of the (25 mm × 25 mm) tray area into an extended (25 mm x 5 mm) area of an angled PR-tray. The extended part of the PR-tray has an opening in the middle, which is connected to a pipe that channels runoff water out of the tray for collections and measurements (Figure 6.3c).

(A) (B) (C)

Figure 6.3. MPPH Rainfall simulator with water supply (a), showing water droplets from drop former through capillaries (b) fall into the PR-tray with agri-mat (c).

Prior to each runoff and permeability test, the rainfall simulator was calibrated and the agri-mat dry mass with a size of 25 mm length, 25 mm width and 3 mm thickness was recorded. The simulations were run for 60 minutes per agri-mat and the time it took to collect the first infiltration and runoff water was recorded using a stopwatch. Thereafter, infiltration and runoff water was collected every 10-minute interval until the 60^{th} minute.

A total of six agri-mat samples were subjected into a runoff and permeability (infiltration rate) test for this study: three agri-mats were made with 100% dry sugarcane bagasse as described above under the agri-mat fabrication process section. For 100% dry sugarcane bagasse agri-mats, 430 g of the pure bagasse was used for each agri-mats. The other three agri-mats were made with (10% dry algae + 90% dry sugarcane bagasse). For this treatment, 387 g of pure bagasse was mixed with 43 g of dry algae to make 430 g of the require quantity for fabricating a single agri-mat. Magnesium oxide (MgO) was used as the binding agent during the fabrication process of the agri-mats.

6.2.3. *Statistical analyses*

Statistical analysis was performed using JMP statistical package (SAS institute, JMP® (Carry, 2016)). Data was subjected to analysis of variance (ANOVA) at 5% probability level to assess statistical significance of agri-mat on infiltration rate and runoff water loss. Student t-test was used to indicate statistical differences between treatment means.

6.3. RESULTS

6.3.1. Agri-mat infiltration rate and runoff out flow

Agri-mats that were fabricated with 100% Bagasse (B) had, on average, lower infiltration rate compared with agri-mats that were made with 90% Bagasse + 10% Algae (BA). The B agri-mat treatment had higher runoff rate of 16.8 mm. hr^{-1} compared to mere 1.7 mm. hr^{-1} recorded under the BA agri-mat during the first 10 minutes of rainfall simulation test (Figure 6.4). The runoff rate increased of the BA agri-mat at every 10-minute interval from the first 10 minutes until the 30th minute where it reached a constant of about 4.4 mm. hr^{-1} until the 60th minute. On the hand, the runoff rate of the B agri-mat treatment decreased at every 10-minute interval from the first 10 minutes until the 30th minute where it reached a constant of about 4.4 mm. hr^{-1} (the same rate with the B agri-mat) until the 60th minute.

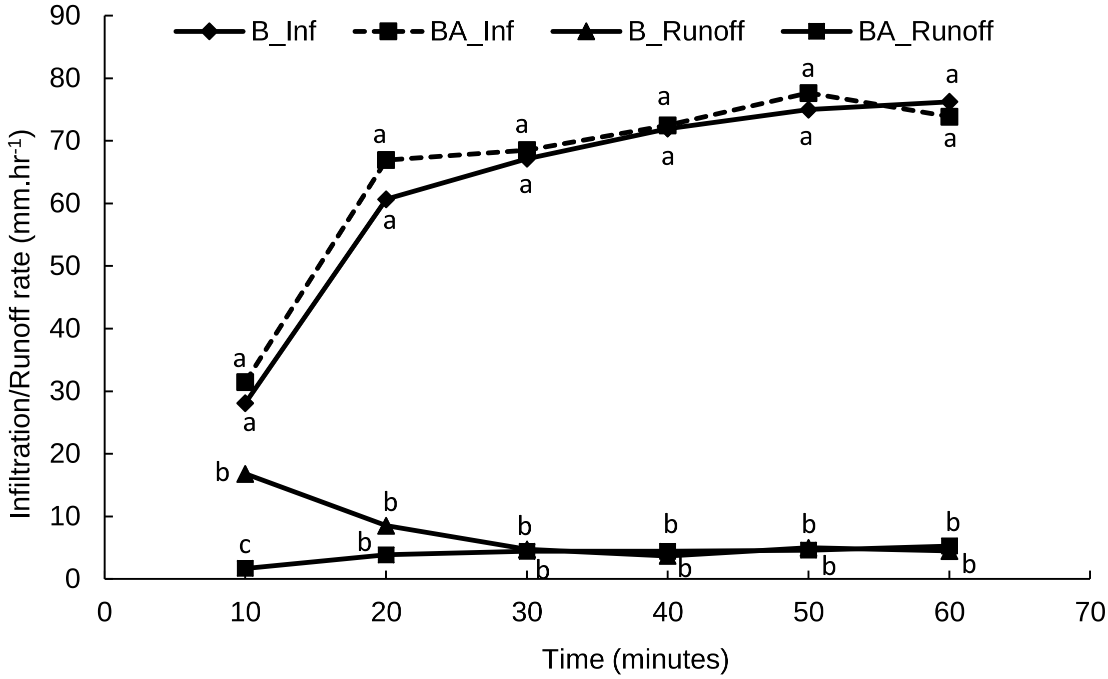

Figure 6.4. Effect of rainfall intensity on average infiltration and runoff rate of an agri-mat fabricated with 100% Bagasse (B) and those made with 90% Bagasse + 10% Algae (BA). Means with the same letter with the same time interval are not significantly different.

The loss of magnesium from the agri-mats either through infiltration or runoff water was investigate since MgO was used as the binding agent during agri-mats fabrication process. Generally, the results show that for agri-mat that contained 10% algae, there was significantly less water which was lost through runoff and less quantities of magnesium during released the first 30 minutes of rainfall simulation compared with agri-mat that had no algae (Figure 6.5). The amount of water lost through runoff in the B agri-mat was 16.8 mm. hr^{-1} compared to a mere 1.7 mm. hr^{-1} recorded under the BA agri-mat treatment. In addition, the B agri-mat released magnesium at a rate of 105.7 mg. hr^{-1} compared to 6.6 mg. hr^{-1} lost from the BA agri-mat treatment. The cumulative amount of magnesium lost under BA agri-mat was 32.81 mg while 136.58 mg was lost under B agri-mat through runoff. The trends show that agri-mats with no algae (B) rapidly lost high quantities (about 125 mg. hr^{-1}) of magnesium during the first 30 minutes. On the other hand, the BA agri-mat lost only about 30 mg. hr^{-1} of magnesium during the first 30 minutes of the rainfall simulations. However, the average quantities of magnesium lost at from both types of agri-mats (B and BA) was almost equal after 30 minutes at about 6 mg. hr^{-1} and drop gradually to reach approximately 3.8 mg. hr^{-1} at the 60th minute of the experiment.

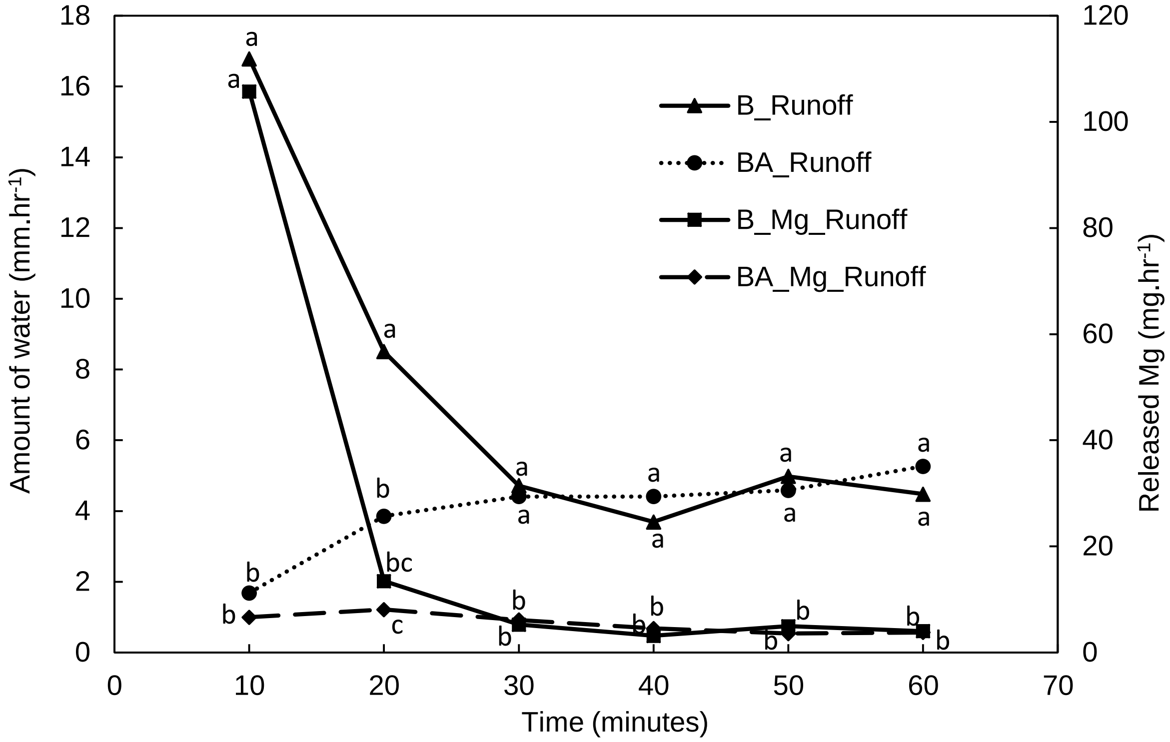

Figure 6.5. Average magnesium quantities detected from runoff water of different agri-mats (B and BA) as over time. Means with the same letter with the same time interval are not significantly different.

Agri-mat that contains 10% algae had a higher capacity to allow more water to infiltrate through and prevent large quantities of magnesium from being lost through runoff compared to agri-mats without algae (Figure 6.6). In both agri-mat types (B and BA), infiltration rate increase rapidly from the 10 to the 20th minute, and dropped gradually thereafter until the 60th minute. However, the amount of water which infiltrated through the agri-mats were always higher in agri-mats with algae (BA) compared to agri-mats without algae (B) at every 10-minute interval when measurements were recorded. The rate at which magnesium was released into the soil from both agri-mat types increased rapidly from the 10 to the 20th minute, and continued to increase thereafter, though gradually, until the 60th minute.

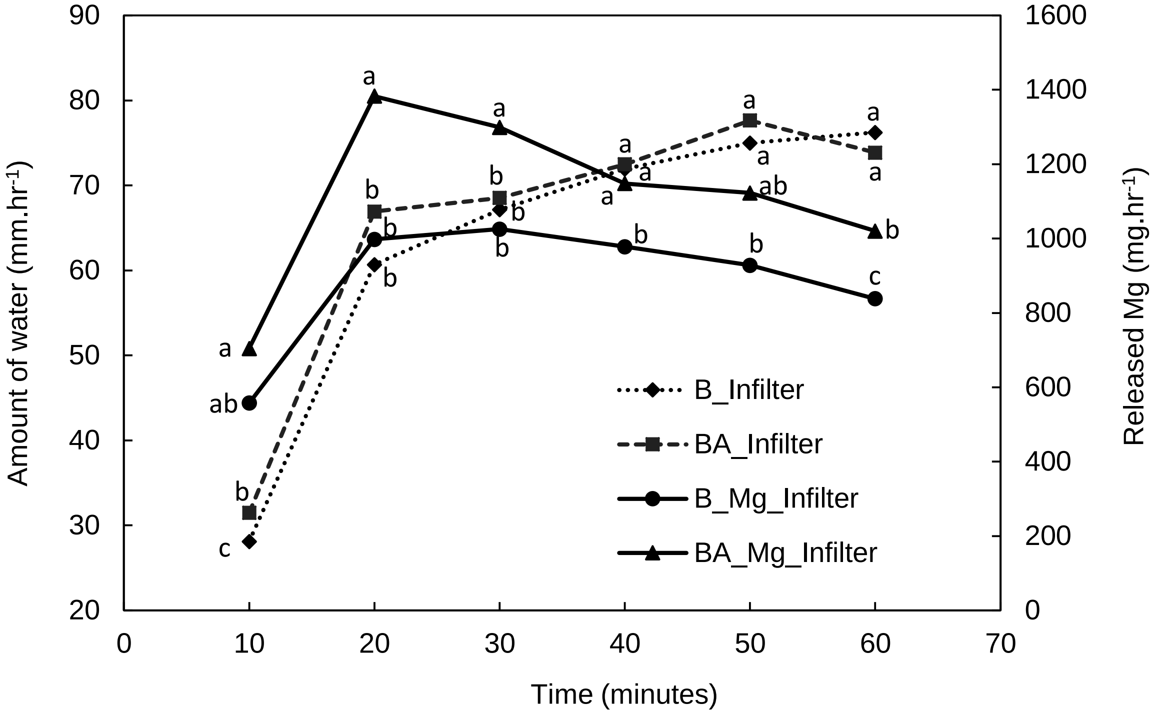

Figure 6.6. Average magnesium quantities detected from infiltration water leached from different agri-mats (B and BA) as over time. Means with the same letter with the same time interval are not significantly different. B_Infilter represents infiltration under agri-mat made with dry Bagasse only. BA_infilter represents infiltration under agri-mat that was made with 90% dry Bagasse and 10% Algae. B_Mg_infilter stands for the amount of magnesium that was released into the infiltration water from agri-mat made with bagasse only. BA_Mg_Infilter stands for the amount of magnesium that was released into the infiltration water from agri-mat made with both bagasse and algae.

The addition of algae influences the electrical conductivity and the trends in both types of agri-mats indicates that the availability of salts was reduced at every 10-minute interval until the end of the experiment (Figure 6.7). The EC of the filtration water from BA was 1713.3 mS/cm during the first 10 minutes, while that of B was 1206.7 mS/cm. However, the EC was reduced to 1033.3 mS/cm and 816.7 mS/cm at the 60th minute for BA and B respectively. On the other hand, difference in pH between infiltration water from agri-mats with algae and agri-mats without algae was minimal and averaged to about 9 at every 10 minutes when measurements were made.

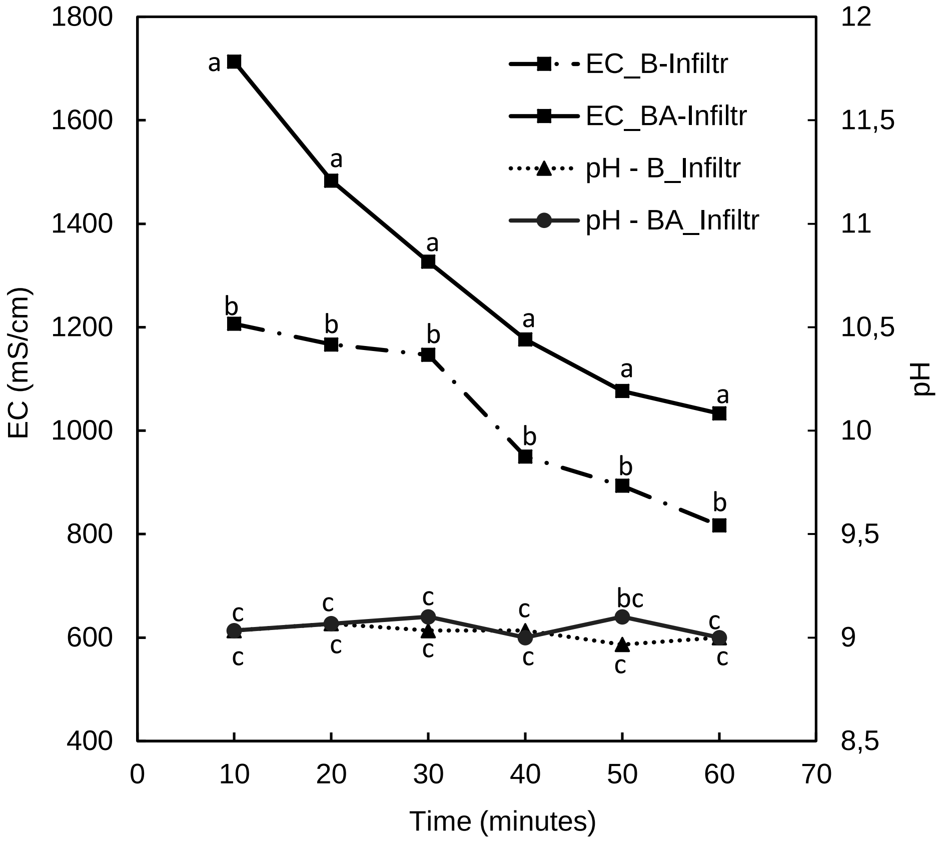

Figure 6.7. Electrical conductivity and pH of infiltration water trends leached from different agri-mats (B and BA) at 10 minutes' interval. Means with the same letter with the same time interval are not significantly different.

6.4. DISCUSSION

Approximately 10 million hectares of cropland are lost annually due to soil erosion mostly through runoff, thus negatively affecting crop production and global food security (Pimentel and Burgess, 2013). In South Africa, the changes in soil organic matter levels and overall soil quality for the past thirty years are alarming, mostly due to soil erosion which affected more than 70% of the countries land surface (Barnard and du Preez, 2004; Le Roux *et al*., 2007). Soil and water loss through runoff are major environmental concerns that threaten croplands worldwide as they lead to unsustainable of agroecosystems (Montenegro *et al.,* 2013). Agri-mats and biogeotextiles are among the numerous technologies that have been developed for use in water and sediment conservation and to promote the adoption of conservation agriculture. Furthermore, the decomposed agri-mats and biogeotextile mats provide nutrients to growing plants and can potentially advance soil erosion control in complex environmental situation (Onwona-Agyeman *et al*., 2012; Subedi *et al.,* 2012). The current study investigates the infiltration rate and runoff of agri-mats and their effectiveness in combating soil water erosion under laboratory conditions. A portable rainfall simulator was calibrated and used in order to understand the interactions between rainfall and agri-mat conditions as they determine the fate of water, nutrient and pesticide releases and losses from agri-mats (Kibet *et al*., 2014). The results from agri-mats infiltration and runoff rate test indicates that agri-mats can reduce soil water erosion due to their ability to allow more water to be absorbed into and infiltrate through the agri-mat instead of being lost through runoff. In addition, agri-mats, especially when algae were used as additional organic material, delays runoff by absorbing more moisture than it losses as it took more time to observe the first drop of runoff than that of infiltration. Generally, the agri-mats fabricated with algae had higher infiltration rate compared with agri-mats made without algae. This is attributed to algae's capacity to improve water absorption and holding capacity when added to the soil (El-Gamal, 2011). Moreover, the results from this study show that algae addition in agri-mats reduce nutrient loss through runoff. Algae helps to release nutrients, as observed with magnesium, slowly over time, and this will help to supply nutrients to crop in a timely manner. However, in soils with high quantities of magnesium it is recommended that magnesium oxide be substituted with other binding agents during the fabrication of agri-mats to avoid undesirable nutrient imbalance in the soils. El-Gamal, (2011) observed that the addition of cyanobacteria algal species improved microbial activities in terms of enzyme activities which accelerated the decomposition of compost and increased the availability of nitrogen content (NH_4^+- and NH_3^-) during a 2-month incubation study.

The current study indicates that addition of algae has an effect on electrical conductivity but not on pH. Generally, the trends indicate that the availability of salts was reduced at every 10-minute interval until the end of the experiment from both agri-mats types at relatively equal amounts. The pH measured at every 10 minutes' interval in the infiltration water of both agri-mats remained constant throughout the experiment at an average of 9. Although a pH of 9 indicated that agri-mats have a potential to increase the pH of the soil from acidic to saline, further research will be needed to verify this possibility through field experiments. The practice of adding fertilizers, pesticides and herbicides into the agri-mats can help to reduce the contamination of estuaries and other water bodies due to the improved infiltration rates in comparison to runoff rates. Various species of aquatic plants and animals face the dangers of dying from polluted water due to runoff water that is contaminated with different synthetic agro-chemicals (Pimentel and Burgess, 2013). According to Onwona-Agyeman et al. (2012), the addition of urea does not only improve the durability of the agri-mats but also allows them to retain moisture. Moreover, the use of agri-mats in general could result in more benefits such as yield improvement, soil moisture retention, elimination of weeding or herbicide application, erosion control, hill slope stabilization and an overall improvement in ecological services (Onwona-Agyeman *et al*., 2012).

6.5. CONCLUSION

Incorporation of algae in the agri-mat technology could improve the functionality and value of agri-mats for agricultural purposes. The current study show that algae has the capacity to increase water absorption and holding capacity of the agri-mats while reducing runoff at the same time. In addition, algae improve nutrient content and the electrical conductivity of the agri-mats, making them more beneficial not only as the runoff controlling technology but as a soil conditioner. However, further research is needed to investigate the accepted limits for algae incorporation into the agri-mat system since they are capable of producing toxic elements such as heavy metals. Moreover, the effects of the leachates such as magnesium and the increased EC noted during the experiment need further research especially on their implication with regard to soil properties. It is also recommended that future studies evaluate few rainfall intensities ranging from low - high to mimic the nature of rainfall in semi-arid environments which is variable.

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CHAPTER SEVEN:

GENERAL DISCUSSIONS, CONCLUSIONS AND RECOMMENDATIONS

Soil degradation through water erosion threatens the health of the rapidly growing global population due to its devastating effects on agricultural production especially in dry areas. The recent observations by climatologists indicate that in the next decade, Southern Africa farmers will be heavily affected by extreme weather conditions due to climate change. Naturally, South African soils have very low soil organic matter (SOM) and soil fertility status, with about 60% estimated to contain less than 0.5% SOM (Swanepoel *et al*., 2018). Conserving and increasing SOC is thus important for soil health, optimum crop production and better food security; it is therefore important to improve SOM by employing various sustainable agricultural techniques that are tailored for specific environments (Thierfelder *et al.,* 2018). The current global agricultural practices must prioritize soil and water conservation practices to promote ecological health as well as social health (through food security) of the current and future generation in a sustainable manner. The practice of applying or retaining crop residues in the field as mulch is imperative not only to prevent soil degradation through erosion, but to maintain soil quality and improve crop productivity and global food security.

Organic residues or biomass from any crop species help to increase the organic matter content of the soil as they decompose over time, and add other minerals into the soil through the process called mineralization. Largely, the quality and quantity of organic residues retained or applied in the field as mulch (Pansu *et al*., 2003; Giller *et al*., 2009) determine the decomposition rate and the degree to which organic matter of any given soil can increase. Mineralization is a process where inorganic substances are transformed into inorganic or mineral N components such as ammonium N (N-NH_4^+) and Nitrate N (N-NO_3^-). The current study investigated the process of N mineralization dynamics through an incubation experiment which took place for a period two months. The experiment was conducted on two different soils types, one with 9.3% clay content and the other with 24.3% clay content, which were treated with various combinations of organic materials with LAN and organic materials alone. Generally, the findings from the incubation study show that mineralization rate in all the treatments where the organic and inorganic fertilizer were combined was significantly higher compared to treatments where only organic amendments were solely applied in both soil types. This indicates that inorganic amendments increase the efficiency of organic fertilizers and vice versa, through some positive interactions on soil biological, chemical and physical properties for different soil types (Shahid and Al-Shankiti. 2013). Therefore, Integrated Nutrient Management (INM) approach can be used to increase crop productivity and improve long-term the fertility status and overall quality of the soil with minimal negative effects to the environment (Jumadi *et al.,* 2014). Although initial characterization of both soils indicates that the loamy soil was more fertile compared with the sandy loam soil, Nitrogen mineralization rate, both N-NH_4^+ and N-NO_3^- was higher in a sandy loam soil. This could be attributed to lower N mineralization rates that are often observed to be lower in fine textured (clay) soils compared to coarse-textured soils (Matus *et al*., 2007). However, there are various components which could contribute to the differences in mineral N dynamics between the two soil types and overall fertility status. According to Malobane. (2015), Soil fertility is a complex term and encompasses a combination of components such as soil texture, soil reaction, soil depth, nutrient content, soil microbial activity, organic matter content and composition, content or absence of potentially toxic substances, etc. The gradual decline in the NH_4^+-N mineralization observed between day 0 and day 7 in the loam soil from Durban could be attributed to N immobilization (Mawonga, 2016). Immobilization is the opposite of mineralization and the difference between the two is referred to as net mineralization (Malobane, 2015).

The same trend noted in the incubation study was also observed in a glasshouse experiment where spinach was planted using the same treatments on the same two-types of soils for a two months' period. The results from the glasshouse experiment indicate that soil amendments had a significant effect on all measured spinach crop growth parameters and yield in both soil types. Among all organic-inorganic amendments, the combination of dried algae and inorganic fertilizer was found to produce higher values for plant height, leaf length, number of leaves and biomass yield compared to other treatments. This could be attributed to minimal or no-loss of Nitrogen since ammonium volatilization does not occur in soils treated with dried algal biomass (Mulbry *et al.,* 2005). In addition, the initial characterization results indicate that dried algae contained the highest content of essential crop nutrients (NPK) and most of the other elements compared to other organic amendments. Although the full application of inorganic fertilizer (100%CF) produced the highest yield compared to 50%GG+50%CF and 50%GA+50CF treatment combinations under loamy sand, the differences in biomass yield values recorded under the loam soil were not significant between the three treatments. This could be ascribed to low mineralization rate in loam soils, which allowed 100%CF treatment to produce higher yield than INM treatments (Matus *et al*., 2007). Generally, inorganic fertilizers get lost easily through leaching in coarse textured soil under field conditions. However, since the current results were obtained in a pot experiments with monitored irrigation, the net loss of N through leaching was minimized. The trends observed under all different organic amendments compared to the control indicates that they have a potential to improved crop production. The quantification of N supplying capacity of organic amendments applied to a soil is of immense importance to examine N release capacity and fertilizer values of organic amendments (Abbasi and Khaliq, 2016).

The results from the field experiment suggest that mulching had a significant effect on maize and spinach growth and development at both experimental sites. The 100% agri-mat mulch treatment (100%AG) produced the highest crop growth parameters (plant height, leaf length and leaf width) at most weeks for both test crops including total biomass yield and leaf nutrient content of spinach. The measurements from soil moisture and temperature indicates that all the plot that were covered with 100% agri-mat mulch treatment had higher moisture content compared to other treatments. The 100%AG treatment resulted in higher soil temperature during with winter seasons and this suggest that agri-mat may retain more heat from radiation and keep the soil warmer for longer periods compared to other mulching materials. Therefore, agri-mats can regulate temperatures in beneficial ways for the growing crop better than loose organic mulching material (Maggard *et al*., 2012). The 6.tons.ha^{-1} grass treatment was the second most performing treatment after 100% agri-mat in most cases. The current results are in line with other findings by several researchers who has shown that the mulching practice can result in high moisture capture and storage with minimal losses through evaporation (Wu *et al.,* 2011; Lalljee, 2013; Amooh and Bonau, 2015; Kakaire *et al.,* 2015).

The spinach yield and leaf quality was generally higher in Durban compared to the Pretoria site in both growing seasons. This is partly attributed to the soil fertility status which was higher in Durban site, compared to soils in the Pretoria site. Moreover, the rainfall amount in Durban was generally higher compared to the Pretoria site for the entire duration of the experiments. The loss of water through soil evaporation amounts to about 30% of the total precipitation in the semi-arid tropics and this also could explain why the yields in Durban were generally higher compared with the crop yields in Pretoria (Amooh and Bonau, 2015). Amooh and Bonau. (2015) iterate “the primary source of moisture loss in agricultural soils is evaporation”. The general mulch application rate of 0.5 – 2.0 tons.ha^{-1} by poor resource farmers due to competition of crop residues has been shown to be inefficient to increase crop yields (Giller *et al*., 2009). According to (Amooh and Bonau. (2015), loamy soil has both sand and clay, with both macro and micro pores, giving a more balance supply balance of both air and water in the macro and micro pores respectively. However, the mere presence of chemical nutrients and good soil structure are not sufficient as indicators of a soil to produce high yields; soil moisture and temperature regimes are equally important suitability attributes of a soil as a medium for plant growth (Amooh and Bonau, 2015). According Uwa and Iwo. (2011), soil moisture is known to enhance efficient use of fertilizer while excellent solar radiation during the growth seasons encouraged higher photosynthetic rates which culminates in higher yields.

The higher maize total biomass yield and cob yield in the Pretoria site during the first and second season recorded under 100% agri-mat compared to other treatments show the importance of conserving moisture in the soil. Mulching has been, for a long time shown to be one of the most effective practices that improves soil water status, and influence soil temperatures in favour of a growing crop as it provides a protective layer on the soil surface (Siczek *et al.,* 2015). Although maize total yield and cob yield were not recorded in Durban as the crops were eaten by monkeys at maturity stage, the crop growth parameters recorded prior to the unforeseen event indicates that mulching is essential for moisture storage even in humid regions. Generally, mulch improves soil quality, moderates soil temperatures and helps to reduce the risk of crop failure at field level through effective capture and use of rainfall water and solar radiation (Giller *et al*., 2009; Uwah and Iwo, 2011; Lalljee, 2013). Mulching essentially increases the organic matter content of the soil as it decomposes, and ultimately improves aggregate stability, porosity, infiltration rate and moisture retention capacity of the soil (Amooh and Bonau, 2015).

The current study investigated the effect of different mulching materials on aggregate stability and soil porosity of a loam and sandy loam soil. According to Le Bissonnais (2016), the results indicates that, in reference to the control, mulching increased the stability of soil aggregates from unstable to medium stability after a period of two years for both loam and sandy loam soil. The practice of adding organic residues such as straw mulch, grasses, as mulch or organic amendments has been promoted in different parts of the world to improve organic matter content, aggregate stability, porosity and overall quality of the soil (Yang *et al*., 2018). The findings from this study indicates that the 100%AG mulching material has a greater stabilizing ability compared to all other mulching materials in both soil types. This can be ascribed to the agri-mats ability to conserve soil moisture, increase and maintain higher soil organic matter content compared to other loose mulching materials (Onwona-Agyeman *et al*., 2012). The stability of soil aggregates can be improved by increasing either the percentage or thickness of mulching material. In addition, the duration of mulching period can play a significant role in improving the organic matter content of the soil. Yang et al. (2018) state "Soil organic matter promote the formation of more and larger aggregates, thereby enforcing the soil aggregate stability and water storage capacity". The distribution of different aggregate classes of any soil type can be influenced by the quality and quantity of organic material applied. Micro-aggregates in both soil types were generally lower in percentage compared to macro-aggregates under all mulch treatment means. Additionally, the degree and speed to which any organic material increase the macro-aggregates of a given soil type depends on other inherent soil binding agents and prevailing conditions (Totsche *et al*., 2018).

The current study shows that the number or frequency of soil micro-aggregate increases with the decrease in mulch thickness or percentage while soil macro-aggregates decreases with the decrease in mulch thickness or percentage. Various aggregate classes in the macro-aggregates range (>250 µm) from both soil types show that when mulch application is increased, the stability of macro-aggregates improves. Similarly, with the results observed in the loam soil, the 100%AG much treatment was responsible for the formation of more macro-aggregates than micro-aggregates in sandy loam soil. The formation and stability of soil aggregates, as observed in this study, is increased by the addition of organic residues. Organic residues improve the population of soil microbes, which aide in the formation of soil organic matter and better soil porosity (Blanco-Canqui and Lal, 2004; Yang *et al*., 2018). The physical architecture of soil aggregates, which refers to how porous, connected and distributed soil aggregates are (e.g. porosity, pore connectivity pore and pore size distribution,) in the soil 3D matrix is responsible for soil microbial activities (Shujie *et al*., 2009; Rabbi *et al.,* 2016). Soil porosity refers to the volume of interconnected soil pores (with various sizes and shapes) that are occupied by water and/or air (Beraldo *et al*., 2014). The findings of the current research indicate that the sandy loam and loam soil studied are extremely porous because the total macro-porosity of both soils is greater than 40% (Pigliai *et al.,* 2004). Although the total macro-porosity of the sandy loam soil was not influenced by mulching, the 100%AG mulch treatment improved the water holding capacity of the loam soil by decreasing total macro-porosity, making it less porous compared to other treatments.

The 100%AG mulch treatment produced the highest percentage for total porosity, which was significantly higher compared to other mulching treatments. Moreover, the 100%AG mulch treatment produced more transmission pores (50 – 500 µm) in both soil types, which indicates that agri-mats can play a significant role in both soil – water – plant relations and in maintaining good soil structure quality for better soil health and improved crop productivity (Pigliai *et al*., 2004). Generally, the X-ray CT analysis results show that, due to higher frequency of storage pores (0.5-50 µm) and feeding root pores (100 - 200 µm) in the loam soil compared to the sandy loam, the loam soil has better capacity to accommodate more roots as well as higher volume of water reservoir for plants and microbes (Pigliai *et al*., 2004). In addition, the loam soil had a higher percentage of pores > 500 µm compared to sandy loam soil, which indicates better water infiltration and drainage capacity particularly as a fine-textured soil (Pigliai *et al*., 2004). The current study investigated the permeability of agri-mats in order to understand their effectiveness in combating soil erosion (infiltration rate in relation to runoff) under laboratory conditions. A portable rainfall simulator was calibrated and used in order to understand the interactions between rainfall and soil conditions as they determine the fate of sediment, nutrient and pesticide losses from agricultural soils (Kibet *et al*., 2014). The results from agri-mats permeability test indicates that agri-mats can improve reduce soil erosion due to their ability allow more water to infiltrate through than runoff. In addition, agri-mats, especially when algae is used as additional organic material, delays runoff by absorbing more moisture than it losses as it took more time to observe the first drop of runoff than that of infiltration. This indicates that algae can improve the agri-mat water absorption and holding capacity.

In conclusion, the Integrated Nutrient Management approach, as shown in this study, has a potential to reduce environmental pollutions challenges through nitrate leaching and runoff by more than 50% since it decreases nitrogen application rates by half or more. Additional, algae or other organic materials with significant initial levels of nitrogen and higher fertilizing capacity can partially substitute the chemical nitrogen fertilizer without affecting the yield and quality of spinach and other crops. The 100% agri-mat mulch treatment can increase soil aggregate stability, improve soil physical architecture for infiltration rate and water holding capacity, and enhance crop yields and crop quality (leaf nutrient content) for better food security. Agri-mats can be adopted as an alternative mulch who wants to maximize their farming outputs with minimal inputs. Agri-mats are an innovative, sustainable and permanent soil cover mulching technology that promise to be a cost-effective option, which can be used to eliminate crop residue competition in the mixed crop-livestock systems since they are manufactured from freely available biological materials. In addition, agri-mats eliminate, for smallholder farmers, the heavy burden of weed control and herbicide use when no tillage is employed and they reduce the cost of irrigation more especially in semi-arid areas where rainfall is scanty. Generally, global food security can be achieved by increasing agronomic productivity from existing land without any conversion of natural land to agroecosystems through eco-intensification and restoration of soil health. This includes the restoration of degraded lands through the incorporation of agri-mats to CA systems, which employ biological nitrogen-fixing legumes in a rotation with other crops

However, it is recommended that extensive research be conducted for longer periods under incubation study to determine the point at which all organic N become mineralized. This will help to predict the time at which they could be applied in the soil under field conditions prior to planting. In addressing crop productivity and food security while preserving the resource base with minimal effects on the environment, the recommendations drawn from all future agri-mat research work must be site-specific and should strictly be used as a guide for areas with similar soils and environmental/climatic conditions where the results will be obtained. Future research work should also be designed to better understanding the effect of agri-mats in the overall soil health by studying their role in microbial population and activity. Generally, further and extensive research needs to be conducted to investigate several aspects of the agri-mats for agricultural use and their efficiency over traditional mulching methods mostly in terms of cost effectiveness or economic viability, and to quantify the extent to which they can (i) improve soil quality (soil physical, chemical, and biological properties), (ii) enhance crop productivity (crop growth and biomass yields) in a sustainable manner and (iii) mitigate global food security especially for poor resource smallholder farmers in semi-arid or arid regions

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APPENDIX

Table A1: ANOVA of NH_4^+ and NO_3^- mineralized into the loam soil mineralized during the two-month incubation study. Asterisk (*) indicates significance.

DBN soil		NH_4^+		NO_3^-	
	DF	F-value	Prob>F	F-value	Prob>F
Day 0	6	99.7646	< 0.0001*	4472.190	< 0.0001*
Day 3	6	29.3858	< 0.0001*	1751.759	< 0.0001*
Day 7	6	1.0985	0.04184	188.7149	< 0.0001*
Day 15	6	2.1208	0.1147	430.5041	< 0.0001*
Day 30	6	9.9317	0.0002*	45.1599	< 0.0001*
Day 45	6	0.6874	0.6817	124.8836	< 0.0001*
Day 60	6	3.5761	0.0227*	25.9383	< 0.0001*

Table A2: ANOVA of NH_4^+ and NO_3^- mineralized into the sandy loam soil mineralized during the two-month incubation study. Asterisk (*) indicates significance.

PTA soil		NH_4^+		NO_3^-	
	DF	F-value	Prob>F	F-value	Prob>F
Day 0	6	12.5645	< 0.0001*	238.9474	< 0.0001*
Day 3	6	10.9700	< 0.0001*	345.1375	< 0.0001*
Day 7	6	27.8397	< 0.0001*	2464.743	< 0.0001*
Day 15	6	11.2066	< 0.0001*	16.8157	< 0.0001*
Day 30	6	29.1856	< 0.0001*	0.7858	<0.6113
Day 45	6	9.3687	0.0003*	26.1066	< 0.0001*
Day 60	6	19.1154	< 0.0001*	13.3915	< 0.0001*

Table A3: ANOVA of PH, LW and NL of spinach during the first the 2nd and 4th week after planting in a loam soil under glasshouse experiment. Asterisk (*) indicates significance.

DBN soil		2WAP		4WAP	
	DF	F-value	Prob>F	F-value	Prob>F
PH	4	3.2955	0.0574	4.9124	0.0188*
LW	4	2.865	0.0806	1.1568	0.3856
NL	4	0.8840	0.5071	0.5537	0.7012

Table A4: ANOVA of PH, LW and NL of spinach during the first the 6th and 8th week after planting in a loam soil under glasshouse experiment. Asterisk (*) indicates significance.

DBN soil		6WAP		8WAP	
	DF	F-value	Prob>F	F-value	Prob>F
PH	4	1.5270	0.2670	1.0000	0.4516
LL	4	1.8932	0.1883	0.3014	0.8705
LW	4	2.1885	0.1437	2.4725	0.1120
NL	4	0.8654	0.5171	0.39272	0.8064

Table A5: ANOVA of spinach from a sandy loam and loam soil under glasshouse experiment. Asterisk (*) indicates significance.

		PTA		DBN	
	DF	F-value	Prob>F	F-value	Prob>F
Yield	4	17.3686	0.0002*	9.0603	0.0023

Table A6: ANOVA of PH, LW and NL of spinach during the first the 2nd and 4th week after planting in a sandy loam soil under glasshouse experiment. Asterisk (*) indicates significance.

PTA soil		2WAP		4WAP	
	DF	F-value	Prob>F	F-value	Prob>F
PH	4	9.814	0.0017*	10.9387	0.0011*
LW	4	6.0583	0.0097*	5.4333	0.137
NL	4	0.5875	0.6792	0.6654	0.6303

Table A7: ANOVA of PH, LW and NL of spinach during the first the 6th and 8th week after planting in a sandy loam soil under glasshouse experiment. Asterisk (*) indicates significance.

PTA soil		6WAP		8WAP	
	DF	F-value	Prob>F	F-value	Prob>F
PH	4	8.7998	0.0026*	12.6616	0.0006*
LL	4	6.1335	0.0093*	10.3694	0.0014*
LW	4	2.6452	0.0967	8.7372	0.0027*
NL	4	1.9853	0.1729	1.0849	0.4145

Table A8: ANOVA of the effect of mulching treatments on aggregate stability classes and MWD of a loam and sandy loam soil after a two-year period. Asterisks (**) indicates significance.

		DBN		PTA	
	DF	F-value	Prob>F	F-value	Prob>F
> 2000 µm	4	9.1450	0.0022**	5.7077	0.0117*
2000 - 1000 µm	4	3.9992	0.0343**	3.3731	0.0541
1000 - 500 µm	4	0.3930	0.8092	1.1738	0.3790
500 - 250 µm	4	1.1410	0.3918	1.5499	0.2612
250 - 53 µm	4	2.2996	0.1302	11.1838	0.0010**
< 53 µm	4	0.9354	0.4819	1.3117	0.3303
MWD	4	10.3720	0.0014**	2.1824	0.1445

Table A9: ANOVA of pore size distribution porosity classes of a sandy loam after a two-year period. Asterisk (*) indicates significance.

		DBN		PTA	
	DF	F-value	Prob>F	F-value	Prob>F
< 50 µm	4	1.8405	0.1978	0.4892	0.7440
50 - 100 µm	4	4.2513	0.0289*	0.3347	0.8485
100 - 200 µm	4	5.5914	0.0125*	0.8243	0.5388
200 - 300 µm	4	2.0493	0.1630	0.9872	0.4574
300 - 400 µm	4	0.5470	0.7061	0.9449	0.4773
400 - 500 µm	4	2.3441	0.1252	1.7134	0.2231
> 500	4	0.6551	0.6366	6.0073	0.0099*
Total porosity	4	0.6456	0.6425	5.9282	0.0104*

Table A10: ANOVA of pore size distribution frequency classes of a sandy loam after a two-year period. Asterisk (*) indicates significance.

		DBN		PTA	
	DF	F-value	Prob>F	F-value	Prob>F
< 50 µm	4	0.7341	0.5893	0.7068	0.6053
50 - 100 µm	4	0.2324	0.9138	0.4766	0.7525
100 - 200 µm	4	0.2059	0.9293	0.9994	0.4518
200 - 300 µm	4	0.2090	0.9275	1.4607	0.2850
300 - 400 µm	4	0.2911	0.8775	1.2776	0.3416
400 - 500 µm	4	0.2662	0.8931	1.2710	0.3439
> 500	4	0.5904	0.6774	0.8130	0.5449
Sum of Pores	4	0.5391	0.7108	0.8409	0.5299

Table A11: ANOVA of aggregate pore shape of a sandy loam and loam soil

		DBN		PTA	
	DF	F-value	Prob>F	F-value	Prob>F
S ≤ 0.2	4	0.4069	0.7998	0.9848	0.4585
0.2 < S < 0.05	4	0.7372	0.5875	2.0549	0.1622
S ≥ 0.05	4	2.2864	0.1317	2.0701	0.1599

APPENDIX B: Innovative and Pro-Smallholder Farmer's Permanent Mulch for Better Soil Quality and Food Security Under Conservation Agriculture.

agronomy

MDPI

Communication

Innovative Pro-Smallholder Farmers' Permanent Mulch for Better Soil Quality and Food Security Under Conservation Agriculture

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Abstract: Soil degradation is the greatest threat to agricultural production globally. The practice of applying or retaining crop residues in the field as mulch is imperative to prevent soil erosion, maintain soil quality and improve crop productivity. However, smallholder farmers resort to maximizing profit by removing crop residues after harvest to sell or use them as feed for livestock. Agrimats are innovative pro-smallholder farming mulching materials that are manufactured using cheap or freely available organic waste materials. These materials include forestry waste, grasses, etc., therefore allowing smallholder farmers to make more profit through improved crop productivity for better food security. The most notable attributes of agrimats include their ability to prevent soil erosion, increase and sustain soil organic matter, suppress weeds, and conserve soil moisture. Food security challenge can be addressed by adopting agrimat technology as a sustainable permanent soil cover to improve soil quality and crop productivity. Agrimat incorporation in conservation agriculture practice could produce more food from less input resources (chemical fertilizers, water, etc.) with minimal or no adverse effect on the environment. This study aims to advocate permanent soil cover using agrimat as an innovative pro-smallholder farmer technology to improve soil quality for better food security.

Keywords: smallholder-farmers; agrimat; conservation agriculture; soil quality; food security

1. Introduction

The current global estimates indicate that about 80% of agricultural land suffers moderate to severe erosion [1]. Moreover, approximately 30% of the world's cropland has become unproductive and abandoned due to soil erosion [2], leading to one in every nine persons in the world being food-insecure [3] and about 66% of the global population being malnourished [1]. Ample evidence is available in literature on the perils of soil erosion as a significant threat to agricultural production more especially in semi-arid regions [4,5]. Sustainable land management strategies such as conservation agriculture (CA) have been identified and adopted in other parts of the world to prevent soil erosion, improve soil quality, conserve soil moisture and preserve the environment but most importantly, to match food production with the increasing world population [6–8]. A management system is considered to be CA if it consists of the following three principles; (i) permanent soil cover through crop residues or mulch, (ii) minimum soil disturbance or no tillage, and (iii) crop diversification through crop rotation and/or cover crops [6,7].

Mulch is categorized as inorganic or organic with the latter being more commonly favored due to its biodegradable nature [5]. The inorganic types (gravel, polyethylene plastics, pebbles, etc.) of mulching material in agriculture are used mainly to control soil erosion and moderate soil moisture and temperatures, thereby increasing crop yield [9,10]. On the other hand, organic mulching materials (crop straw, grasses, sawdust, etc.) improve soil quality i.e., physical, chemical and biological characteristics by adding organic matter into the soil during the decomposition process [11]. The practice of applying or retaining crop residues in the field as mulch after harvest is imperative in maintaining soil health and productivity [7]. Permanent soil cover though mulching helps to reduce run-off by dissipating raindrop impact on the soil surface, thereby reducing soil erosion. Mango et al. [12] states that "Minimum soil disturbance and permanent soil cover help in improving soil organic matter content, reducing water run-off leading to increased infiltration, as well as increased biological activity". However, organic waste material applied as mulch in the field can be easily washed or carried away by adverse weather conditions (high wind speed and high-intensity rainfall) in semi-arid regions [13]. Thereby leaving the soil prone to (i) rain drop impact, which leads to soil erosion through runoff, (ii) high rates of evaporation due to high temperatures and (iii) poorly aerated soils because of low organic matter content in the soil. In addition, smallholder farmers practicing in sub-Saharan Africa (SSA) especially under semi-arid regions resort to maximizing profit by removing crop residues after harvest to sell or use them as feed for livestock, a practice that has led to poor adoption of CA in sub-Saharan Africa [14–16].

To address the problem of loose biological waste materials being easily washed away by adverse weather conditions, Onwona-Agyeman et al. [13] used a pressurized steam and compression technology to produce stable mulching materials called agrimats from forestry residues and placed them in gentle and steep slopes in the field. The results from the study by Onwona-Agyeman et al. [13] indicated that agrimats can reduce soil erosion by 94.4% and 92.3% on steep (30°) and gentle (5°) slopes respectively. Moreover, agrimats absorb and retain more moisture (67–77%) for up to two days. Agrimats are manufactured using cheap or freely available organic waste materials such as grass or weed biomass, municipal sewage sludge, algae residues, bagasse and forestry waste (thinned logs, woodchips, sawdust etc.) and therefore allow farmers to make more profit from selling crop residues after harvest as livestock feed or fuel [13].

This research study attempts to answer the following research questions: what is the best way to effectively use different and freely available organic materials as mulch to combat pervasive soil erosion, increase soil quality, improve crop productivity and food security with the minimum effects on the environment? What are the main challenges that prevent smallholder farmers from adopting conservation agriculture? Google scholar was used as a search engine to gather different scientific papers published over the past 20 years on the similar subject. Soil erosion, soil quality, permanent soil cover, agrimat, conservation agriculture, organic matter, crop productivity and food security were used as key words in the search engine to find relevant articles. The aim of this study is to assess the status of soil erosion and address it using CA as a conservation technique with more focus on permanent soil cover (agrimat), which improves soil quality for better, sustainable crop production, and food security.

2. Soil Degradation: The Biggest Threat in Agriculture

Soil degradation is a global challenge that threatens agricultural food production and food security [17]. According to Vaezi et al. [18], soil degradation is a consequence of the bare or scarcely covered soils in semi-arid lands. They further stated that "Approximately 40% of the world's land surface is classified as arid or semi-arid regions. About 35% of the lands in semi-arid areas are used for agricultural purposes." The decline in soil organic matter content due to drought and traditional agronomic practices employed by smallholder farmers has led to significant soil degradation in semi-arid parts of Southern Africa [18]. In South Africa alone, the changes in soil fertility status and quality (loss of soil organic matter, declining N, soil acidity, expanding extent of saline and alkaline areas, soil acidity etc.) over the past three decades are worrying [19]. Moreover, South African soils are naturally very low in soil organic matter (SOM) content, with about 60% of the soils estimated to contain less than 0.05% SOM [20]. This could be the reason why over 70% of South Africa's land surface has been affected by varying intensities and types of soil erosion [21]. Although South Africa has various agro-ecological areas, it is generally classified as semi-arid region or water scare country since it receives less than 500 mm of rainfall per year on average [15]. Soil erosion through runoff and loss of soil moisture and sediments are the leading causes of soil degradation more especially in semi-arid regions [13,22]. According to Mohamadi and Kavian [23], soil erosion is an extremely dynamic and complicated process that is influenced by many factors, which include the topographic position of a slope, vegetation and soil type. Soil erosion occurs when raindrop kinetic energy overcomes the bonds holding soil particles together in the soil surface. The kinetic energy impact of raindrops on soil surface in high intensity storms causes increased soil particle detachment and sediment loss, excess runoff and surface sealing [23]. According to Khan et al. [24], the triggering of this process is related to slope, rainfall intensity and surface cover. The detached soil particles are transported away from the site of drop impact through runoff, which exacerbates land degradation [1,5]. Runoff is the principal erosive agent in water erosion processes that results in the loss of valuable plant nutrients together with soil sediments as well as soil water necessary for food production [2].

Figure 1, demonstrates the importance of leaving crop residues in the field under no-tillage systems in order to combat the devastating effect of soil erosion through runoff. The authors state that runoff rates were three to four times lower with a 50% reduction in sediment loss under a no-tillage system containing 50% residues compared to conventional tillage at the end of rainfall simulation events in the experiment shown in Figure 1. The soils (Regosols, Vertisols, and Calcisols) in the site where the experiment was conducted had poor physical and structural properties and were low in organic matter, which made them susceptible to both wind and water erosion. Moreover, the area is classified as an arid environment [22]. Figure 1 indicates that runoff is further exacerbated by increases in rainfall intensity. These results are in line with findings by Khan et al. [24], who reported an increase in sediment and water loss with an increase in rainfall intensity and slope steepness, in a laboratory experiment conducted under rainfall simulation using Calcaric Regosols. Xin et al. [25] also conducted a laboratory rainfall simulation experiment using black soils (Udic Argiboroll) at 7% fixed slope, five levels of residue cover (bare, 15%, 35%, 55%, and 75%) and four rainfall intensities (30 mm/h, 60 mm/h, 90 mm/h, and 120 mm/h). Their results indicated that residue cover strongly affects runoff, soil loss and infiltration. The authors reported that "The mean runoff reductions were 30.3%, 37.1%, 56.8%, and 72% for the 15%, 35%, 55%, and 75% residue covers compared to bare soil, respectively. The mean soil loss reductions were 41.5%, 58%, 89%, and 96% for the 15%, 35%, 55%, and 75% residue covers, respectively. When the rainfall intensity was higher, the protection effectiveness of the residues was weakened".

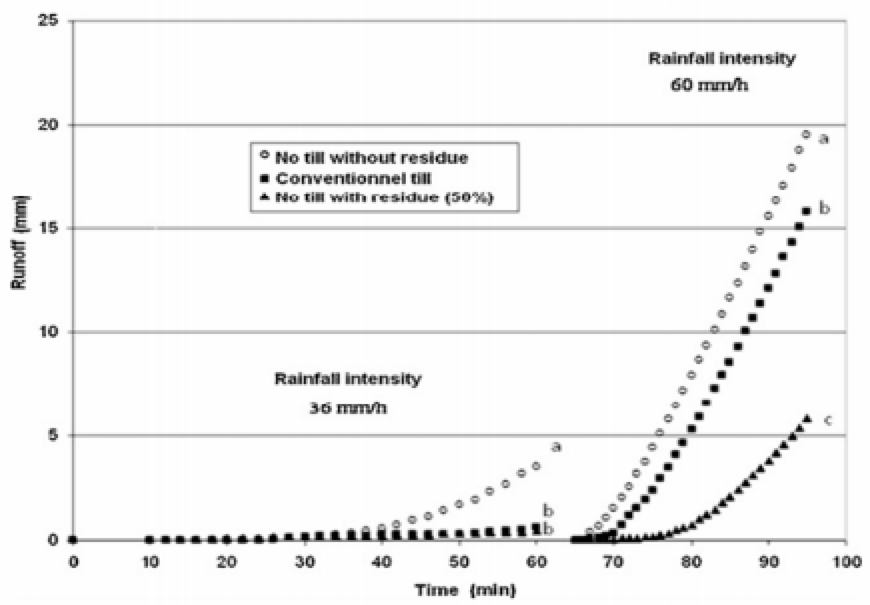

Figure 1. Runoff loss as affected by conventional tillage and no tillage with or without residue removal under two rainfall intensities in Zaers region [22].

Globally, erosion rates range from a low 0.001 t/ha/year on relatively flat land with grass or forest cover, to rates ranging from 1 to 5 t/ha/year in mountainous regions with natural vegetation. In croplands, however, global estimates for soil erosion ranges from 0.5 to 400 tons/ha/year and averages to approximately 30 tons/ha/year [1]. The numerous soil problems are further exacerbated by the seasonality and erratic distribution of rainfall, which results in varying periods of dry spells separated by wet periods [26]. Soil erosion and soil moisture loss are two major issues that need serious consideration when dealing with degraded soils especially in semi-arid regions as well as projects attempting to rehabilitate deserted or abandoned lands [13]. The loss of soil sediments (fertile top soil) together with runoff water is attributed to unstable soil structure due to drought and mostly, to erratic or erosive rainfall caused by climate change. Thierfelder et al. [18] states that "Conservation Agriculture (CA) is a key approach to address declining soil fertility and the adverse effects of climate change in southern Africa, however, CA alone is often not enough, and complementary practices and enablers are required to make CA systems more functional for smallholder farmers in the short and longer term."

3. Conservation Agriculture (CA) for Improved and Sustained Soil Quality, Crop Production and Food Security

Out of the global land mass of 13.2 billion ha, only 1.6 billion ha is currently in use for the cultivation of agricultural crops. Global population is projected to reach about 8.5 billion by 2030 and therefore an additional cropland of 81 to 147 million ha will be needed to meet global food demands [4]. Food and Agricultural organisation (FAO) estimates that by 2050, the demand of new croplands due to population pressure (of about 9.5 billion people), diet change and demand for biofuels is expected to reach approximately 3.2 billion ha, mostly at the expense of grasslands, forests and rangeland ecosystems. Shahid and Al-Shankiti. [27] further states that "By 2050, rising population and incomes are expected to result in a 70 percent increase in global demand for agricultural production". Gomiero [4] warns, "Concerning the future, we must take into account the potential effect of climate change on soils and agriculture". On the other hand, it is also important to consider the impact that agriculture and soils have on climate change and global warming because current estimates indicate that 10–12% of global anthropogenic greenhouse gas emission are attributed to agriculture [28].

So how can the world produce enough food to feed 9.5 billion people in 2050 and achieve food and nutritional security with minimal or zero impact on climate change? Presenting during the Nobel Conference 54 held at Gustavus Adolphus College in Minnesota, USA, on the 2nd of October 2018, Rattan Lal stated that, inter alia, by "Increasing agronomic productivity from existing land, restoring degraded lands, enhancing biological nitrogen fixation by legumes and converting some agricultural land for nature conservancy without any conversion of natural land to agroecosystems, through eco-intensification and restoration of soil health". He defined eco-intensification as the strategy to produce more food from less land, per drop of water, per unit of input fertilizers and pesticides, per unit of energy, and per unit of carbon emission. Shahid and Al-Shankiti. [27] assert that, "Increased production is projected to come primarily from intensification on existing cultivated land, or on improving marginal lands, with irrigation playing a key role". The approach suggested by Rattan Lal can be achieved by employing proven and practical climate-smart agriculture techniques such as conservation agriculture, improved water and nutrient management, integrated nutrient management, improved grazing, intercropping livestock management, etc. [27]. The practice of increasing agronomic productivity from existing land without any conversion of natural land to agroecosystems is key to preserving the soil organic matter content. According to Giller et al. [29], conversion of land from forest or grassland to agriculture rapidly increases the rate of decline in soil organic matter (SOM), with up to 50% of the SOM being lost within 10 to 15 years.

In addressing crop productivity and food security while protecting the resource base with minimal effect on the environment, the formulation for the combination of conservation techniques must be site specific and should strictly be used as recommendations in other areas where similar soils and environmental/climatic conditions may exist. Conservation agriculture is one of the effective and sustainable land management strategies falling under climate-smart agriculture that can be adopted to achieve eco-intensification and restore soil quality. As stated by Malobane et al. [30], conservation agriculture is an agricultural management practice promoted in many regions worldwide because of its ability to enhance soil quality while conserving natural resources with minimal negative impact to the environment". Integrated nutrient management is another climate-smart conservation technique that combines the use of both organic and inorganic sources to rebuild soil organic matter in nutrient depleted soils, improve soil quality, increase crop yield and protect the natural resource base [27].

3.1. The Effect of CA on Soil Quality

Soil quality is the capacity of a soil to function within ecosystem boundaries, sustain biological productivity, maintain environmental quality, and promote plant and animal health [8]. The beneficial effects of CA in terms of better soil quality are reflected through an improvement in soil organic carbon in the top 10 cm soil depth [7,31], enhanced water infiltration rate as indicated in Figure 2 [22,32], enhanced water holding capacity [11,22], lower bulk density [11,33], higher aggregates stability [7,33] and better soil structure [33]. For improved water infiltration and capture, SOM can be maintained by limiting soil aggregates and structure breakdown through tillage practices. The results in Figure 2 were obtained in an experiment conducted by He et al. [32] in the semi-arid south central Shanxi province of China under Chromic Cambisol (sand 23.1%, silt 43.3% and clay 33.6%). The area receives mean annual temperature and rainfall of 10.7 °C and 555 mm, respectively. The researchers reported that total infiltration under no-till (NT) was greater, and the final (steady state) infiltration rate for NT plots (17.0 mm.min^{-1}) was four times that of the conventional tillage (CT) plots (4.25 mm.min^{-1}). Figure 2 indicates that no-till practice enables the soil to significantly absorb more water volumes since it has a better infiltration rate compare with the soil under CT practices. These results are congruent with the findings by Wang et al. [34] who investigated the effects of wheat stubble and traditional ploughing on runoff, infiltration, and soil loss in laboratory plots under rainfall simulation using clay loam soil in

Yanglin, China. The treatments in this experiment comprised of wheat stubble cover and traditional ploughing using 80 mm ha^{-1} rainfall intensity for 1 h at three slope gradients (5°, 10°, and 15°). They found that the infiltration amount was higher under wheat stubble treatment (94.8–96.2%) than that from traditional ploughing (35.3–57.1%) and the trends were consistent at all three slopes. The practice of covering the soil surface using organic mulch suppresses runoff and increases the infiltration rate under various rainfall intensities more especially under no-till practice [6,25]. Conversion of conventional to conservation tillage, in line with the principles of CA, may improve soil structure, increase soil organic carbon, minimize soil erosion risk, conserves soil moisture, decrease fluctuations in soil temperature and enhance soil quality and its environmental regulatory capacity [6].

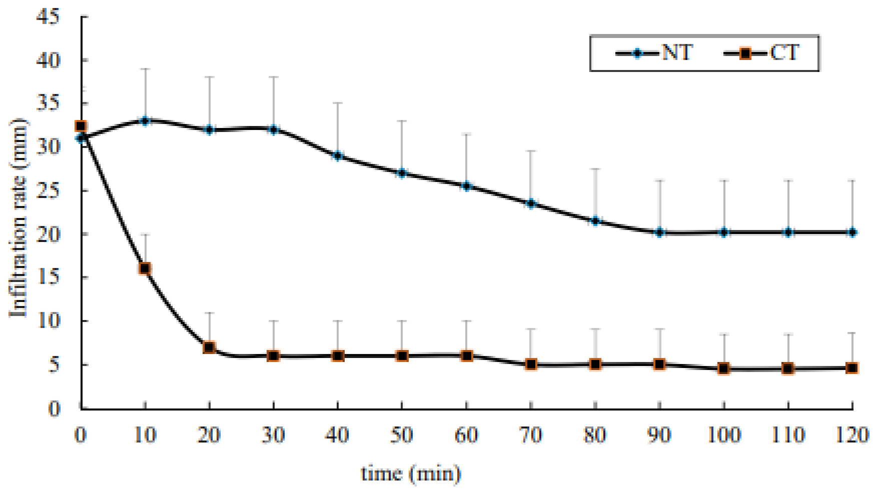

Figure 2. Changes in soil infiltration rate within 120 min under no tillage (NT) and conventional tillage (CT) treatments. LSD ($p < 0.05$). Redrawn from He et al. [32].

Figure 3, shows soil organic carbon content and bulk density in three different soil types (Vertisol, Cambisol and Luvisol) after 5 years under NT and CT treatments in a study conducted at the Merchouch Plateau in Morocco. The area is classified as a Mediterranean climate and receives a low average rainfall of 450 mm per year [31]. Contrary to many studies, the results shown in Figure 3 indicate that soil bulk density was significantly higher under CT in all three soil types after a period of five years compared to NT. This discrepancy can be explained using a statement from Castellini et al. [33] which says: "Several studies have found that implementation of NT results in over compaction of the soil but in other studies there was no significant soil compaction. In other words, when NT is used, soil compaction may still occur but this does not always cause a detrimental effect on crop production. In any case, its effect should always be assessed for a specific site, taking into consideration the type of agricultural cultivation and the soil types, as well as climatic condition". However, NT is an effective strategy in CA that can help to improve organic carbon (Figure 3) and carbon sequestration in the soil and ultimately reduce the negative impacts on climate [31,33]. In a study conducted by Dube et al. [7] on a Haplic Cambisol (62.4% sand, 16.0% silt, and 19.5% clay), it was demonstrated that in irrigated low-input systems as found in the Eastern Cape Province of South Africa, the levels of total SOM in the top 0–20 cm soil depth can be increased from as low as 10 g/kg to ranges above 20 g/kg after four years of CA. The site where this study was conducted is characterized by a warm temperate climate with average annual temperature and rainfall of 18.1 °C and 575 mm, respectively. SOM in the CA system is enhanced by the addition of mulch and/or the practice of leaving residues in the field as mulch, which, over time, decompose and increase the quality and overall fertility of the soil [7].

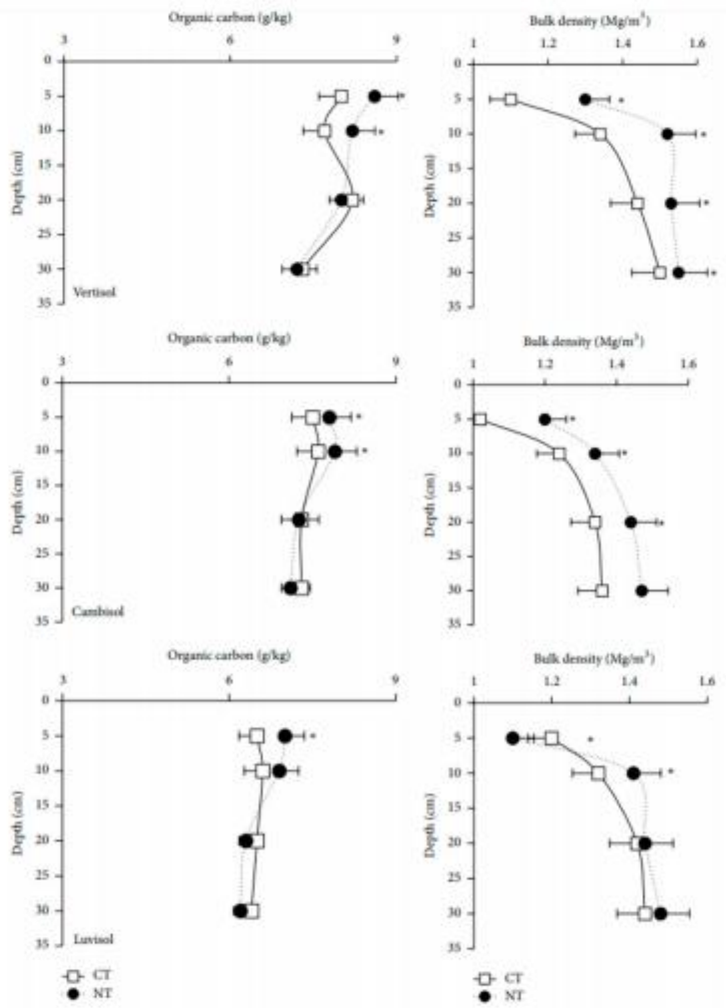

Figure 3. Soil organic carbon content (SOCc) and bulk density (Db) in three soil types after 5 years under NT and CT. At each depth (*) means the presence of significant differences between treatments ($p < 0.05$). The error bar represents one standard error [31].

In Rakai district, south central Uganda–an area dominated by Regosols (41.4%), Luvisols (22%) and Planosols (16.62%)–the decomposition of corn mulch that was applied at the thickness of 0.1 m by Kakaire et al. [35] resulted in 3.44%, 4.87% and 109.28% increase in field capacity (FC), permanent wilting point (PWP) and soil organic matter content, respectively. According to Kakaire et al. [35], in East Africa, especially in Uganda, Tanzania and Kenya, intercropping for green manure is rare because of the fear of competition for soil moisture. The disappearance of mulch on the soils has been worsened by human exports of crop residues, high termite activity and the long dry seasons. Reicosky. [36] state that "In all texture groups, as SOM content increased from 0.5 to 3%, available water capacity of the soil more than doubled. Increased water-holding capacity plus the increase in infiltration rate with higher SOM and decreased evaporation due to presence crop residues on the soil surface all contribute to improve crop water-use efficiency". Soil water is a solvent utilized by plants to carry essential nutrients and a principal constituent of the growing plant, which also regulates soil temperatures [37].

Microorganisms also require water and favorable soil temperatures for metabolism and other activities such as decomposition of organic matter [38]. Soil temperatures, moisture and aeration are all essential for healthy soil and are the main edaphic factors controlling soil respiration [39]. In addition, water and nutrient (especially phosphorus) uptake is limited at temperatures below 10 °C [15]. In the wake of global warming, organic mulch plays a crucial role in soil productivity by moderating soil temperatures [9,40]. The combination of mulch and NT plays a crucial role in combating climate change by sequestering more carbon in the soil with minimal emissions of CO_2 into the atmosphere. As indicated in Figure 4, NT emits significantly lower CO_2 compared to other tillage systems. The study was conducted in an arid environment in Morocco, on a site dominated by soils of poor or no profile development (Rogosols), dark cracking clays (Vertisols), and calcareous soil (Calcisols). In addition, the area is characterized with low mean annual precipitation and high rates of evapotranspiration [22]. According to Paustian et al. [41], improved soil management can substantially reduce greenhouse gas emissions and sequester some of the CO_2 removed from the atmosphere by plants, as carbon (C) in soil organic matter. More than 25% of the greenhouse gas emissions attributed to agriculture could be reduced by employing soil management strategies such as zero or no-till [6] and the addition of plant derived C external sources like compost or biochar. Paustian et al. [41] noted that both compost and biochar are more slowly decomposed compared to fresh plant residue, with compost typically having a mean residence time several times greater than un-composted organic matter, and biochar mineralizes 10–100 times more slowly than uncharred biomass. Thus, a large fraction of added C–particularly for biochar–can be retained in the soil over several decades or longer, although residence time vary depending on the amendment type, nutrient content and soil conditions (such as moisture, temperature and texture). According to Davidson and Janssens. [42], the production of CO_2 in soils is almost entirely from root respiration and microbial decomposition of organic matter. Conservation Agriculture (CA) is part of climate smart agriculture that can be used to address climate change issues [41]. Currently, CA is being promoted in many regions of the world [30] especially in semi-arid areas, to rehabilitate degraded soils and improve ecosystem services [43]. The beneficial effect of CA reflects not only in terms of increased crop productivity and labor saving but it also helps in achieving environmental sustainability beside soil and land regeneration [11].

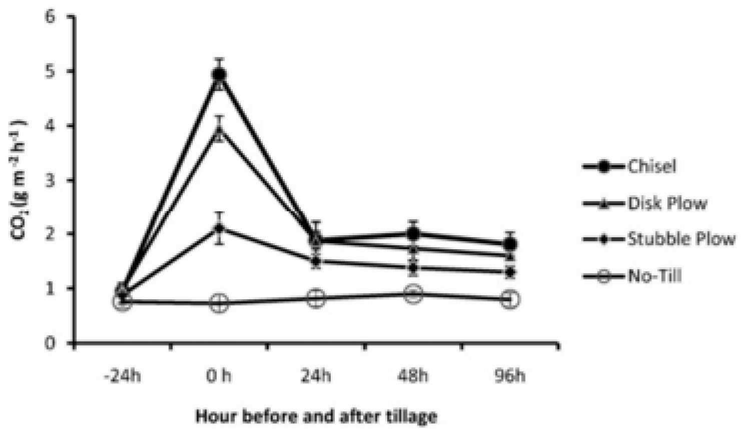

Figure 4. Soil CO_2 flux associated with primary full tillage as compared to no tillage (NT) systems [22].

3.2. The Role of CA in Crop Production and Food Security

The prevalence of undernourishment and food insecurity varies in different regions of the world. Currently, out of a world population of approximately 7.3 billion, about 66% of people are malnourished [1], with the majority of them located in sub-Saharan Africa and Asia [3]. In addition, The World Health Organization (WHO) and Food and Agricultural Organization (FAO) reports that one in every nine persons are food insecure. The mandate of FAO is to raise levels of nutrition, improve agricultural productivity to increase food security, better the lives of rural population and contribute to the growth of the world economy. Food security exists when all people at all times have physical, social and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active, healthy life [27].

Soil degradation especially through erosion has for a long time been a threat to food security since it reduces crop yields and causes soil abandonment in severe cases. The growing population further exacerbates soil degradation and this challenge needs to be addressed by focusing on increasing soil quality and soil sustainability so that the crop yields may be improved [11]. As stated by Yadav et al. [11], "Experts warn us that addressing the stagnating yields of our most important croplands is of paramount importance; failure to identify and alleviate the causes of yield stagnation, or reduction, will have a major impact on the future of global food security." Conservation agriculture (CA) is one of the climate-smart and sustainable land management strategies which helps to achieve eco-intensification and therefore increases global food security and nutrition [27]. The combination of CA principles can effectively improve soil quality; enhance food production and food security without any detrimental effects on the environment [30]. The goals of CA are to optimize crop productivity and farm income through maximum use of available resources and their effective recycling in the agroecosystem while arresting the adverse impacts on the environment [11]. In addition, CA is grounded in the principles of soil rejuvenation, envisioned to maximize the use efficiency of agricultural inputs e.g., seed, nutrient, water, energy, and labor, leading to higher profits to the grower [11]. However, in order for CA to work effectively in increasing crop production and hence reduce food insecurity, all the three principles of CA; 1, minimum soil disturbance; 2, permanent soil cover, and 3, crop rotation) must be followed first and performed properly [43].

The major challenge facing researchers and other proponents of CA is to convince smallholder farmers and other food producers to adopt CA as one of the effective techniques that helps to increase food security. Currently, the adoption rate of CA is very low, especially in Europe, Asia and Africa [7,11]. Out of the 1.6 billion ha currently in use for the cultivation of agricultural crops [18], CA occupies only approximately 156 million ha worldwide, increasing with the pace of 7 million ha annually mostly in the Americas [3]. Approximately 45% of the total area under CA is in South America, 32% in North America, 14% in Australia and New Zealand, 4% in Asia and 5% in the rest of the world including Europe and Africa. The top five pioneer countries leading the race in the adoption of CA are; United States of America (35 million ha), Brazil (31.8 million ha), Argentina (29 million ha), Canada (18.3 million ha) and Australia (17.6 million ha) [11]. In South Africa, the majority of farmers have not adopted CA yet, despite all its benefits. In the 2008/2009 planting season, only 7% of the total cultivated area was under no till [20]. Figure 5 show an estimate of the adoption status of CA in South Africa with Western Cape and Kwa-Zulu Natal provinces leading the race with more than 70% and 50–60% adoption rates, respectively. The areas with the lowest adoption rate of CA in the country include Springbokflats in the Limpopo province (10–20%), Eastern Cape province (approximately 5%), Easter Free State province (less than 5%), Orange River in the Northern Cape province (approximately 5%), and central Free State province (less 1%). Le Roux et al. [21] state that "at a scale of 1:2.5 million, Predicted Water Erosion Map (MWEP) indicates that a very large percentage of the Limpopo (60%) and Eastern Cape (56%) provinces are under severe threat to water erosion, whereas the Gauteng and North West provinces seem to be the least threatened by water erosion".

Figure 5. An estimate of CA adoption in South Africa [15].

Generally, the perils of soil erosion have led to soil loss from agroecosystems being 10–40 times faster than the processes of soil formation worldwide, exacerbating the problem of global food insecurity [1]. CA is among the top most effective and sustainable management strategies that prevent soil erosion, improve soil quality and conserve soil moisture but most importantly, to match food production with the increasing world population [7,8]. CA has the potential to significantly reduce soil erosion and improved land regeneration but all the three principles must be implemented in order for it to work effectively [11,43]. For instance, Giller et al. [14] state that "When no till is practiced in the absence of effective soil mulch cover, the effects can be disastrous with rapid surface sealing leading to increased run-off and accelerated soil erosion". On the other hand, researchers and other proponents of CA have failed to convince smallholder farmers and other poorly resourced food producers to adopt CA because they prioritize the use of crop residues for livestock feed rather than soil mulch cover and they prefer traditional tillage over no till for weed control purposes [14].

3.3. *Agrimats: The Innovative and Sustainable Mulching Materials*

Generally, mulch as a permanent soil cover decreases the effects of raindrop splashes on soil surfaces and hence slowing the detachment of soil particles and decrease the velocity of water on the soil surface [2,5]. Mrabet et al. [22] states that "Soil cover is the most important factor that influences water infiltration into the soil, thus reducing runoff and erosion." In addition, vegetation or canopy cover and plant residues protect the soil surface from water erosion by dissipating rainfall kinetic energy and therefore halt runoff and sediment loss [44]. The continuous accumulation of plant residues not only reduces runoff and erosion but also improves soil organic matter content, especially when adopted with minimum or no till and crop rotation as practiced in conservation agriculture [7,22]. Moreover, mulch conserve soil moisture by acting as a sediment trap that reduce surface runoff and enhance infiltration rate [5]. Dahiya et al. [45] conducted a field experiment to investigate the effect of straw mulch and tillage in soil water and temperature regimes on a silty loam Typic Hapludalf at the University of Hohenheim research center, Germany. They found that mulching decreased soil water loss on average by 0.39 mm per day, while rotary hoeing increased water loss on average by 0.12 mm per day compared with the control. In an experiment conducted by Alliaume et al. [46] in a Uruguayan sub-humid agro-ecological zone (with mean annual rainfall of 976 mm), in a with silty clay sub horizon and silty loam top soil, mulching increased water capture by 9.5% and reduced runoff by 37%. In addition, reduction of runoff, under reduced tillage mulch when compared with conventional tillage was 33%, 39% and 27% during the tomato, sweet maize and onion crop growing seasons, respectively [46]. This indicates that mulching, no-till or reduced tillage practices or CA in general should not only be limited to dry (arid and semi-arid) regions because soil erosion threatens agriculture across different agro-ecological areas. According to Dahiya et al. [45], the major advantage of maintaining crop residues in sub-humid and semi-arid regions, is improved soil and surface conditions that allow better water infiltration.

The extreme weather events such as floods due to aggressive hailstorms with high-wind speed as a result of climate change are causing not only damage to the crops in semi-arid areas but they wash away all the loose organic materials used as mulch, together with top fertile soil through run-off [13,47]. This challenge has led to many agricultural soils in semi-arid areas becoming prone to (i) rain drop impact, which leads to soil erosion through runoff, (ii) high rates of evaporation due to high temperatures and (iii) poorly aerated soils because of low organic matter content in the soil [13]. The effect of soil erosion and impact of adverse weather conditions on mulching materials used as permanent soil cover could be reduced even by poor resourced smallholder farmers practicing in semi-arid regions. Onwona-Agyeman et al. [13] proposed and used a pressurized steam and compression technology to produce mulching materials called agrimats from different types of organic waste materials. In an experiment conducted at Gifu University in Japan to study soil erosion, Onwona-Agyeman et al. [13] placed agrimats on gentle and steep slopes in the field and their results indicated that agrimats could reduce soil erosion by 94.4% and 92.3% on steep (30°) and gentle (5°) slopes, respectively. Although the paper by Onwona-Agyeman et al. [13] does not describe the climatic conditions and soil properties of the study site, the area received 254.3 mm of rainfall during the four-month period of the experiment. Agrimats are designed to withstand high-speed runoff water and blowing away by heavy storms and strong winds respectively, as typically experienced in semi-arid environments. In addition, the agrimats serve as an innovative permanent and sustainable soil cover that lasts for at least two years before they completely decompose into the soil [13]. However, extensive research is needed, especially in Southern Africa; to critically compare and contrast the effectiveness of agrimats to other traditional soil amendments and mulching methods (especially compost, manures and biochars) across different climatic conditions and soil types. The current study puts emphasis on dry areas since they are more susceptible to crop failure and food insecurity due to global climate change [4]. The low adoption rate of conservation agriculture (CA) in semi-arid areas by smallholder farmers is attributed to the prioritization of crop residues for livestock use rather than soil mulching [14]. Theirfelder et al. [48] states that "Although the practice of CA can provide many benefits for smallholder farmers in Southern Africa, large-scale spontaneous adoption has been hampered by a number of constraints. The constraints include trade-offs between residue retention and livestock feed in mixed crop-livestock systems".

3.4. The Role of Agrimats in the Adoption of CA

Conservation Agriculture (CA) is defined as a method of managing ecosystems for improved and sustained productivity, increased profits and food security while preserving and enhancing the resource base and the environment [6]. Several researchers have proved over years that permanent soil cover is one of the most effective practices in CA systems that help to increase soil organic matter [6,7,31]. Since soil is a living entity, organic matter is to the soil what a heart is to the body–without organic matter, soil is dead. Increase in soil organic matter promotes aggregation, pore geometry and stability of aggregates as it acts as a binding/cementing agent and most importantly, it improves soil fertility and overall quality of the soil [7,49]. However, the major constraints keeping smallholder farmers from leaving and/or applying crop residues in the field as permanent soil cover is the prioritization of using crop residues to feed livestock instead of for mulching [14].

Agrimats could prove a viable option even for farmers who want to maximize profit since they are manufactured using freely available biomass instead of valuable crop residues that remain after grain harvest. Agrimats of various sizes and thicknesses are manufactured using forestry waste (thinned logs, woodchips, sawdust etc.) grass or weed biomass, municipal sewage sludge, algae residues, bagasse etc. [13]. Agrimats are laid out on top of the soil surface as organic mats or boards to serve as permanent soil cover that, inter alia, prevent soil erosion, preserve and increase soil moisture, moderate soil temperature regimes, improve soil quality and crop productivity as well as food security. However, it is important to note that other organic waste materials such as algae residues and municipal sewage sludge may contain high quantities of heavy metals that may pose hazards not only to crop growth but also to human health. Whilst preliminary work by Onwona-Agyeman et al. [13,50] has shown the advantages of agrimats over conventional mulch, extensive research is still needed to determine and quantify acceptable limits for the application of heavy metal containing organic materials in agricultural soils and how they can be incorporated into agrimat technology for better efficiency. In addition, the future research must also investigate the possibility of utilizing various weed materials classified as invasive species and/or allelopathic in different quantities together with environmentally friendly organic materials in the agrimat fabrication process. Future research will also need to look at the possibilities of reducing toxicity levels in heavy metals and the allelopathic effects of various organic materials using traditional methods such converting them into biochar or composting and innovative techniques prior to pressing them into agrimats. Moreover, future studies can investigate if the agrimats could prove a better and viable option for smallholder farmers as a soil conditioner compared to compost or traditional manures. Globally, there is dearth of information on how agrimats affect soil microbial population and activity, soil pH and other soil chemical properties including soil fertility in general, including in Japan where the agrimat mulching practice was first developed and tested. Onwona-Agyeman et al. [50] soaked urea-impregnated agrimats and compost-manufactured agrimats in water for 24 h and later found that urea-impregnated agrimats absorbed more water (77%) than the compost-manufactured agrimats (67%). Therefore, agrimats can also be used as a nitrogen use efficiency tool and provide a solution for semi-arid farmers weary of nitrogen fertilizers being lost through leaching as a result of erratic and erosive rainfall.

However, further field research is needed in the future to investigate the decomposition rates of agrimats made with various organic materials and how they influence soil biology (including soil microbial population and activity) and chemistry. Generally, the rate of decomposition and mineralization rate of any organic material is controlled by many factors, inter alia, soil moisture, soil microbial activity, temperature etc. [42,51]. Therefore, the utilization of agrimats may allow farmers to use their crop residues as livestock feed or sell them to other farmers for profit maximization. Several attempts by researchers to promote the adoption of CA to smallholder farmers in semi-arid regions has failed not only because of competition for crop residues, but also due to erratic and erosive hail storms that wash away loose organic mulching materials. In addition, the labor burden induced by no-tillage practice especially when herbicides are not used is unbearable for smallholder farmers. Rather, they believe that traditional tillage is a cost effective practice for weed control with minimal or no use of herbicides [14]. However, agrimats are an innovative technology that will eliminate not only the need to control weeds or use herbicides but also reduce the cost of irrigation in semi-arid regions where rainfall is scanty.

In addition, considering the physical status and durability of agrimats compared to loose organic residues, they can also be used to address the concerns pointed by Giller et al. [29], who stated that "retention of mulch is not always possible". They observed that in Mozambique, the mulch is often removed in a matter of weeks by termites. In such cases, agrimats mulching practice may delay the removal rate and allow the farmers more time to control termites effectively. Therefore, future research studies will look at the viability of injecting coated pesticides into the agrimats in order to minimize crop failure in areas with severe cases of termites and other pest/disease infestations. Although the agrimats serve as a permanent soil cover, they can be temporarily removed at planting to facilitate sowing and be laid back again on the soil surface after a week or so when the seedlings have fully developed. Currently, the most effective method is to place the agrimats between the rows of growing seeding to cover the entire soil surface irrespective of inter-row plant spacing. This method does not only prevent water loss through evaporation from the soil surface but suppress weed growth below the agrimats as they act as a firm protective soil cover. Onwona-Agyeman et al. [13] states that "The use of agrimats as mulch could reduce weed growth from 0.5 tons/ha/month to 0.05 ton/ha/month". Moreover, "agrimats absorb and retain more moisture (about 70%) for up to 24 h". Despite all the benefits highlighted in this communication, one of the most important factors that is likely to influence the adoption of the agrimats is the economic viability of using agrimats versus prevailing practices. Extensive feasibility studies with the active participation of smallholder farmers still needs to be done to ascertain the costs of purchasing the agrimats and whether farmers are willing to take up this technology.

4. Conclusions

Soil erosion is a global phenomenon that negatively affects human health and environmental quality more especially in semi-arid regions. The combination of CA principles can effectively improve soil quality; enhance food production and food security with little or no detrimental effects on the environment and human health. No till is an effective strategy in CA that helps to maintain organic carbon and carbon sequestered in the soil and ultimately reduce the negative impacts of climate change. Most importantly, mulching is a practice that maintains and improves soil organic matter in the soil especially under CA systems. Although many farmers resort to maximizing profit by selling crop residues, or using them as livestock feed instead of leaving or applying them as mulch for soil organic matter improvements, the findings of this communication indicate that agrimat mulch could be employed by poor resource smallholder farmers as an alternative to their valuable crop residues. Agrimats are an innovative, sustainable and permanent soil cover mulching technology that promise to be a cost-effective option, which can be used to eliminate crop residue competition in the mixed crop-livestock systems since they are manufactured from freely available biological materials. In addition, agrimats eliminate, for smallholder farmers, the heavy burden of weed control and herbicide use when no tillage is employed and they reduce the cost of irrigation more especially in semi-arid areas where rainfall is scanty. However, more extensive research needs to be conducted to investigate several aspects of the agrimats for agricultural use and their efficiency over traditional mulching methods mostly in terms of cost effectiveness or economic viability, and to quantify the extent to which they can (i) improve soil quality (soil physical, chemical, and biological properties), (ii) enhance crop productivity (crop growth and biomass yields) in a sustainable manner and (iii) mitigate global food security especially for poor resource smallholder farmers in semi-arid or arid regions

In addressing crop productivity and food security while preserving the resource base with minimal effects on the environment, the conclusions and recommendations drawn from all future agrimat research work must be site-specific and should strictly be used as a guide for areas with similar soils and environmental/climatic conditions where the results will be obtained. Generally, global food security can be achieved by increasing agronomic productivity from existing land without any conversion of natural land to agroecosystems through eco-intensification and restoration of soil health. This includes the restoration of degraded lands through the incorporation of agrimats to CA systems, which employ biological nitrogen-fixing legumes in a rotation with other crops.

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