Manure and biochar effects on soil properties, in addition to crop growth and yield characteristics, with sweet sorghum as a test crop

by

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Declaration

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Summary

Manure use in smallholder farming is common in managing soil and crop productivity but consists of drawbacks like high greenhouse gas emissions and rapid mineralisation. Biochar is currently identified as a sustainable organic amendment that sustains soil and crop productivity, mainly because of its gradual mineralisation and recalcitrant carbon. Regardless of the growing global attention on biochar use, little is known about its effects on soil properties and sweet sorghum (*Sorghum bicolor* (L.) Moench) productivity. This study aimed at evaluating the best manure application management practices in smallholder farming and the potential of sole or co-applied biochar with manure in improving marginal soil functioning, and sweet sorghum performance. Specific objectives: (1) evaluate manure management practices that can best improve crop yields and soil fertility in smallholder farming by conducting a meta-analysis; and (2) evaluate the potential of sole or co-applied biochar with manure (cattle and kraal) on soil physicochemical properties and growth, yield and biofuel components of sweet sorghum. A meta-analysis containing 114 articles from sub-Saharan Africa was conducted to determine the best manure application rate, time, method, and manure type, on crop productivity (biomass and yield), and soil fertility. The findings showed that low and high application rates had the highest crop and biomass yields respectively, whereas all soil fertility parameters were highest with the medium rate except pH. On the application method, all yield and fertility parameters were highest when manure was incorporated than broadcasted. Crop yields did not show differences between application times, but biomass yield was highest when manure was applied before planting, while soil fertility properties were highest with the application before planting besides total nitrogen. Cattle and poultry manure had the highest crop and biomass yield, respectively. Goat manure had the highest total nitrogen and pH, whereas poultry manure had the highest increase in soil organic carbon, available phosphorus, and potassium. Overall, the meta-analysis revealed that if appropriate manure practices are utilised, farmers can optimise their soil and crop productivity. For the second objective, an experiment was conducted at Welgevallen Experimental Farm (Stellenbosch University) under two different fields (Field A and Field B) and a follow-up trial in Field A. We used a randomised complete block design with 6 treatments: control; cow manure; biochar; kraal manure; kraal manure and biochar; and cow manure and biochar. Results in Field A showed that sole biochar and sole kraal manure were significantly higher than the control and other treatments on various soil nutrients, while Field B was inconsistent. Despite no visible differences in growth traits, both co-applied biochar and manure treatments had the highest yield and biofuel traits, followed by sole biochar. Field B performed better than Field A on yield and biofuel components. The Field A follow-up trial decreased the sweet sorghum performance more than the primary trial, both co-applied biochar and manure treatments remained high on all sweet sorghum

performance. This objective generally verified that biochar and manure either applied individually or combined are valuable organic materials in modifying soil fertility and sweet sorghum production.

Opsomming

Die gebruik van veemis in kleinboerderye is algemeen in die bestuur van grond- en gewasproduktiwiteit, maar bestaan uit nadele soos hoë kweekhuisgasvrystellings en vinnige mineralisering. Biokool word tans geïdentifiseer as 'n volhoubare organiese wysiging wat grond- en gewasproduktiwiteit handhaaf, hoofsaaklik vanweë sy geleidelike mineralisering en weerspannig koolstof. Ongeag die groeiende wêreldwye aandag op biokool gebruik, is min bekend oor die uitwerking daarvan op grond eienskappe en soet sorghum (*Sorghum bicolor* (L.) Moench) produktiwiteit. Hierdie studie het ten doel gehad om die beste mistoedieningbestuurspraktyke in kleinboerderye te evalueer en die potensiaal van alleen- of saamtoegediende biokool met veemis om marginale grondfunksionering en soetsorghumprestasie te verbeter. Spesifieke doelwitte: (1) evalueer veemisbestuurspraktyke wat oesopbrengste en grondvrugbaarheid in kleinboerderye die beste kan verbeter deur ’n meta-analise uit te voer; en (2) die potensiaal van alleen- of saamtoegediende biokool met mis (beeste en kraal) op grond fisies-chemiese eienskappe en groei, opbrengs en biobrandstofkomponente van soetsorghum te evalueer. ’n Meta-analise wat 114 artikels van sub-Sahara Afrika, bevat is uitgevoer om die beste mistoedieningshoeveelheid, tyd, metode en mistipe, op gewasproduktiwiteit (biomassa en opbrengs), en grondvrugbaarheid te bepaal. Die bevindinge het getoon dat lae en hoë toedieningshoeveelhede die hoogste oes- en biomassa-opbrengste onderskeidelik gehad het, terwyl alle grondvrugbaarheidsparameters die hoogste was met die medium dosis behalwe pH. Op die toedieningsmetode was alle opbrengs- en vrugbaarheidsparameters die hoogste wanneer mis ingewerk is as wat uitgesaai is. Oesopbrengste het nie verskille tussen toedieningstye getoon nie, maar biomassa-opbrengs was die hoogste wanneer mis voor plant toegedien is, terwyl grondvrugbaarheidseienskappe die hoogste was met die toediening voor plant naas totale stikstof. Bees- en pluimveemis het onderskeidelik die hoogste oes- en biomassa-opbrengs gehad. Bokmis het die hoogste totale stikstof en pH gehad, terwyl pluimveemis die hoogste toename in grondorganiese koolstof, beskikbare fosfor en kalium gehad het. Oor die algemeen het die meta-analise aan die lig gebring dat indien toepaslike mispraktyke gebruik word, boere hul grond- en gewasproduktiwiteit kan optimaliseer. Vir die tweede doelwit is 'n eksperiment by Welgevallen Proefplaas (Universiteit Stellenbosch) uitgevoer onder twee verskillende velde (Veld A en Veld B) en 'n opvolgproef in Veld A. Ons het 'n ewekansige volledige blokontwerp met 6 behandelings gebruik: kontrole ; beesmis; biokool; kraalmis; kraalmis en biokool; en beesmis en biokool. Resultate in Veld A het getoon dat tongbiokool en tongkraalmis aansienlik hoër was as die kontrole en ander behandelings op verskeie grondvoedingstowwe, terwyl Veld B inkonsekwent was. Ten spyte van geen sigbare verskille in groei-eienskappe nie, het beide saamtoegediende biokool- en misbehandelings die hoogste opbrengs en biobrandstof-eienskappe gehad, gevolg deur enigste

biokool. Veld B het beter gevaar as Veld A ten opsigte van opbrengs en biobrandstofkomponente. Die Veld A-opvolgproef het die soetsorghumprestasie meer verlaag as die primêre proef, beide saamtoegediende biokool- en misbehandelings het hoog gebly op alle soetsorghumprestasie. Hierdie doelwit het oor die algemeen geverifieer dat biokool en mis, hetsy individueel of gekombineer, waardevolle organiese materiale is om grondvrugbaarheid en soetsorghumproduksie te verander.

Dedication

I dedicate this work to my Mum and my late Father.

Love not to sleep, lest thou come to poverty; open thine eyes, and thou shalt be satisfied with bread.

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Preface

This thesis is presented as a compilation of five (5) chapters. Each chapter is introduced separately and are all written according to the style of the South African Journal of Plant and Soil. Chapter 3 is submitted for publication to the journal Soil Use and Management.

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List of abbreviations and acronyms

ANOVA	Analysis of variance
Al	Aluminium
AP	Available Phosphorus
AS	Aggregate Stability
B Plots	Biochar Treatment Plots
B	Boron
BIS	Biofuel Industrial Strategy
BD	Bulk density
C	Carbon
Ca	Calcium
CCI	Chlorophyll Content Index
CEC	Cation Exchange Capacity
CH_4	Methane
CM Plots	Cattle Manure Treatment Plots
cm	centimetres
CMB Plots	Cattle Manure and Biochar Treatment Plots
cmol(+) kg^{-1}	centimoles per kilogram
C: N	Carbon: Nitrogen ratio
C:P	Carbon: Phosphorus ratio
Cu	Copper
CSY	Conservative Sugar Yield
DGW	Dried Grain Weight
DLW	Dried Leaves Weight
DLY	Dry Leaf Yield
DPW	Dried Panicles Weight
DSW	Dried Stalk Weight
DPY	Dry Panicle Yield
DSY	Dry Stalk Yield
Fe	Iron
FGW	Fresh Grain Weight
FLW	Fresh Leaves Weight
FPW	Fresh Panicles Weight
FSW	Fresh Stalk Weight
FSY	Fresh Stalk Yield

g cm^{-3}	grams per cubic centimetres
GHG	Greenhouse Gasses
g kg^{-1}	grams per kilograms
GW	Grain Weight
GY	Grain Yield
ha	hectares
JCY	Juice Yield
K	Potassium
kg	kilograms
kg ha^{-1}	kilograms per hectares
kg m^{-3}	kilograms per cubic meters
KM Plots	Kraal Manure Treatment Plots
KMB Plots	Kraal Manure and Biochar Treatment Plots
L ha^{-1}	litres per hectare
LAI	Leaf Area Index
LN	Leaf Number
m	meters
m^2	meters squared
Mg	Magnesium
mL	millilitres
mg kg^{-1}	milligrams per kilograms
mm	millimetres
mmol kg^{-1}	millimoles per kilograms
Mn	Manganese
MWD	Mean Weight Diameter
MC	Moisture Content
Mo	Molybdenum
N	Nitrogen
Na	Sodium
NO^{3-}	Nitrate
N_2O	Nitrous Oxide
NH^{4+}	Ammonium
OC	Organic Carbon
OM	Organic Matter
P	Phosphorous

PAR	Photosynthetically Active Radiation
pH	potential hydrogen
PH	Plant Height
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-analyses
RCBD	Randomised Complete Block Design
REML	Residual Maximum Likelihood
S	Sulphur
SA	South Africa
SD	Stem Diameter
SCJ	Sugar Concentration of Juice
SGY	Sugar Yield
SP	Soil Porosity
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
SSA	Sub-Saharan Africa
TC	Total Carbon
TDBY	Total Dry Biomass Yield
TEY	Theoretical Ethanol Yield
t ha^{-1}	tonnes per hectare
TN	Total Nitrogen
UN	United Nations
WAP	Weeks After Planting
WBP	Weeks Before Planting
WEF	Welgevallen Experimental Farm
Zn	Zinc

CHAPTER 1: General Introduction

1.1. Background

Soils in South Africa (SA) are severely degraded and are characterised by low soil nutrient composition, low soil organic matter (SOM), and are highly acidic (Nyambo *et al.*, 2018). This inevitably reduces soil and crop productivity, which consequently threatens food security (Fatondji and Ibrahim 2018). Raw (unprocessed) manure use in SA is a common practice in smallholder farming communities to manage soil fertility at minimal costs (Dzvene 2017; Ndukwe *et al.* 2021). Manure improves soil characteristics, including pH, electrical conductivity, organic carbon (OC), and plant nutrients (Mokgolo *et al.* 2019). The preferred use of manure in these farming systems is due to its availability and accessibility compared to synthetic fertilisers. However, while the vital role of manure in managing soil fertility has been documented in SA (Dzvene 2017; Mokgolo *et al.* 2019; Ndambi *et al.* 2019), manure is associated with certain demerits, mainly its rapid decomposition due to its labile OC, which determines how it sustains soil and crop productivity (Nyambo *et al.*, 2018). Therefore, different technologies such as biochar are being recommended for soil improvement and crop productivity as opposed to raw manure.

Biochar is defined as a stable carbon compound produced from organic materials burnt at high temperatures (300-800 $^{\circ}$C) under limited oxygen supply in a process termed "pyrolysis" (Yu *et al.*, 2019). Biochar is attracting a considerable amount of attention globally because of its recalcitrant OC, which decomposes gradually (Castellini *et al.* 2015), and becomes a more stable solid over ordinary manure. Evidence from carbon dating suggests that biochar can remain in the soil for millennia (Lehmann *et al.*, 2011). Generally, biochar has a positive influence on hydraulic, biological, physical, and chemical properties of soil (Nyambo *et al.*, 2018). Benefits of biochar to soil are attributed to its high OC content, large surface area, a porous structure, and a negatively charged surface with high charge density (Castellini *et al.* 2015), which are attributed to feedstock (type of organic material used to produce the biochar) and the pyrolysis conditions (Dodor *et al.* 2019).

Additionally, the beneficial effects of biochar may vary with soil type and conditions. Data existing on positive effects of biochar have been largely observed on marginal soils, especially acidic (Hass *et al.* 2012; Nyambo *et al.* 2018) and sandy soils (Kavitha *et al.* 2018). For instance, Hass *et al.* (2012), reported an increase in soil pH by 7.8 % in highly weathered acidic soil after adding chicken manure biochar at 40 g kg^{-1}. Likewise, Nyambo *et al.* (2018) observed a similar trend in acidic soil after maize residue biochar was incorporated. Głąb *et al.* (2016) observed a significant increase in physical properties in sandy soil following the addition of wheat and miscanthus straw biochar.

Agbede *et al.* (2020) also observed a similar increase in physicochemical properties of sandy soil, which in turn promoted cocoyam yield after the addition of hardwood biochar. Therefore, these predominant abilities of biochar indicate its crucial role in remediating poor soils. This study focuses on the effect of incorporating biochar in marginal soils to observe the productivity of sweet sorghum (*Sorghum bicolor* (L.) Moench).

Sweet sorghum is one of the various sorghum varieties indigenous to Africa and is mainly cultivated by smallholder farmers (Malobane *et al.*, 2020). Sorghum ranks 4th globally in production after maize, wheat, and rice among cereals. Sudan and Nigeria are major producers of sorghum in Africa, with more than 6 million ha in production area (Nasidi *et al.* 2019), while SA's production area is around 0.12 million ha (Woods 2001). Like other sorghum varieties, sweet sorghum is primarily produced for biofuel, and secondarily for food, grain and fodder. Sorghum varieties are cultivated under marginal conditions, inherently affected by poor climate and low soil fertility (Olugbemi *et al.* 2018). Due to the increasing demand for food and raw materials, sweet sorghum can be a viable option for improving food security and poverty alleviation in subsistence farming (Nasidi *et al.* 2019; Motsi *et al.* 2022).

In addition to the potential of sweet sorghum for biofuel production, it is a suitable feedstock option due to its greater advantages over other feedstocks (Naoura *et al.* 2020). The South African Biofuel Industrial Strategy, BIS) considered first-generation feedstocks that consist of sugarcane, soybeans, sunflower, and oil seeds, but excluded sweet sorghum. These crops require highly intensive input, such as high fertiliser doses and irrigation, and require labour-intensive crop residue removal. This confronts the BSI aim of elevating rural livelihoods due to insufficient resources by these farmers, and these practices can be detrimental to soil and the surrounding environment. Also, these crops (sugarcane, soybeans, oil seeds, and sunflower) may fail to address the "food and fuel" strife (Malobane *et al.* 2018). Therefore, sweet sorghum may address these disadvantages of other biofuel feedstocks due to its robustness (Malobane *et al.* 2020). As such, as a neglected crop, research on sweet sorghum is currently gaining momentum along its value chain and it is, therefore, necessary to investigate how yields can be improved.

In places where the evaluation of sweet sorghum is at peak, a consensus is yet to be reached on the appropriate harvesting stage which can optimise both the grain and ethanol yield. This is crucial because sweet sorghum is a multipurpose crop in which farmers benefit grains for food security and ethanol for energy, while the remaining stover is utilised as animal feed (Teixeira et al. 2017). The perfect harvest timing minimises both grain and ethanol yield losses, thus optimising both end products of interest. However, in literature the information is scanty under two dimensions on this aspect. Firstly, numerous studies evaluating sweet sorghum's potential give their attention only on bioethanol traits, neglecting the grain yield (Olugbemi and Abiola Ababyomi 2016; Teetor et al. 2017; Olugbemi et al. 2018; Maw et al. 2019). Secondly, studies which seeks to evaluate both ethanol and grain yield do not consider harvest stages to determine at what period farmers can harvest for both ethanol and grain yield when they are optimum (Erickson et al. 2011; Upadhyaya et al. 2014; Briand et al. 2018; Naoura et al. 2020). Thus, the current study evaluated the last four weeks to determine both the yield and bioethanol qualities.

1.2. Problem statement and justification

Despite the benefits of manure in replacing inorganic fertiliser and improving soil fertility and SOM in smallholder farming, manure is underutilised and its rapid mineralisation after addition to soil remains a doubt in its long-term sustainability of soil fertility and SOM. Mineralisation rate depends on the strength of carbon contained in organic material which is also based on the extent of utilisation by microorganisms. Additionally, the continuous application of greater amounts of manure together with their rate of decomposition may also lead to intensified greenhouse gas emissions. In the long run, manure with its high decomposition rate reduces its stabilization of soil OC, reducing the capacity to sustain soil fertility and SOM. Therefore, in consideration of such limitations, there is a need to recognise other available options of soil organic materials which can perform better beyond manure in terms of sustaining soil properties, especially those with recalcitrant OC that cannot simply be exploited by soil microbes, and with a slow turnover rate.

The pyrolysis process can be a dynamic alternative to counteract the rapid decomposition of manure, therefore, guaranteeing sustainable soil fertility and SOM management. Biochar decomposes gradually due to its recalcitrant OC, which ensures a continuous supply of necessary functions to the soil for the long term. Biochar technology can be easily adopted by rural farmers and the process of making biochar is not difficult for farmers to adopt. Studying neglected crops like sweet sorghum is important due to their adaptability and contribution to nutritional, economic and energy needs of subsistence farmers. In addition, little is known about the best harvesting time for optimum grain and ethanol yield, since grain yield increase towards maturity whereas ethanol yield declines. Therefore, it will be interesting to investigate how biochar technology can improve soil fertility and sweet sorghum productivity under smallholder farmers of South Africa.

1.3. Aims and objectives

The aim of this study was to evaluate manure application management practices and to investigate the potential of biochar either solely or co-applied with manure (cattle and kraal) in improving marginal soil functioning, focusing on fertility and physical soil properties for crop growth using sweet sorghum (*Sorghum bicolor* (L.) Moench) as a case study. The specific objectives of the study were to:

1. Evaluate manure management practices which can best improve crop yields and soil fertility in smallholder farming systems by conducting a meta-analysis (Chapter 3).
2. Evaluate the effect of biochar either applied alone or applied co-applied with manure (cattle and kraal) on soil physicochemical properties and crop growth, phenological, yield and biofuel components as well as the harvesting stages of sweet sorghum (*Sorghum bicolor* (L.) Moench) (Chapter 4).

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CHAPTER 2: Literature Review

2.1. Manure and its significance in smallholder farming

2.1.1. Manure use and its effects on soil and crop productivity

Despite efforts in introducing inorganic fertiliser globally to enhance the challenge of soil fertility, smallholder farmers in SSA continue to be lagging behind in adoption (Fatondji and Ibrahim 2018). Fertiliser application in this region continues to be relatively less than 10 kg ha^{-1} in comparison to higher amounts applied in other regions (Berge *et al.* 2019; Ndambi *et al.* 2019). As an alternative, animal manure is used as a source of nutrients to supplement soil fertility and, in due course, crop productivity in this region (Githongo *et al.* 2021). Mixed crop-livestock agriculture has been practiced since ancient times, and thus livestock manure plays a significant role in improving soil fertility and crop production, whilst crop residues collected after harvesting are fed to livestock (Ayantunde *et al.* 2018; Ndambi *et al.* 2019). This in turn decreases external inputs requirements.

Manure is a prominent source of organic matter (OM) and a source and sink of crop nutrients. The mineralisation of manure releases essential macro- and micronutrients important for crop productivity mostly N, P and K (Musumuvhi 2018). Earlier on, Bayu *et al.* (2005) reported that generally the addition of 3 t ha^{-1} of dried manure can add 35-82 kg N, 7-21 kg P, 32-163 kg K, 30-74 kg Ca, 10-37 kg Mg, 11-67 kg Fe, 0.8-5.7 kg Mn, 0.02-0.26 kg Cu and 0.15-0.65 kg Zn per hectare per year. Sileshi *et al.* (2019) also reported that 10 t ha^{-1} of cattle manure can supply 127 kg N, 50 kg P, 150 kg K, 7 kg S, 70 kg Ca and 44 kg what? per hectare per year. These nutrient compositions may vary with animal type, feeding habits, application practices and storage of the manure. Unlike inorganic fertilisers, manure releases these nutrients in a manner that reduces possibility of leaching, thus enhancing soil fertility retention (Adekiya and Agbede 2017). Manure also adds and sequesters organic carbon (OC) which is important for improving soil strength and supplying energy for soil microorganisms which are important in numerous soil processes (Githongo *et al.* 2021).

The addition of manure has also proved to have positive influence on physical soil properties through enhancing the organic matter (OM) composition either by adding the OM it contains or reducing its loss (Ayantunde *et al.* 2018). Manure improves soil aggregate stability which in turn improves soil macro structure, hydraulic conductivity, infiltration, water holding capacity and ultimately water retention. Additionally, increased aggregate stability after the addition of manure facilitates pore volume and size distribution and reduces bulk density and soil crusting. The application of manure also increases soil pH due to numerous mechanisms. Manure contains alkali cations which are basic in nature, and, during decomposition, these cations are released into soil and increase pH. The increase in soil pH prevents the masking of crucial nutrients such as P from Al and Fe, therefore improving nutrient availability (Adekiya and Agbede 2017). Also, ion exchange reactions occur between terminals of hydroxyl ions of Al^{3+} or Fe^{2+} and particular organic anions mineralised from manure, like citrate, malate and tartrate (Agbede *et al.* 2020a). Thus, manure has the potential to resolve some challenges of soil acidity, which is among the major bottlenecks in crop productivity globally and most critical in tropical regions (Fatondji and Ibrahim 2018). However, some manure types can reduce pH, for instance poultry manure may reduce soil pH which is alluded to high ammonium content. When the ammonium dissociates in solution, hydrogen ions are released which then increases acidity thereby reducing soil pH (Azeez and Van Averbeke 2010).

The nutrients released from manure stimulate vigorous plant growth which facilitates plant morphological features such as leaf area and leaf area index which improves dry matter production and ultimately yield (Musumuvhi 2018). Moreover, the enhancement of soil physical properties after manure application, such as a decrease in bulk density and increase in porosity is significant for root development and improves its activities of water and nutrient uptake. In literature, positive effects on crop growth and yield after manure addition have been documented in crops such as tomato (Adekiya and Agbede 2017; Chipomho *et al.* 2018), millet (Fatondji and Ibrahim 2018), sunflower (Mokgolo *et al.* 2019), spinach (Dikinya and Mufwanzala 2010), passion fruit (Ndukwe *et al.* 2021), ginger (Adekiya *et al.* 2020a), maize (Lyimo *et al.* 2012; Githongo *et al.* 2021), rice (Nguyen *et al.* 2018) and cocoyam (Agbede *et al.* 2020b). Therefore, manure in the soil ultimately improves crop growth and yield, which is derived from its ability to add soil nutrients and enhance various soil physicochemical properties (Ndambi *et al.* 2019).

Even though the significance of manure in improving crop nutrition and productivity in smallholder farming has been widely acknowledged by various scholars (Dikinya and Mufwanzala 2010; Adekiya and Agbede 2017; Fatondji and Ibrahim 2018; Ndambi *et al.* 2019; Ndukwe *et al.* 2021), farmers in this region continuously utilise manure irregularly. This is mostly visible in the final segment of manure application in the field, which includes application rates, application time, and application methods. Some of the major causes of these irregularities which are frequently highlighted in literature consist of insufficient manure availability, which is usually defined by herd size, intensive labour, transportation, improper grazing plots, lack of technical knowledge, and some socioeconomic attributes (Mkhabela 2007; Ndambi *et al.* 2019). These irregularities may ultimately threaten soil fertility and crop yields. In addition, the lack of proper grazing systems to feed the livestock has a negative influence on supporting and expanding livestock production in smallholder farmers, which in turn affects manure quality and quantity (Ayantunde *et al.* 2018). The situation is worsened during winter periods when there is limited rainfall.

2.1.2. Demerits of manure which necessitates utilisation of other organic amendments

Currently, sustainability is a "hot topic" in several fields of study and is particularly a high priority in agriculture. The sustainability of manure is compromised by certain factors which justify the consideration of other organic amendments or in combination with the manure. Manure can release greenhouse gasses (GHG), and the move to intensify manure production by improving livestock size can further intensify GHG release (Ayantunde *et al.* 2018). In Africa, manure releases about 45 % of GHG emissions mainly N_2O and CH_4 which are accounted from pasture lands and their management (Tongwane and Moeletsi 2018). In Niger, it has been reported that yearly N_2O emissions increased by 63 % when 8 t ha^{-1} of manure was added, while an increase of 44 % on average was observed in Zimbabwe with application rates that range between 15 to 30 t ha^{-1} (Sileshi *et al.* 2019). However, increasing livestock size in SSA has been suggested as a way of improving manure quantity but may jeopardise global efforts in reducing GHG emissions.

For manure to supply nutrients and enhance other soil properties, it must mineralise, but its mineralisation is rapid which may result in undesired consequences. It has been highlighted that manure is easily decomposed because of its low C: N ratio (Gross and Glaser 2021) and labile carbon which is easily utilised by soil microbes (Dzvene *et al.* 2019). Rapid release of manure may increase the chances of nutrient leaching, volatilisation, and denitrification. The decay series has been used as a significant tool in predicting manure decomposition patterns from the first year of application. In literature, some authors indicated the decay series for poultry manure as 0.90, 0.10, and 0.05, and for cow manure as 0.70, 0.15, 0.10, and 0.05 (Mkhabela 2007). This suggests that 90 and 70 % of N in poultry and cow manure respectively is released during the first year of application and little is released in subsequent years. Because of this high N release during the first application year, farmers must apply manure annually which continuously increases chances of GHG emissions and nutrient loss to the environment. This may also decrease the stabilisation of soil OC and its sustenance of soil fertility and soil organic matter (SOM). Thus, there is a need for considering other organic amendments which can sustain soil functioning better than manure while also being able to hold nutrients (Subedi *et al.* 2017).

2.2. Biochar

2.2.1. Biochar production and characteristics

Biochar is a carbon (C) rich product from the pyrolysis process whereby any organic material is burnt under elevated temperatures and limited or null oxygen conditions (Subedi *et al.* 2017). The organic materials, normally called "biochar feedstock" can originate from plant and agriculture residues, wood, animal manure, municipal waste, forest residues and industrial waste (Kavitha *et al.* 2018). During pyrolysis, various physicochemical transformations occur on biochar surfaces which defines the fate of biochar influence on soil properties (Zhang *et al.* 2021). Moisture and volatile materials are released through volatilisation, while ash content and fixed C is formed, which ultimately result in physicochemical rearrangement of biochar (Subedi *et al.* 2017). Thus, these physicochemical rearrangements make biochar unique from other organic materials.

Biochar has a large surface area and total pore volume which influences bulk density, root penetration, water retention, nutrient retention, microbial shelter, and heavy metals and toxic organic compounds adsorption (Ni *et al.* 2022). Functional groups on biochar surface significantly improve chemical attributes like alkalinity, pH buffering, surface charge, CEC, hydrophilicity and hydrophobicity (Subedi *et al.* 2017; Kavitha *et al.* 2018; Yu *et al.* 2019; Zhang *et al.* 2021). The alkalinity of biochar is a result of high ash content which increases at elevated temperatures, therefore, enriching biochar with basic metals (K, Ca, Mg, Na) (Muigai and Ravi 2021; Zhang *et al.* 2021). In addition, biochar fundamentally constitutes C, H, O and N as the major structural elements, with C as the primary building block representing more than 60 %, while other elements including P, Ca, Mg, K, S, Si, Fe, Mn, B, Zn and Cu are available in minor concentrations (Zhao *et al.* 2017; Yu *et al.* 2019; Zhang *et al.* 2021; Ni *et al.* 2022).

2.2.2. Effects of biochar in combination with manure on soil physicochemical properties

2.2.2.1. Effects on soil pH

The effects of biochar on soil pH are highly attributed to ash content that constitutes alkali metals (Ca, K, Mg, Na) and their respective oxides and carbonates which are formed during the pyrolysis process (Yu *et al.* 2019). The effects may also differ with feedstock type, and it has been noticed that manure derived biochar is superior in increasing soil pHcompared to wood-based biochar, which is attributable to high ash content in manure derived biochar (Nyambo *et al.* 2018). Thus, when biochar is added to soil, exchangeable acidity is reduced through reactions with H^+ and Al^{3+} (Yu *et al.* 2019). A substantial increase in soil pH following biochar application has mainly been witnessed in tropical soils which are highly acidic (Rollon *et al.* 2020; Zhang *et al.* 2021). For instance, Nyambo *et al.* (2018) observed that after 140 days of incubating maize cob biochar and tropical soil, pH was increased by 1.51, 1.12, 0.83, and 0.34 units at 10, 7.5, 5, and 2.5 % biochar application rates respectively from the control with pH 4.1. Also, effects of biochar may vary with soil texture. Dzvene *et al.* (2019) evaluated four different biochars on sandy loam and clay loam soils and observed that soil pH in sandy loam had an increase of 13.6 to 16.2 %, while clay loam had an increase of 1.2 to 2.9 %.

Evidence in literature has shown that combining biochar and manure normally does not differ significantly with sole biochar application, except in a few cases. For example, Nguyen *et al.* (2018) reported no significant difference between rice straw biochar and cattle manure on soil pH under an incubation study. Adekiya *et al.* (2020b), reported that combining biochar and poultry manure did not differ significantly from sole biochar. Similar results have also been reported by others (Agbede *et al.* 2020a; Riziki *et al.* 2020; Abagandura *et al.* 2021; Apori and Byalebeka 2021; Apori *et al.* 2021; da Silva *et al.* 2021; Romero *et al.* 2021). These results are well-received, especially in areas where biochar production or feedstock is limited, and where blending may guarantee soil acidity correction without requiring large quantities of biochar. In addition, the proper description of why combining biochar and manure do not significantly differ is still unclear as various authors explain their findings based on biochar, without elaborating on the combined biochar-manure effect.

2.2.2.2. Effects on soil organic carbon

Soil organic carbon is the main component (58 %) of SOM, and is derived from the decomposition of OM (Dzvene 2017). Soil contains the largest terrestrial C pool, which has significant implications for climate change mitigation, terrestrial biodiversity, and agricultural productivity (Zhang *et al.* 2021; Singh *et al.* 2022). Despite its significance, environmental losses such as erosion and greenhouse gas emissions (CO_2 and CH_4) threaten C longevity which ultimately reduces land productivity (Subedi *et al.* 2017). Organic matter amendments, conservation agriculture and reforestation are among the major measures being taken in sequestrating C and reducing its loss (Dzvene *et al.* 2019). However, these measures are short term and tend to result in compromised C sustainability because the labile C is easily decomposed by microorganisms (Subedi *et al.* 2017; Nyambo *et al.* 2018).

Biochar is principally rich in recalcitrant and aromatic C (Subedi *et al.* 2017), with a half-life between 100 and 1000 years in soil, sequestering about 25-50 %, whereas conventional organic materials can sequester 10 to 20 % of C for only 5-10 years (Musumuvhi 2018). The richness of C in biochar is attributed to the thermochemical conversion of aliphatic to aromatic C which usually occurs at 500 °C and beyond. Thus, after soil incorporation, biochar significantly increases SOC, which also varies with application rates, feedstock type, soil texture and study type (Singh *et al.* 2022). A two-year field experiment by Agbede and Adekiya (2020) reported that SOC increased with increase in application rates (0, 10, 20 and 30 t ha^{-1}) and the second year was more pronounced than the first year. The trend was similarly reported by Nyambo *et al.* (2018) with application doses of 2.5, 5, 7.5 and 10 %, but over a 130-day incubation study.

When biochar is combined with manure, it readily absorbs OM from the manure, increasing OC (Apori *et al.* 2021). Studies that have evaluated the interaction of biochar and manure on SOC have reported that either the combination increased OC compared to sole biochar or reported no differences between the combination and sole biochar. For instance, Agbede *et al.* (2020b) evaluated three biochar application rates (10, 20 and 30 t ha^{-1}), with and without 7.5 t ha^{-1} of poultry manure, and observed that OC was higher every time each biochar application rate was combined with poultry manure than biochar alone. Apori *et al.* (2021) reported that combining corn cob biochar and farmyard manure significantly increased OC in comparison to biochar alone. A similar trend was reported by others (e.g. Lentz and Ippolito 2012; Romero *et al.* 2021) under different biochar-manure blends and biochar types. Conversely, others (Riziki *et al.* 2020; Abagandura *et al.* 2021; Apori *et al.* 2021) did not observe any significant differences between combined biochar-manure and sole biochar.

2.2.2.3. Effects on soil nutrients and CEC

The mechanisms by which biochar influences nutrient availability can be categorized as direct and indirect (Palansooriya *et al.* 2019). Directly, biochar consists of mineral nutrients (N, P, K, Ca, Mg, S, Mn, Zn, Cu, Na, Fe) (Adekiya *et al.* 2020b) and following application, these nutrients are added to soil to enhance soil fertility (Zhang *et al.* 2021). This is despite criticism on biochar's slow release due to recalcitrance (Musumuvhi 2018). The quantity of nutrients in biochar is affected by feedstock type and pyrolysis temperature. Animal and sewage-based biochars are enriched with nutrients more than plant-based biochars; thus, animal and sewage-based biochar may have a pronounced effect on soil fertility (Subedi *et al.* 2017). Regarding the pyrolysis temperature, biochar produced under high temperatures (>500 ^{0}C) contains high nutrient quantity than when produced at a lower temperature, except for N, which may influence biochar dynamics on soil fertility.

Indirectly, biochar improves soil nutrients by manipulating other soil properties which improves nutrient retention. The increase in soil pH following biochar application enhances the availability of several nutrients and reduces Al and Fe availability (Palansooriya *et al.* 2019). The surface negative charges on biochar improve its CEC and enhance the retention of cations (Ca^{2+}, Mg^{2+}, K^{+}, $NH4^{+}$, Na^{+}) (Zhang *et al.* 2021). In addition to the negative charge and its porous surface, biochar can hold nutrients and organic matter which reduce losses to the environment, especially by erosion and leaching (Musumuvhi 2018). Also, the porous nature of biochar creates shelter and provides energy respectively to soil microorganisms, as well as soil pH manipulation creates a conducive environment for these microbes (Palansooriya *et al.* 2019; Adekiya *et al.* 2020a). These microbes have various responsibilities in organic mineralisation and symbiosis. Therefore, the simultaneous influence of direct and indirect effects of biochar ultimately improves soil and crop productivity.

The criticism associated with biochar slow nutrient release justifies the necessity to combine it with manure and other organic amendments (Subedi *et al.* 2017). Manure instantly releases nutrients compared to biochar, and when manure is applied alone these nutrients are susceptible to environmental losses (Riziki *et al.* 2020). Thus, when manure is combined with biochar, environmental losses are reduced because biochar adsorbs nutrients released from manure due to biochar's CEC, large surface area, and density. Adekiya *et al.* (2020a) reported that, in a two-year study, total N, available P and exchangeable cations increased more when biochar was combined with poultry manure than when biochar was applied alone. Similar observations on different nutrients and conditions have been reported by others (e.g. Lentz and Ippolito 2012; Adekiya *et al.* 2020a; Agbede *et al.* 2020b; Riziki *et al.* 2020; Apori *et al.* 2021; Apori and Byalebeka 2021; Romero *et al.* 2021).

2.2.2.4. Effects on soil bulk density, soil porosity and soil moisture content

Bulk density (BD), soil porosity (SP) and moisture content (MC) are critical soil parameters significant in root penetration and water movement in the soil. Low BD and high SP promote proper root growth and water retention which lead to appropriate crop growth, while high MC represents the amount of water that the soil pores hold. High BD as well as low SP and MC have negative impacts on both root growth and water retention. This can be caused by low SOM and compaction, especially in sandy soils. Biochar's low BD (0.05–0.57 $kg{\cdot}m^{-3}$) and high SP (55-60 %) (Zhang *et al.* 2021) is a consequence of its porous structure, and after application enhances soil BD, SP and MC due to dilution effect with the soil. Biochar improves moisture content through its porous nature which enhances water retention (Adekiya *et al.* 2020), and can rearrange soil particles leading to the formation of other soil pores in the soil. Additionally, BD, SP and MC are affected by other factors such as biochar application doses, soil texture and type, climate and experimental time. For instance, Nyambo *et al.* (2018) reported a gradual decrease and increase in BD and SP respectively as application rates increase from 2.5 to 10 %. Similarly, Githinji (2014) observed a decrease in BD and an increase in SP and MC as application rates increased from 25 to 100 %.

The effects of combined application of biochar and manure on BD, SP and MC are still scanty in literature and the few available studies have shown inconclusive results. Agbede *et al.* (2020), evaluated biochar application rates of 10, 20 and 30 t ha^{-1} with and without 7.5 t ha^{-1} of poultry manure and found that every time that biochar application rate was combined with manure, BD decreased while SP and MC increased compared to biochar alone. Similarly, Adekiya *et al.* (2020b) reported that combining biochar and poultry manure both at 15 t ha^{-1} decreased BD and increased SP and MC compared to biochar applied alone at 15 t ha^{-1}. Conversely, Lima *et al.* (2021) evaluated biochar application at 10, 20 and 40 t ha^{-1} with and without 5 t ha^{-1} of poultry manure and observed that there was no significant effects on BD, TP, FC, PWP, and PAW in all the biochar amendments either applied with or without manure. This might be related to the soil texture, as clear positive results are usually noticed under coarse textured soils (Dzvene *et al.* 2019). Further investigation is still required on how the combination of biochar and manure affects BD, SP and MC.

2.2.2.5. Effects on soil aggregate stability

Aggregate stability is another crucial soil indices of soil structure and stability which influences broad soil functions and processes such as nutrient cycling, nutrient storage and movement, infiltration, drainage and erosion (Hu *et al.* 2021). Soils with smaller aggregates are more prone to wind and water erosion than large aggregates (Blanco-Canqui 2017). Aggregate stability improves soil structure, and a good soil structure indicates better soil fertility and reduced loss of nutrients (Wang *et al.* 2017). Thus, aggregate stability is significant for soil productivity and environmental quality and stability.

Generally, biochar addition in the soil significantly improves soil aggregate stability, which occurs through numerous mechanisms. Biochar can bind small aggregates into macroaggregates, which occurs through the sorption of SOM under biochar surfaces (Obia *et al.* 2016). The carboxyl functional groups on biochar surfaces can bind with mineral ions to form organo-mineral complex ions (Hu *et al.* 2021). This additionally becomes more effective due to biochar CEC, improving its binding ability with organic and mineral materials (Ma *et al.* 2016). The labile part of biochar provides energy while its porous surface provides shelter for microorganisms which are responsible for facilitating the binding of aggregates in the soil (Nyambo *et al.*, 2018). On the other hand, the aromatic part of biochar makes it difficult for microorganisms to decompose the C mineralisation in biochar, thereby reducing aggregate disintegration (Wang *et al.* 2017). Also, biochar promotes proper root growth and elongation which increases soil aggregation but may vary with crop type, as monocotyledonous plants are more efficient than dicotyledonous plants (Obia *et al.* 2016).

The influence of biochar on aggregate stability may differ under different conditions such as soil texture, climate, biochar type and biochar application rates. Wang *et al.* (2017) evaluated how two different biochars (softwood biochar and walnut shell biochar) affected aggregate stability under sandy loam and silty loam soils. It was observed that softwood biochar significantly increased aggregate stability by 200 to 250 % more than walnut shell biochar which increased by 107.5 to 125

% in comparison to the control under silty loam soil, while under sandy loam, no significant differences were observed between both biochars (Wang *et al.* 2017). Hu *et al.* (2021) reported that the application of biochar at doses of 2.5, 5 and 7.5 % increased aggregate stability by 49.8, 78.3 and 188 % respectively in comparison to the control.

2.2.3. Effects of biochar and its combination with manure on crop productivity

The goal of adding biochar to soil is to improve crop productivity sustainably. As mentioned earlier, biochar supplies nutrients it contains and directly or indirectly manipulates other soil properties for crop growth (Apori *et al.* 2021). Biochar changes soil pH, which improves the availability of certain elements and their adsorption with roots (Adekiya *et al.* 2020a). Moreover, the interaction of biochar with soil on how it influences crop productivity varies with different factors such as biochar feedstock, pyrolysis temperature, soil texture, climate, crop type and biochar application dose. Coarse textured soils tend to have much more response to biochar on crop growth and yield than fine-textured ones (Singh *et al.* 2022). Wood-based biochars may strongly bind nutrients because of high lignin content, therefore greater crop productivity response is expected in non-wood biochars. Increasing the amount of biochar increases its effects, but to a certain extent increasing biochar may not show results or may give negative results.

A great deal of evidence on the improvements in crop productivity is available in the literature. A recent meta-analysis by Singh *et al.* (2022) reported that numerous crops consisting of wheat, maize, canola, barley, rice, sorghum, tomato, groundnut, faba bean, turnip, and peanuts significantly increased yields by 34 and 30 % under greenhouse and field studies, respectively, when biochar was present compared to the control. Cornelissen *et al.* (2018) observed that maize yield grown for 4 months in a field using rice husk biochar at 5 and 15 t ha^{-1} increased yield by 100 and 120 % respectively in comparison with the control. Sikder and Joardar (2019) reported that the yield of radish grown for 6 weeks using poultry litter biochar amended at 1 t ha^{-1} decreased by 46 % while amendments at 2, 3 and 4 t ha^{-1} increased by 66.9, 123 and 146 %, respectively, when compared to the control. Plant height, on the other hand, increased by 23. 5, 25, 28.4 and 33 % respectively at 1, 2, 3 and 4 t ha^{-1} when compared to the control. Other positive results have been reported on maize (Jin *et al.* 2020) and ryegrass (Subedi *et al.* 2016).

Nonetheless, some authors remain sceptical about the direct effect of biochar on crop productivity due to observed negative responses (Palansooriya *et al.* 2019) or no responses (Singh *et al.* 2020; Abagandura *et al.* 2021; Banik *et al.* 2021) to crop productivity after biochar application. Limited responses observed could be resultant from localization of nutrients in some biochar complexes which become unavailable and insoluble prior to biochar application or volatilisation of some nutrients during high pyrolysis temperature, especially N (Subedi *et al.* 2017). Others suggest that biochar may contain toxic compounds which are detrimental to microbial activity, therefore reducing nutrient release (Palansooriya *et al.* 2019). For instance, Huang *et al.* (2019) reported that grain yield and grain yield attributes decreased during the first three seasons and increased for the next three seasons afterwards. Also, other authors observed that biochar might have an influence a certain application rate, and beyond that, it will decrease crop productivity (Adekiya *et al.* 2020b). Upadhyay *et al.* (2014) reported that biochar was beneficial up to 30 t ha^{-1} on lettuce shoot dry and wet biomass and total dry and wet weight and beyond this application dose these characteristics declined.

As such, combining biochar and manure has become a new approach to supplementing biochar's which are poor in nutrients, especially those derived from wood biomass, pruning residues etc. These combinations increase crop growth and yield probably because manure may have more readily available nutrients than biochar. This enhances nutrient use efficiency and improves positive crop growth and yields. In literature, evidence is available on a greater influence on crop growth and yield when biochar is applied in combination with manure than when applied alone. This has been evident in crops such as ginger (Adekiya *et al.* 2020a), cocoyam (Agbede *et al.* 2020a), maize (Lentz and Ippolito 2012; Lima *et al.* 2018) and cucumber (Apori *et al.* 2021). However, in the literature there is no proper description on the synergic effect of biochar and manure combination as numerous authors describe the effects based on biochar, and there are limited studies on the combined effects of biochar and manure on soil physical properties.

2.3. Conclusion

The depletion of soil fertility and crop productivity in SSA is a reality which is limiting the agenda of food security and poverty alleviation in this region. Manure has been used in mixed crop-livestock systems and it supplies soil nutrients and additionally improves soil physical, biological, and chemical properties relative to inorganic fertilisers. However, although the significance of manure in improving soil fertility and crop productivity is acknowledged, it is associated with certain demerits, mostly an increase in GHG emissions and its rapid mineralization which compromise sustainability in farming systems. Biochar is currently identified as a sustainable organic amendment which can sustain soil functioning and crop productivity mainly because of its recalcitrant carbon which is hardly mineralised by microorganisms. These effects are derived from its properties such as high pore sizes, high surface area, surface functional groups, alkaline pH and nutrient content which are predetermined by pyrolysis temperature and feedstock type. In addition, combining biochar and manure has become a new approach to supplementing biochars which are poor in nutrients, and this approach can be competitive in improving soil fertility and crop productivity relative to biochar and manure applied alone. Therefore, the adoption of biochar in smallholder farming can be a panacea for improving their livelihoods.

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CHAPTER 3: Meta-analysis on manure utilisation under smallholder farmers in sub–Saharan Africa

Abstract

Animal manure plays a pivotal role in improving soil fertility and crop productivity under smallholder farming in sub-Saharan Africa (SSA). However, manure management practices are inappropriately done which jeopardises its fate in improving soil fertility and crop productivity. To provide appropriate utilisation, a meta-analysis study containing 114 articles from SSA was conducted on how smallholder farmers apply practices such as application rate (low, medium, and high), application time (before and after planting), the application method (incorporating and broadcasting), and manure type (poultry, cattle, and goat), on crop productivity (crop and biomass yield) and soil fertility (pH, Soil Organic Carbon (SOC), Total Nitrogen (TN), Available Phosphorus (AP), and Exchangeable Potassium (K)). Results revealed that generally addition of manure increases soil fertility and crop productivity. The low and high application rates resulted in the highest crop relative yields and biomass yield respectively. The highest SOC, TN, AP, and K were observed at a medium rate, apart from pH. All measured parameters were highest when manure was incorporated rather than broadcasted regarding application methods. Crop yields did not show differences between application times, but biomass yield was highest when manure was applied before planting. All the soil fertility properties except TN were highest when manure was applied before planting. Cattle and poultry manure had the highest crop and biomass yield respectively. Goat manure had the highest TN and pH, whereas poultry manure had the highest increase in SOC, AP, and K. Overall, this meta-analysis revealed appropriate manure utilisation for optimum soil and crop productivity. Additionally, this meta-analysis was specific to management practices of application, other management practices like storage, collection, and treatment require deeper investigation.

Keywords; crop productivity, manure, smallholder farmers, soil fertility, smallholder farmers, SSA.

3.1. Introduction

Soil fertility decline under smallholder farming systems in the sub-Saharan Africa (SSA) region is a major bottleneck in boosting crop production (Brien and Hatfield 2019). Inappropriate activities which promote soil nutrient mining without recovering lost nutrients such as continuous mono-cropping, crop residue removal, burning, and conventional tillage, continue to exacerbate soil fertility depletion (Dzvene 2017), subsequently threatening food security in this region. To mitigate this, supplementing with synthetic fertilisers has been a global approach to managing soil fertility, but in SSA, the application is sub-optimal (Sileshi *et al.* 2019). While in other regions the average synthetic fertiliser application rates can be 50-100 kg ha^{-1}, in SSA it can be as low as 10 kg ha^{-1} (Mkhabela 2007), which is mainly attributed to the high costs associated with fertilisers (Ndambi *et al.* 2019). Consequently, manure can be a desirable alternative for promoting soil fertility because of its availability, accessibility, and lower costs to smallholder farmers (Mhlontlo *et al.* 2007).

The application of manure in smallholder farming systems is an ancient practice that was set aside following the introduction of inorganic fertilisers but is currently gaining relevance and re-establishment (Mkhabela 2007; Fatondji and Ibrahim 2018). Subsistence farmers' agricultural systems are essentially based on crop and livestock integration (Dzvene 2017; Ayantunde *et al.* 2018) where animal manure is utilised to supplement soil nutrients and crop residues are used as feedstuff for the livestock (Sileshi *et al.* 2019), creating on-farm nutrient recycling. Since small-scale and subsistence farmers tend to be financially disadvantaged, and many cannot secure inorganic fertilisers, integrating crops and manure is a worthwhile alternative to sustain soil fertility, with limited environmental consequences. This option is more sustainable than inorganic fertiliser because manure is commonly available locally, and affordable to farmers with few or no livestock at reasonable costs.

Considerable evidence associated with escalating crop yields in SSA, following manure addition is extensively available in the literature, mostly on goat manure (Gichangi *et al.* 2009; Chipomho *et al.* 2018; Zhu *et al.* 2020), poultry (Dikinya and Mufwanzala 2010; Jn-baptiste *et al.* 2013; Agbeshie *et al.* 2020; Ndukwe *et al.* 2021) and cow manure (Fatondji *et al.* 2006; Fatondji and Ibrahim 2018; Mokgolo *et al.* 2019). These elevated crop yields are ascribed to the potential of manure in supplementing nutrients (Mhlontlo *et al.* 2007) especially N, P, and K (Brien and Hatfield 2019), and facilitating other essential soil properties like pH, organic carbon, soil organic matter, cation exchange capacity, soil microbial diversity, water-holding capacity, hydraulic conductivity, infiltration, porosity and decrease in bulk density (Materechera 2010; Agbeshie *et al.* 2020; Ndukwe *et al.* 2021).

However, within this perspective, the efficiency of manure to exhibit these properties depends extremely on the proper application of numerous management practices.

In SSA, manure management practices such as time, method, and rate of application are inappropriately done, whereas in literature results on these management practices are sometimes inconclusive and contradictory. For example, Materechera (2010) reported that maximising crop yields following the application of 2.5 t ha^{-1} of manure (mostly cattle manure) was unsuccessful, but earlier Fatondji *et al.* (2006), reported that 1-3 t ha^{-1} of cattle manure increased millet yield by 115 % compared to rates of 3-5 t ha^{-1} which increased yields by 12 % relative to no manure. Jn-baptiste *et al.* (2013) observed that incorporating poultry manure at 9 t ha^{-1} increased maize yield compared to broadcasting, whereas broadcasting at 18 t ha^{-1} resulted in higher yields than incorporating manure. Also, over a three-year study, Cambareri *et al.* (2017) observed that incorporating and broadcasting cattle manure did not differ statistically. On application time, manure added five months before planting showed reduced maize yield (7.7 t ha^{-1}) than when applied two weeks prior to planting (8.7 t ha^{-1}) (Cambareri *et al.* 2017). These inconsistencies are a general representation of how manure is utilised by smallholder farmers. Factors such as improper understanding, scarcity of suitable guidelines, and insufficient knowledge are the primary reason for inefficiencies in manure utilisation, which confronts the significance of manures in substituting inorganic fertilisers.

Research efforts for gathering information concerning how manure is utilised in SSA smallholder farming has extensively been conductedby means of survey (Materechera 2010; Dzvene 2017; Ndambi *et al.* 2019), experimental (Mhlontlo *et al.* 2007; Ndukwe *et al.* 2021), and literature review studies (Mkhabela 2007; Ayantunde *et al.* 2018). Right now, there is no comprehensive quantitative review that summarises literature using meta-analysis on the utilisation of manure. Therefore, this study aims to determine the best application practices on how smallholder farmers apply and incorporate manure in their cropping systems. Meta-analyses are becoming a vibrant instrument across various research fields, through their comprehensive integration of individual studies which are synchronised to answer one general question while considering different experimental factors (Brien and Hatfield 2019). As such, a meta-analysis is a relevant tool in synthesising information regarding SSA smallholder farming, because they are diversified by variation in climatic regions, management practices, cropping patterns, soil types etc.

3.2. Materials and methods

3.2.1. Literature search and study selection

An explicit search of several publications was performed to collect data on the effects of livestock manure on soil fertility properties and the yield of crops grown in the SSA region. Numerous databases from the Stellenbosch University Library were used for searching articles, including Web of Science, Cab Abstracts, Scopus, and Google Scholar. In addition, browsing of other article's reference sections was done to look for potential articles that could have been missed from the databases. The combination of subsequent keywords was used to retrieve the articles. *("animal manure" OR "cattle manure" OR "sheep manure" OR "goat manure" OR "poultry manure" OR "chicken manure") AND ("crop yields") AND ("soil fertility" OR "nitrogen" OR "phosphorus" OR "potassium" OR "pH" OR "Soil Organic Carbon" OR "Soil Organic Matter") AND ("sub-Saharan Africa" OR "East Africa" OR "Southern Africa" OR "West Africa" OR "Central Africa")*. The search was run from the 29th of December 2020 to the 6th of February 2021. All the articles selected in this meta-analysis had to fulfil the successive criteria:

a) The study should have been conducted in SSA under on-farm trials or field studies that represent smallholder farming systems. Studies that were conducted under pot, greenhouse, and laboratory-controlled conditions were excluded since this meta-analysis was targeting smallholder farmers and those conditions are therefore not applicable.
b) Treatments must have included at least one treatment of animal manure with a control (without an amendment). Manure had to be derived from cattle, poultry, and goat, without decomposition prior to commencement of a study, without mixing with either fertiliser or any other organic material. These three types of manure together with sheep manure are regularly used by smallholder farmers (Mokgolo *et al.* 2019). However, sheep manure could not be used in this study due to scarce studies available in the literature. Farmyard manure was not included because it consists of manure and other materials such as bedding materials, household waste and crop residues (Sileshi *et al.* 2017; Rena *et al.* 2019) which compromise the original characteristics of the manure and their influence, which also applies to composted manure.
c) The studies had to clarify either manure application rates, application method, or application time they used with only any of the three types of manure included in the study. The application rates should have been clearly stated on a dry matter basis.
d) At least one of the targeted response variables (crop yields, dry biomass, soil pH, SOC, N, P, and K) results must have been given.

3.2.2. Data collection and grouping

The effects of livestock manure on soil fertility properties and yield of crops grown in sub-Saharan Africa (SSA) were assessed on the successive 7 response variables: crop yields, crop dry biomass yields, soil pH, soil organic carbon (SOC), total nitrogen (TN), available phosphorus (AP) and exchangeable potassium (K). The means of each response variable of interest were taken from the results of the selected articles and compiled into an Excel Database. Crop and biomass yield was expressed in t ha^{-1} as the base unit and in cases where both crop and biomass yield were given as weight per plant, the plant population was useful for converting to t ha^{-1}, and if other units were used, conversions were simply done to t ha^{-1}. The SOC was collected in % and if soil organic matter (SOM) was given, the van Bemmelen factor (0.58) was applied to convert from SOM to SOC (Lin *et al.* 2018; Rena *et al.* 2019). Nitrogen, phosphorus, and potassium were expressed as total nitrogen, available phosphorus, and exchangeable potassium respectively because numerous authors in the literature expressed these nutrients in these forms/units. In some studies, data collection was done multiple times during the trial period, for instance at each physiological stage, thus only results from the last data collection were considered for the meta-analysis.

Besides the above-mentioned variables, additional data on study location (country, location, country region, and climatic region), experimental information (study duration, number of experimental years, rain-fed or irrigated, other agronomic practices, and experimental design), initial soil information (texture, classification, pH, SOM, SOC, N, P and K), manure information (pH, SOM, SOC, N, P, K and C: N), and crop information (type, scientific name, variety, and classification) was involved. In situations when multiple soil types, years, locations, crops, and cultivars were included in the same study, observations were treated as independent and considered as separate studies. Nonetheless, this aspect of treating multiple observations under one study has criticism in metanalytical studies, because considering multiple observations from one study as independent increases the chances of type I error (Lin *et al.* 2018). Thus, some authors average multiple observations (Xia *et al.* 2017), while others consider only one observation e.g., results obtained in the final year of the trial, if the study was conducted for several experimental years (Rena *et al.* 2019). In contrast, averaging multiple observations may lead to the loss of some crucial information (Schütz *et al.* 2018), and reduce statistical power (Lin *et al.* 2018). Numerous meta-analyses handle multiple observations as independent studies (Schütz *et al.* 2018; Zhang *et al.* 2020). Additionally, if similar results were repeated by one author in two or more articles, only the results of one article were considered.

The independent variables were manure application rate, method of manure application, time of manure application and type of manure. Manure application rates were categorized as (i) low (<5 t ha^{-1}), (ii) medium (5 - 10 t ha^{-1}) and (iii) high (<10 t ha^{-1}). Method of application was categorized as (i) incorporation and (ii) broadcasting. Incorporation was defined as when manure was added to the soil surface and mixed with soil or when manure was applied sub-surface and mixed with the soil. Broadcasting was defined when manure was applied on the soil surface only without incorporation. Manure application time was categorized as (i) before planting, defined as the application of manure one day backwards before planting or transplanting if plants were transplanted and (ii) after planting, which was defined as the application of manure from the date of planting or transplanting onwards. The type of manure was categorized as (i) poultry, (ii) cattle, and (iii) goat manure.

Results reported graphically were extracted using Web Plot Digitizer. If some crucial data (e.g., units and type of manure) were missing, a requesting email was sent to the respective corresponding authors, but only four authors managed to respond, out of numerous contacted authors.

3.2.3. Statistical analysis

Publication bias was firstly assessed by plotting the effects size of all parameters on density plots. Normally, publication bias is interrogated through funnel plots (Lin *et al.* 2018; Sileshi *et al.* 2019) which requires the standard errors or standard deviations from the studies where data is extracted, but unfortunately in this study, few articles had standard errors or standard deviations, therefore publication bias was adopted with density plots as similarly done by Brien and Hatfield (2019). Publication bias can be a norm in meta-analysis due to the "file drawer problem" which arises from articles or journals that publishes results that are only significant leaving behind the ones not significant.

Meta-analysis was conducted to investigate the effect of experimental and intervention factors on variables concerned in this study. The effect of a factor on a given variable was assessed by comparing the overall effect of that factor with the individual effects of sub-groups of that variable. The overall effect was obtained from calculations of "Standardized effect size". These calculations were done using the function "ESC_MEAN_SE" from the "ESC" package of R software which also served to generate the standard deviations and the estimates (coefficients of size model) of variables. Effect size tells us how meaningful the relationship between variables or the difference between groups is and it indicates the practical significance of a research outcome (Zhang *et al.* 2020). A large effect size depicts that research finding has practical significance, while a small effect size indicates the opposite.

The random-effects model using the residual maximum likelihood (REML) approach was applied on assumption that the effect sizes in the dataset are not essentially associated with each study k using the rma function of R software. Random effects models are more ideal than fixed-effects models for statistical procedures in environmental data analysis due to the satisfaction of heterogeneity of variance. Therefore, Cochran's Q and Higgins' I^2 were used to determine the heterogeneity of effects size. The obtained standardized effect size, the calculated standard deviations and the model coefficients were then used to obtain the percentages of the impact of each factor on concerned variables, using the METAFOR package of R software. The conversion of effect size to percentage changes is known to strengthen the explanatory power in meta-analysis. Positive percentage changes show an increased effect of manure relative to no manure, while negative percentage show a decrease due to manure substitution (Xia *et al.* 2017). The impact of each factor was graphically illustrated using forest plots constructed using the GGPLOT2 package, and graphs were combined and arranged by the ggarange function of R software version 4.1.2

3.3. Results and discussion

3.3.1. General characteristics of the studies

The search of studies using search string {*("animal manure" OR "cattle manure" OR "sheep manure" OR "goat manure" OR "poultry manure" OR "chicken manure") AND ("crop yields") AND ("soil fertility" OR "nitrogen" OR "phosphorus" OR "potassium" OR "pH" OR "Soil Organic Carbon" OR "Soil Organic Matter") AND ("sub-Saharan Africa" OR "East Africa" OR "Southern Africa" OR "West Africa" OR "Central Africa")*} identified 1449 articles from Scopus, CAB Abstracts, Web of Science and Others, yielding 841, 530, 20 and 40 respectively (Figure 3.1). After the screening process, 114 articles finally met the inclusion requirements. Articles excluded were largely review and survey studies, greenhouse/glasshouse studies, studies where manure was blended with fertilisers or other organic materials, and studies that had used composted or farmyard manure.

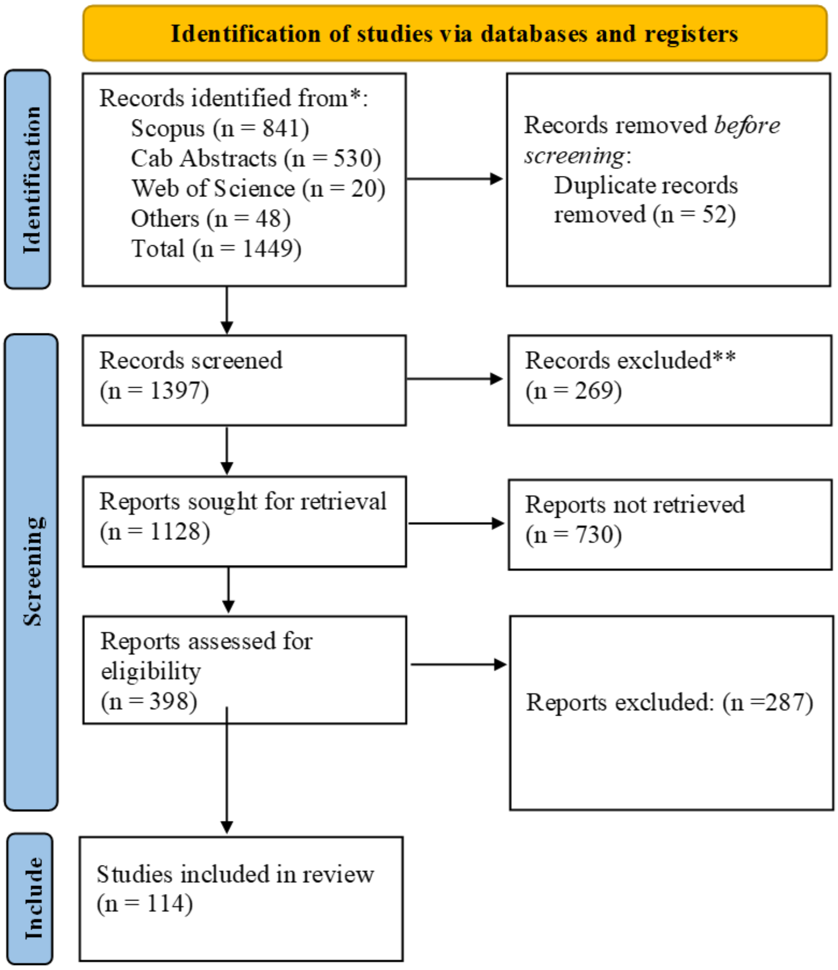


Figure 3. 1:: Preferred reporting items for systematic reviews and meta-analyses (PRISMA) for effects of manure application techniques on crop yields and soil fertility studies in SSA.

Geographically, West Africa dominated the number of articles (82) which were mainly from Nigeria (about 60 %). Articles in the Southern and East Africa region were 16 and 12 respectively, and last was Central Africa with only 1 article. The most common soil texture was sandy loamy, followed by sandy. The soils were low in pH, which ranged from 4.07 to 7.66 and 90 % of soils were below pH 7, indicating high soil acidity prevalence in smallholder farming which is deleterious to plant growth by reducing nutrient availability. The SOC was between 0.33 and 8 % with numerous soils having less than 1 % which signifies susceptibility to erosion, degradation, and plant nutrient loss compromising everlasting soil fertility and productivity (Dzvene 2017; Brien and Hatfield 2019). Total nitrogen ranged between 0.003 and 2 % and over 90 % were less than 1 %. Available P ranged between 0.76 to 161.33 mg kg^{-1}, while K ranged from 0.1 to 86 mmol kg^{-1}. These initial nutrient concentration reveals the deteriorated soil fertility situation under smallholder farming which requires supplementing nutrients.

3.3.2. Publication bias and heterogeneity of the study

The density plots of all effects size distribution from parameters evaluated in this study are shown in Figure 3.2. All parameters evaluated (crop yields, biomass yields, pH, soil organic carbon, total nitrogen, available phosphorus, and potassium) were entirely close to zero which implies that publication bias was limited in the articles used in this meta-analysis. Remarkably high heterogeneity between different treatments of experimental variables was observed (Table 3.1). This is normal in meta-analysis studies, the reason being that studies are derived from different authors. Thus, the I^2 test of all tested variables was at least 99.0 %, which were all statistically significant ($p < 0.0001$). Meta-analysis is basically used to assess the influence of sub-factors of experimental variables on the response variables. It is therefore expected that a very high heterogeneity would be observed in the overall effect size of the response variable (Lin *et al.* 2018). This guarantees that the application rates, manure application time, application period, application methods and manure type are significant variables and deserve further subgroup investigation as they strongly impact response variables and in different ways.

This is particularly important because, up to the present day, smallholder farmers are applying diverse and inconsistence manure rates, at different times based on speculation, without having informed and scientific evidence that supports their practices, although some scientific information is unable to reach them because of unreliable extension services. In addition, studies that report optimal techniques of manures are limited to the ANOVA test which cannot provide the extent to which each dose impacts the response variable. Furthermore, the reported studies are generally a result of a single investigation that does not include other studies. This study involved the data from numerous authors to test the influence of each experimental variable.

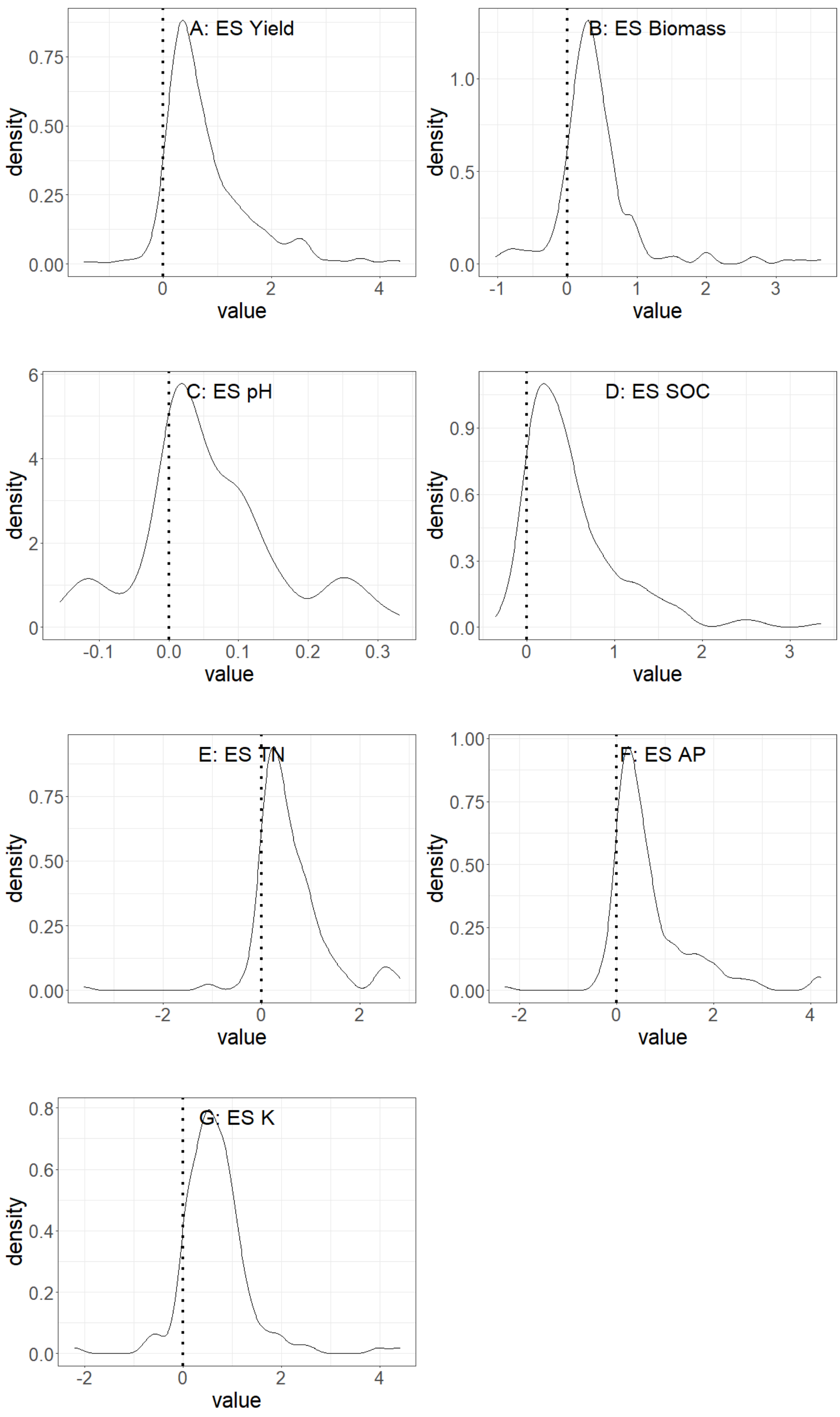


Figure 3. 2:: Density plots of effect sizes for (A) crop yields, (B) biomass yields, (C) pH, (D) soil organic carbon, (E) total nitrogen, (F) available phosphorus and (G) potassium.

Table 3. 1 Statistical I^2 heterogeneity report of effect sizes of experimental variables on response variables. The p-value shows the I^2 test reported at a 95% confidence interval.

*SOC; Soil organic carbon, TN; Total Nitrogen, AP; Available Phosphorus, K; Potassium

Experimental variable	Response variable		*I*-squared heterogeneity (%)	Heterogeneity level	Heterogeneity *p-value* report
Manure application rates	crop yield		99.9	very high	0.0001
	biomass		99.9	very high	0.0001
	soil fertility	pH	99.5	very high	0.0001
		SOC	99.9	very high	0.0001
		TN	99.9	very high	0.0001
		AP	99.9	very high	0.0001
		K	99.9	very high	0.0001
Manure application methods	crop yield		99.8	very high	0.0001
	biomass		99.9	very high	0.0001
	soil fertility	pH	99.4	very high	0.0001
		SOC	99.7	very high	0.0001
		TN	99.9	very high	0.0001
		AP	99.9	very high	0.0001
		K	99.9	very high	0.0001
Manure application period	crop yield		99.4	very high	0.0001
	biomass		99.9	very high	0.0001
	soil fertility	pH	99.5	very high	0.0001
		SOC	99.8	very high	0.0001
		TN	99.9	very high	0.0001
		AP	99.5	very high	0.0001
		K	99.6	very high	0.0001
Manure types	crop yield		99.2	very high	0.0001
	biomass		89.1	very high	0.0001
	soil fertility	pH	99.0	very high	0.0001
		SOC	99.3	very high	0.0001
		TN	99.9	very high	0.0001
		AP	99.4	very high	0.0001
		K	99.1	very high	0.0001

3.3.3. Effect of manure application rates on crop yields, biomass yield and soil fertility

3.3.3.1. Crop and biomass yields

This study revealed that the application of manure increased crop yields by 120 % compared to "no manure" as illustrated by the summary of effect sizes (Figure 3.3a). Specific to the application rates, low application of manure had the largest increase with 370 %, followed by the high (330 %) and moderate rate (220 %). In terms of crop biomass (Figure 3.3b) an overall effect of 52 % increase was noticed due to the addition of manure, and the percentage impact increased with increasing application rates.

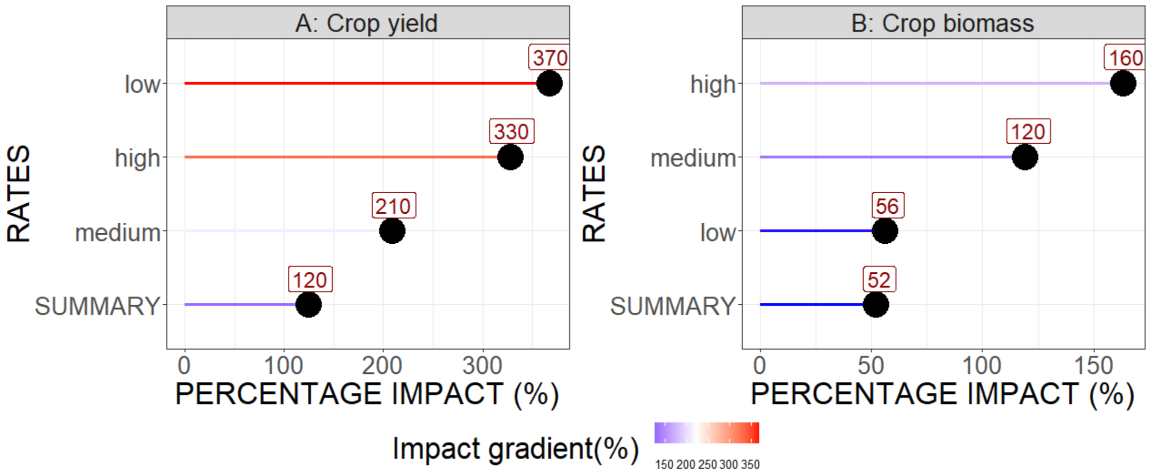


Figure 3. 3a-b:: Meta-analysis summary impact of the effect of manure application rates on (A) crop yields and (B) biomass yields.

The overall increase in crop and biomass yields after manure application is an expectation because manure supplies substantial quantities of nutrients and enhances soil physical properties which effectively increase crop and biomass yields (Uwah and Eyo 2014). It is worth noting that crop yields are highly dependent on manure rates (Sileshi *et al.* 2019), thus, an increase in application rates is correlated to a subsequent increase in crop and biomass yields. For instance, relative to the control, yield increase of 73 %, 104 %, and 116 % was noticed on the low, medium, and high application rates respectively (Jn-baptiste *et al.* 2013), thus, relative lower increase with low rates is due to failure of supplementing enough nutrients for crop needs. However, despite this consensus, our meta-analysis observed the highest yield increment with low application rates. This unusual trend might be possibly due to numerous factors primarily initial soil fertility, climate, soil type, manure type, quality, etc.

In addition, manure quality is of significance as far as manure application rates are concerned because it defines the quantity of nutrients available per a certain amount of manure. Hence, if manure is of high quality, the high application is abandoned, endorsing the application of low rates (Sileshi *et al.* 2019). High doses of high-quality manure often lead to excessive application beyond plant nutrient requirements, potentially hindering plants and the surrounding environment (Brien and Hatfield 2019; Sileshi *et al.* 2019). Therefore, the application of superior quality at low rates may additionally accommodate farmers acquiring enough manure to improve their produce (Ndambi *et al.* 2019). Sileshi *et al.* (2017) estimated that in SSA, communal households have on average, 9 cows that produce 5 t ha^{-1} of dry mass manure per annum, with a production rate of 0.4 - 0.5 t cow^{-1}, whereas *ca*. 57 goats are required to produce similar amounts per year. This implies that if farmers wanted to increase application rates to medium, they should double the number of animals, but this could be impracticable under smallholder setup due to lack of proper grazing feedlots. Thus, the number of livestock per head determines the quantity and availability of manure which influences the choice of application rates.

3.3.3.2. Soil fertility

Addition of manure generally increased soil pH (6.2 %), SOC (71 %), TN (78 %), AP (98 %) and K (94 %) compared to absence of manure (Figure 3.4a, Figure 3.4b, Figure 3.4c, Figure 3.4d, and Figure 3.4e) respectively. Apart from pH, a maximum increase of SOC, TN, AP, and K was observed with a medium application rate, followed by high and low rates respectively. Thus, a high manure application rate increased soil pH by 8.6 %, followed by low (7.8 %), and lastly medium rate (5.2 %). The SOC increased by 150 % with a medium application rate, while high and low rates increased by 91 % and 43 % respectively. On TN, the medium application rate had a 190 % increase, while high and low rates increased by 98 % and 90 % respectively. Regarding AP, the medium rate increased by 300 %, whereas both high and low application rates increased by 230 %. Lastly, K increased by 310 %at medium application rate, while high and low rates had 140 % and 45 % respectively.

The increase in soil pH is primarily attributed to the liming effect of manure due to the presence of Ca and other basic cations released during decomposition (Uwah and Eyo 2014). Thus, adding higher doses of manure elevates the presence of basic cations. The increase in SOC after manure addition is consistent with the general understanding that carbon contained in the SOM pool directly injects carbon into the soil, hence facilitating energy provision to soil microbes and carbon sequestration in the soil (Brien and Hatfield 2019). Soil organic carbon plays a significant role in strengthening soil and nutrient loss prevention, especially through erosion (Sileshi *et al.* 2017). Nutrient loss is common in smallholder farming where inappropriate and irregular agronomic practices prevail, exacerbating the prevailing nutrient loss challenge affecting smallholder farmers.

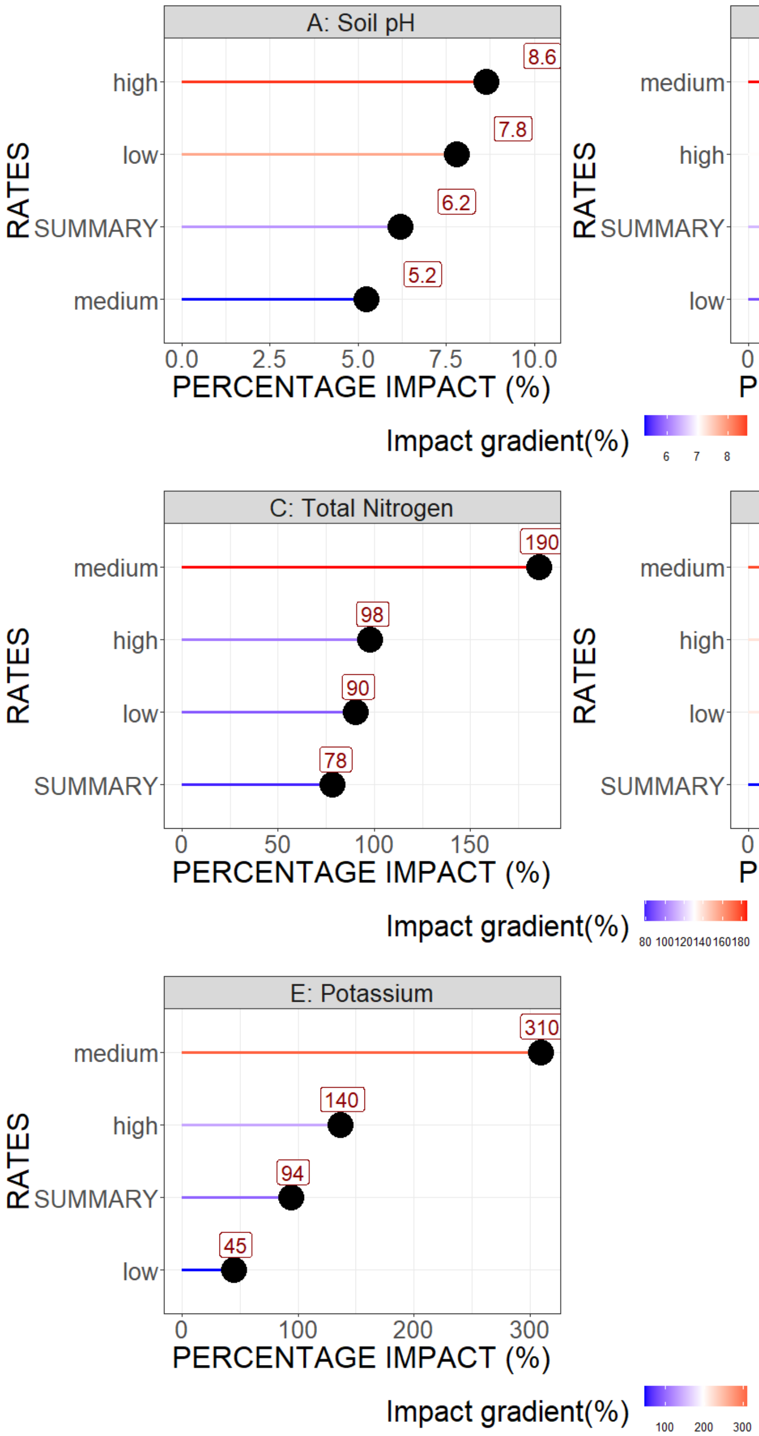


Figure 3. 4a-e:: Meta-analysis summary impact of the effect of manure application rates on (A) pH, (B) soil organic carbon, (C) total nitrogen, (D) available phosphorus and (E) potassium.

The higher N, P, and K content, due to the increase in application rates of manure, arise from the fact that microbial decomposition is higher with increased amounts of organic materials from the organic forms of N, P, and K to inorganic forms and correspondingly increase the content of other essential elements such as Ca, Mg, and S (Brien and Hatfield 2019). Additionally, an increase in soil pH and reduce the fixation of nutrients, improving their availability and accessibility to plant roots (Uwah and Eyo 2014). In this study, except for soil pH, the effect of soil fertility after the addition of manure was largely pronounced with the medium application rate, which implies that manure moderately guarantees an efficient supply of nutrients in the soil, thus low application may fail to supply adequate nutrients, while high application rates may exacerbate manure loss to surrounding environments. However, very high doses may decrease soil pH due to high amounts of nitrates, reducing the availability of soil nutrient concentration, especially fixation of phosphorus. Dikinya and Mufwanzala (2010) evaluated the effects of different manure application rates (0, 5, 10, 20, and 40 t ha^{-1}) on soil pH under different soil types (luvic calcisol, ferallic arenosol and vertic luvisol). Luvic calcisol pH was reduced beyond 10 t ha^{-1}, while vertic luvisol pH was reduced beyond 20 t ha^{-1}. This also reveals that manure effects under different soil types vary.

3.3.4. Effect of application method on crop yield, biomass yield and soil fertility

3.3.4.1. Crop and biomass yield

The overall effect of using different application methods had an average influence of 120 and 44 % on the crop and biomass yield respectively compared to not applying manure (Figure 3.5a and b). Incorporating manure outperformed broadcasting with a percentage increment of 310 % compared to 65 % of broadcasting. Likewise, maximum biomass (Figure 3.5b) increase was observed when manure was incorporated (69 %) than when broadcasted (21 %).

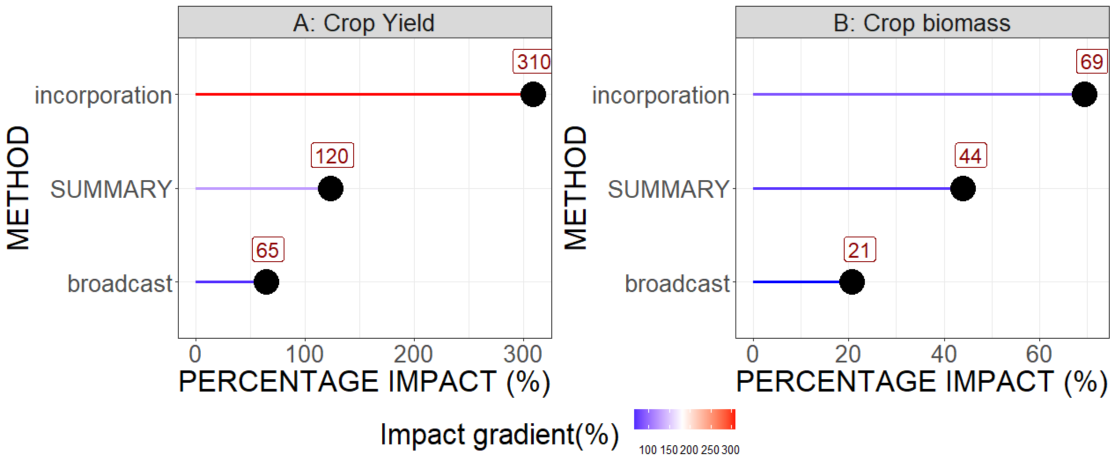
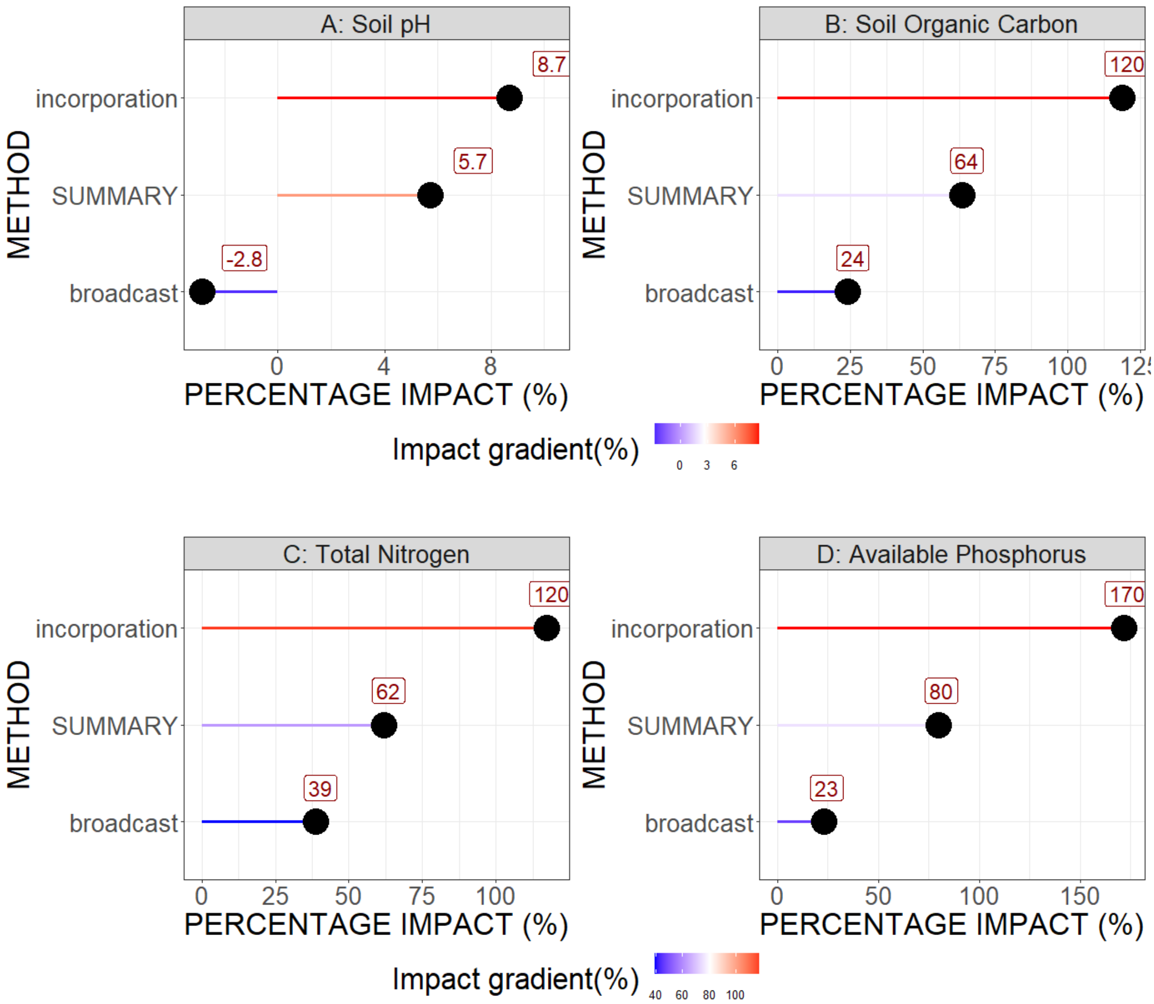


Figure 3. 5a-b:: Meta-analysis summary impact of the effect of manure application method on (A) crop yields and, (B) biomass yields.

These results corroborate with Jn-baptiste *et al.* (2013) who demonstrated that maize yield was improved by 12 % to 14 % when manure was incorporated than when it was broadcasted. This was also in line with Adekiya and Agbede (2017) who reported an average increment of 12.5 % with manure incorporation relative to broadcasting over a two-year study period. The increase in crop and biomass yield with manure incorporation ensures proper synchronisation of soil and manure and closer placement of manure to plant roots where nutrients are effortlessly available and absorbed after early release from manure mineralization (Jn-baptiste *et al.* 2013; Ndukwe *et al.* 2021). This facilitates early plant growth and development which ultimately escalates high yields (Adekiya and Agbede 2017). Nevertheless, incorporating manure does not only bring nutrients closer to roots but also prevents volatilization, which is promoted when manure is broadcasted, consequently increasing N losses (Cambareri *et al.* 2017).

3.3.4.2. Soil fertility

The overall effect of the application method on soil pH was 5.7 % (Figure 3.6a) compared to the control group. Incorporation increased soil pH by 8.7 %, whereas broadcasting decreased pH by 2.8 %. The summary effect of SOC increased by 64 % and was higher with incorporating (120 %) than broadcasting (24 %) manure (Figure 3.6b). Similarly, TN's overall increase was 62 %, whilst a pronounced increase was observed by incorporating (120 %) than by broadcasting (39 %) manure (Figure 3.6c). Both AP (Figure 3.6d) and K (Figure 3.6e) gave a summary effect of 80 % and 73 % increase, respectively, after the addition of manure. Moreover, incorporating manure had a larger effect on AP and K of the soils by 170 and 120 %, respectively.



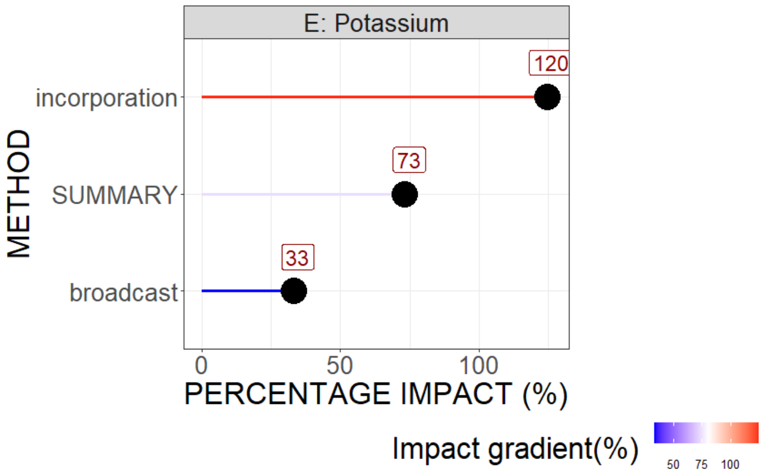


Figure 3. 6a-e:: Meta-analysis summary impact of the effect of manure application method on (A) soil pH, (B) soil organic carbon, (C) total nitrogen, (D) available phosphorus and (E) potassium.

The high pH, SOC, N, P and K after incorporating manure is principally driven by facilitating carbon sequestration and reducing nutrient loss, thereby improving nutrient availability in the soil for effective root absorption (Jn-baptiste *et al.* 2013; Adekiya and Agbede 2017). When manure is broadcasted, the possibility of nutrient loss is aggravated because manure can be eroded by wind or water, and with ammonia volatilization. Some authors suggested that about 50 % to 90 % of ammonia volatilization is reduced by incorporating manure than by broadcasting (Adekiya and Agbede 2017). This is because by incorporating, soil aeration is deliberately improved, which reduces denitrification risks under oxygen-depleted conditions (Cambareri *et al.* 2017). The decline of nutrient use efficiency due to nutrient loss is another bottleneck in boosting crop productivity under smallholder farming (Sileshi *et al.* 2019) although most of the farmers continue with broadcasting, which is inefficient (Muhereza *et al.* 2014).

3.3.5. Effect of the manure application period on crop yield, biomass yield and soil fertility

3.3.5.1. Crop and biomass yield

The overall effect on the manure application period of both crops (Figure 3.7a) and biomass yield (Figure 3.7b) increased by 120 % and 53 % respectively against the absence of manure. Crop yields did not reveal any difference between applying manure before and after planting, but application before planting increased crop biomass by 71 % than with application before planting (50 %).

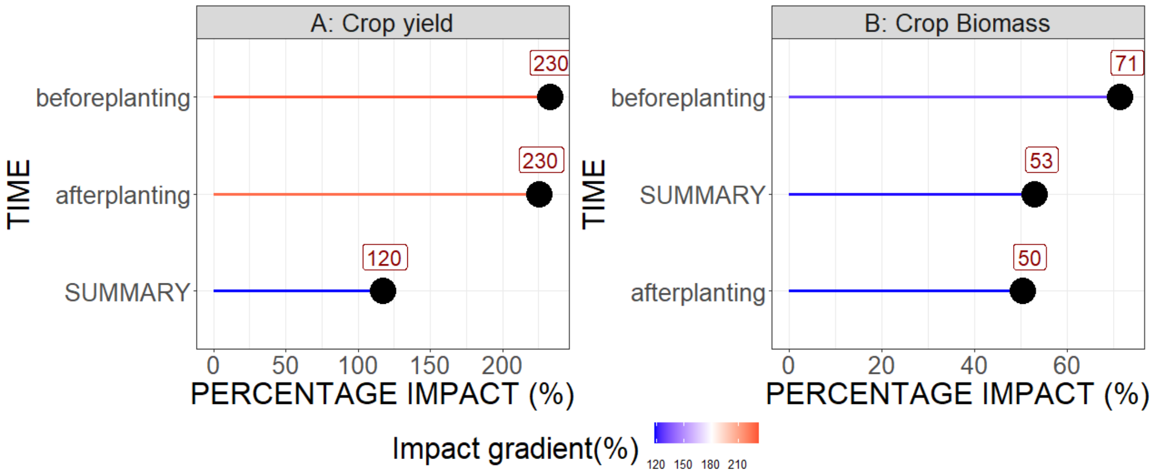


Figure 3. 7a-b: Meta-analysis summary impact of the effect of manure application time on (A) crop yields, and (B) biomass yields.

The timing of manure application is a fundamental factor for enhancing crop yields because it ensures the supply of nutrients at the correct time when crops demand them. This also guarantees the prevention of nutrient loss. Application of manure before planting enhances early mineralisation and release of plant-available nutrients for crop uptake, specifically N and P (Kolawole 2014), although a prolonged delay in planting after manure application leads to nutrient loss (Fatondji and Ibrahim 2018). For instance, the findings of Kolawole (2014), reported that maize yield was twice higher when manure was applied 2 weeks before planting (WBP) than applied 2 weeks after planting (WAP). Similarly, Adekiya and Agbede (2017) reported that the two-year average tomato yield was highest when manure was incorporated 3 WBP (10.2 t ha^{-1}), and decreased to 8.7 t ha^{-1}, 7.4 t ha^{-1} and 6.2 t ha^{-1} when manure was applied at 0 WAP, 3 WAP, and 6 WAP respectively. Fatondji and Ibrahim (2018) observed that when manure was incorporated at 2 WBP, millet grain yield increased by 16 % and 20 % more than when incorporated at 0 and 2 WAP, respectively, and the trend was replicated on crop biomass. However, the results of crop yields in this study slightly deviate from the agreements mentioned above and might be due to other factors such as climate, manure type, release patterns, etc. (Mkhabela and Materechera 2013).

3.3.5.2. Soil fertility

Effect of manure on time of application generally increased soil pH (5.8 %; Figure 3.8a), SOC (58 %; Figure 3.8b), TN (71 %; Figure 3.8c), AP (81 %; Figure 3.8d), and K (64 %; Figure 3.8e) relative to absence of manure. Except for TN, all the soil fertility properties showed the biggest increase when manure was applied before planting compared to after planting. Thus, the increase in pH was highest by 9 % when manure was applied before planting than after planting (0.58 %), SOC increased by 120 % when manure was applied before planting than after planting (56 %). Total N had a maximum increase when manure was added after planting (160 %) than before planting (92 %), Available P increased by 200 % with adding manure before than after planting (42 %), while K increase was observed when manure was applied before planting (95 %) than after planting (78 %).

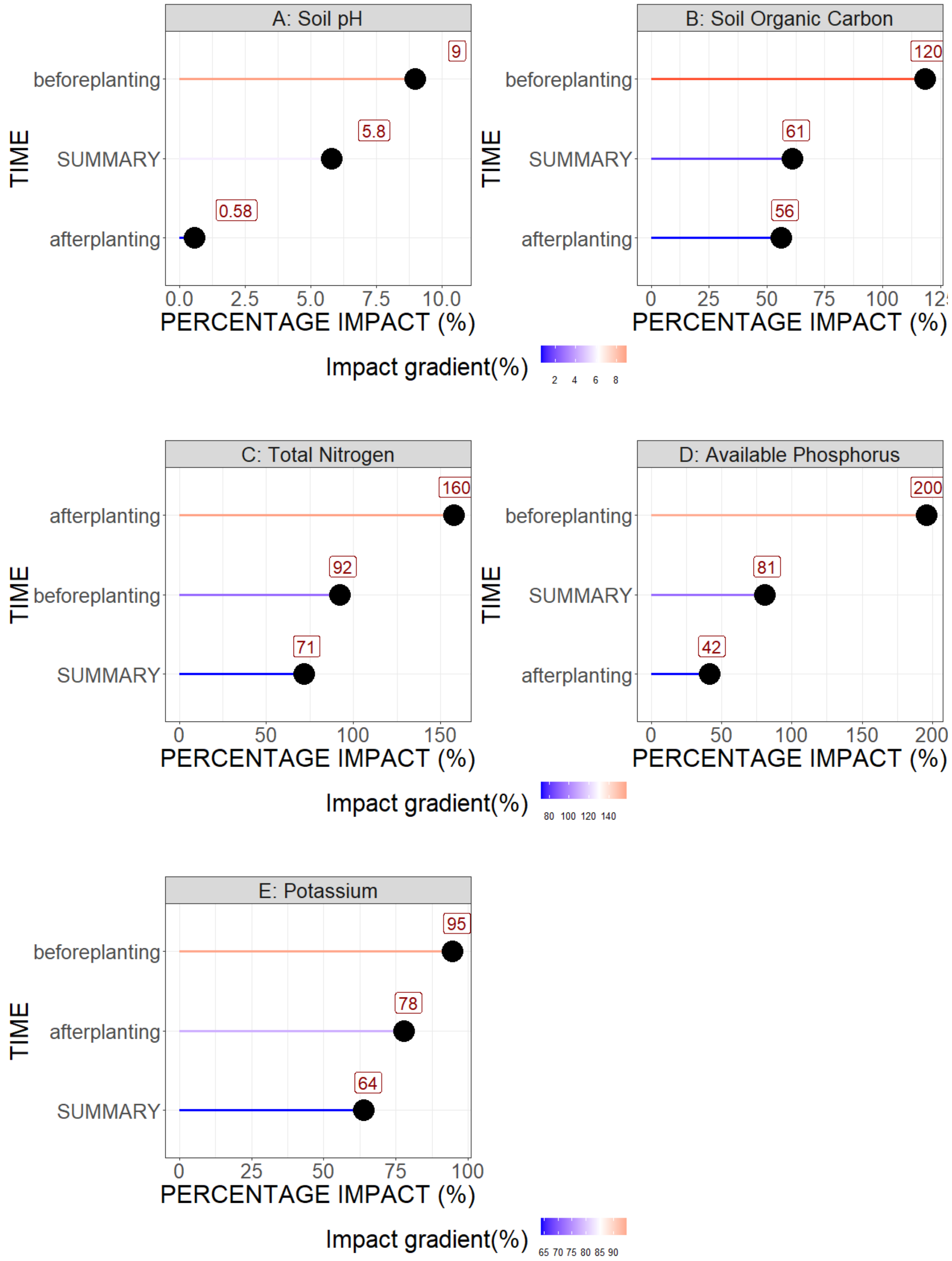


Figure 3. 8a-e: Meta-analysis summary impact of the effect of manure application time on (A) soil pH, (B) soil organic carbon, (C) total nitrogen, (D) available phosphorus and (E) potassium.

These results are in accordance with Kolawole (2014) who observed the highest increase in pH, SOC, TN and P when manure was applied at 2 WBP than at 0 and 2 WAP. It has been suggested that more than 80 % of manure mineralization happens in the first fortnight after incorporation (Mkhabela and Materechera 2013). Therefore, applying organic materials earlier facilitates manure breakdown into smaller particles by insects such as termites and ants which enhances smooth microbial mineralization (Fatondji and Ibrahim 2018; Zhu et al. 2020), ensuring early nutrient release and availability for crop absorption. In addition, the C: N ratio is something to be aware of as far as manure application time and mineralization dynamics are concerned because manure with an extreme C: N ratio, such as cattle manure, is recalcitrant (Azeez and Van Averbeke 2010; Zhu et al. 2020). Manure with a high C: N ratio mineralise slowly and reduce the growth and development of plants; hence they should be applied earlier than manure with low C: N, which decomposes more rapidly (Mkhabela and Materechera 2013). The exceptional case of a larger increase in TN, after planting than before planting, can be attributed to delayed application which leads to the failure of plants to utilise the nutrients (Adekiya and Agbede 2017).

3.3.6. Effect of manure type on crop yield, biomass yield and soil fertility

The application of different manure types influenced the crop yield by 120 % in comparison to the absence of manure (Figure 3.9a), whereas crop biomass increased by 52 % (Figure 3.9b). Cattle manure demonstrated the highest percentage crop yield increase (350%), followed by poultry (220 %), then goat manure (200 %) as shown in Figure 3.9a. For crop biomass, on the other hand, poultry manure displayed the highest increase (210 %), followed by goat (46 %), and cattle manure (45 %) as shown in Figure 3.9b.

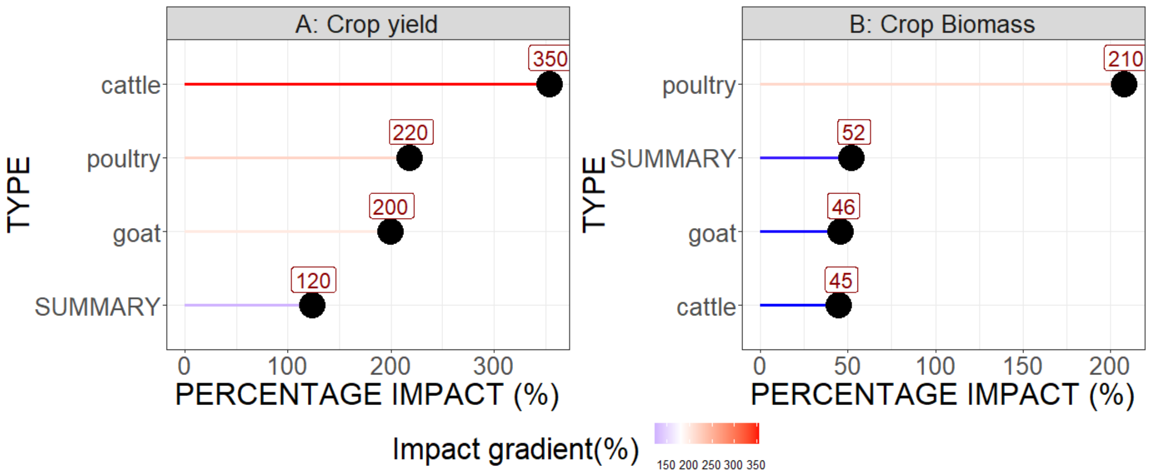


Figure 3. 9a-b:: Meta-analysis summary impact of the effect of manure application time on (A) crop yields and, (B) biomass yields.

On average amending manure in soil increased soil pH (Figure 3.10a), SOC (Figure 3.10b), TN (Figure 3.10c), AP (Figure 3.10d), and K (Figure 3.10e) by 6.2, 71, 78, 98 and 94 % respectively in comparison to the absence of manure. Goat manureresulted in the highest TN and pH, with a percentage increase of 310 % and 12 % respectively, while the largest increase in SOC, AP, and K was observed after the addition of poultry manure with 150 %, 380 %, and 280 % respectively. Moreover, poultry manure had the lowest pH increase, while cattle manure had the lowest increase in SOC and TN, and goat manure had the lowest increase in AP and K.

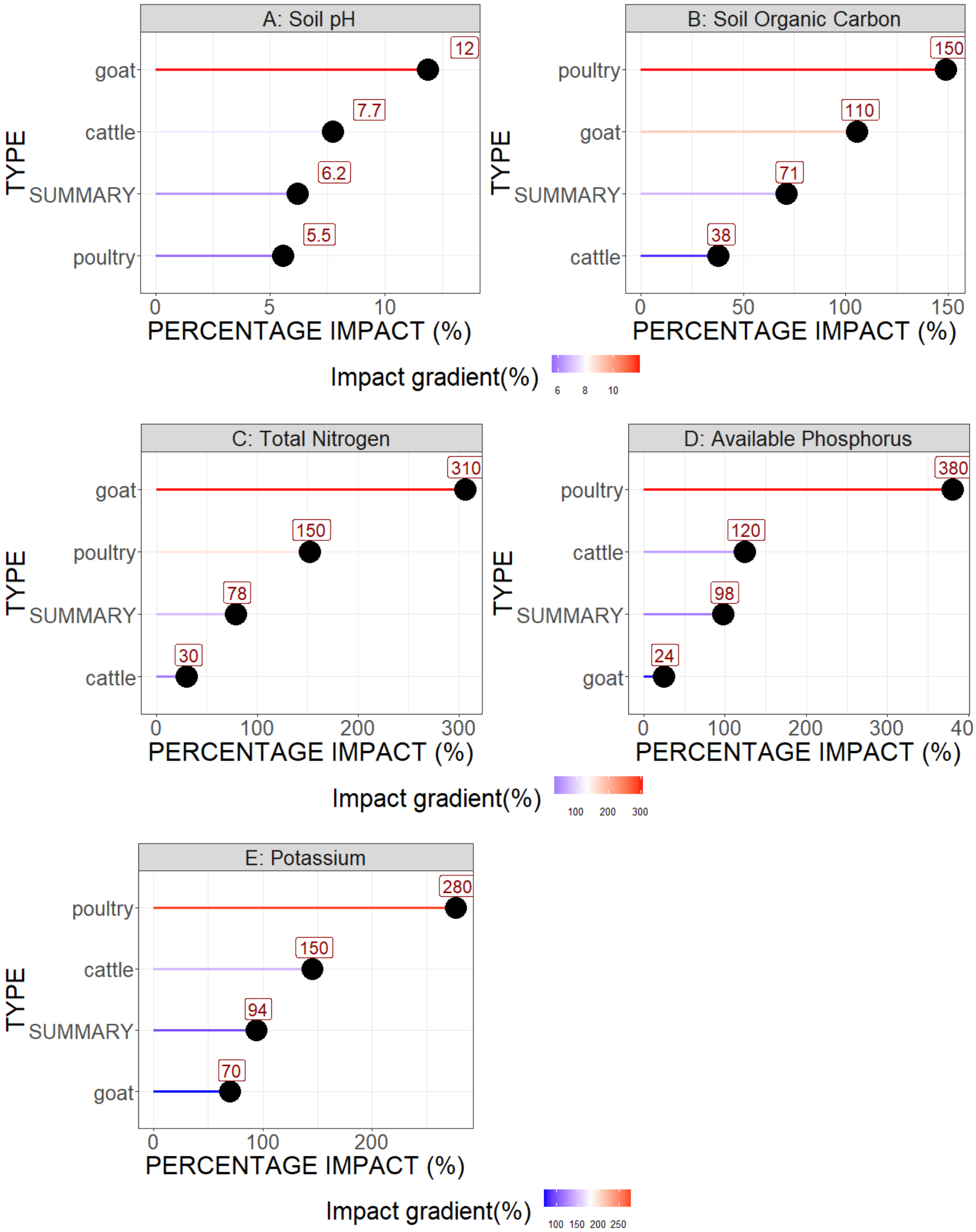


Figure 3. 10a-e:: Meta-analysis summary impact of the effect of manure application time on (A) soil pH, (B) soil organic carbon, (C) total nitrogen, (D) available phosphorus and (E) potassium.

A great deal of evidence is available on the outstanding richness of nutrients in poultry manure compared to other types of manure, which is the absolute reason for the significant crop yield increases. For instance, higher N and P content was reported in poultry than in cattle manure (Mkhabela and Materechera 2013). Azeez and Van Averbeke (2010) reported the highest SOM, TC, TN, Ca, P, Na, Cu, and Mn in poultry compared to cattle and goat manure. Similarly, Chipomho et al. (2018) reported the highest TN, K and Ca in poultry compared to cattle and goat manure. The reason for these increases is that poultry excretes urine and manure as a mixture, compared to cattle and goats which excrete separately (Azeez and Van Averbeke 2010), subjecting the urine to evaporation because it contains high nitrate concentration. In addition, kraals of ruminants are outside without a roof and base (Dzvene 2017), which exposes manure to leaching and volatilization, while poultry is kept in proper shelters which prevents losses of manure. Hence, this wealth in poultry manure nutrient content subsequently contributes to yield increase.

However, while poultry manure may have wider domination in increasing various parameters, an exception was observed in soil pH and crop yields. The inferior effect of poultry manure on soil pH than other manure types is common (Azeez and Van Averbeke 2010; Saka et al. 2017; Chipomho et al. 2018; Mokgolo et al. 2019), and to some extent reducing soil pH relative to untreated control (Dikinya and Mufwanzala 2010). This decline can mainly be explained by the excessive concentration of ammonium ions in poultry manure, which releases H+ ions when dissolved in solution diminishing soil pH (Azeez and Van Averbeke 2010). Some authors also suggested that the high presence of Ca^{+} and Mg^{+} ions in goat and cattle manure may contribute to higher pH relative to poultry manure (Azeez and van Averbeke 2012). Therefore, this decline in pH correspondingly can mask the availability of Na, K, Ca, and Mg cations and intensify P fixation by Al and Fe oxides/hydroxides, leading to yield reduction. This could explain why in this study cattle manure had a larger crop yield increment than poultry manure. This notion was also demonstrated by Hossain and Ishimine (2007), who reported 125.29, 171.44 and 85.72 mg kg^{-1} of nitrate, 2682.62, 116.93 and 56.79 mg kg^{-1} of ammonia, and 40 500, 26 800 and 26 200 mg kg^{-1} of TN in poultry, goat and cattle manure respectively, but observed the lowest crop and biomass yields on poultry manure, notwithstanding its high ammonia and TN.

Despite the general superiority of poultry manure, the influence of different manure types on crop yields and soil fertility is usually heterogeneous. This is primarily because of the digestive system of animals (ruminants and non-ruminants) and the feed animals consumed and, to a lesser extent, handling techniques like storage and collection of manure, cause disparities in nutrient composition (Zhu et al. 2020), but the underlying view is that all manure types increase crop yields and soil fertility. The nutrient content of manure is dependent on the livestock feed, but it is generally understood that animals in smallholder farming settings consume poor feed and receive inadequate feed supplementation (Sileshi *et al.* 2019). These animals mostly scavenge on natural pastures and remaining crop residues after harvest, and the manure quality and quantity are additionally compromised in dry agro-ecological zones or during drought years.

3.4 Conclusions and recommendations

This meta-analysis was conducted to determine the correct application of manure management strategies, how they affected crop and biomass yields and some major soil fertility parameters. Based on the findings, it can be concluded that the medium application rate is the best rate for optimum crop yields and soil fertility. This rate is congruent with the affordability of manure by farmers than high rates (above 10 t ha^{-1}). Undoubtedly, incorporating manure is the appropriate application method rather than broadcasting because manure can mix with soil rapidly accelerates synchronisation of manure and release nutrients earlier as well as preventing manure loss which is high if broadcasted. Application before planting can be the best option for improving yields and soil fertility. This facilitates early mineralization of manure for nutrient release especially phosphorus, which is required for primary root growth, and may apply mostly to manure with a high C: N ratio, which decomposes slowly. Lastly, regarding manure types, all manure types evaluated in this meta-analysis can be recommended based on their availability to farmers, but attention may be required to poultry manure because it may be detrimental. Even though this meta-analysis was specific to management practices of application, other management practices such as manure storage, collection and treatment should need deeper understanding. Future experimental studies in SSA should focus more on the method and timing of manure because plenty of studies have been constant on application rates only. Lastly, since meta-analysis is a significant tool in summarising and analysing different studies, researchers may need to adequately include all statistics especially standard deviations and standard errors which strengthens the power of the meta-analysis as these can pose challenges when developing comparative datasets from published literature.

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CHAPTER 4: The effect of biochar and manure on soil properties, and growth, yield and biofuel characteristics of *Sorghum bicolor*

Abstract

There are growing efforts for use of biochar as a soil amendment in improving soil and crop productivity. However, little is known about biochar applied as sole or co-applied with manure effects on soil functioning in sweet sorghum cultivation. This study aimed to investigate the effects of amending co-applied (with cattle and kraal manure) or sole biochar, on soil physicochemical properties and sweet sorghum growth, phenological, yield and biofuel components. An experiment was conducted two different fields (Field A (2020/2021) and Field B (2021/2022)) with a follow-up trial in Field A (2021/2022) the next season at Welgevallen Experimental Farm, Stellenbosch University. A complete randomised block design with 6 treatments was applied; i.e., control, cow manure, biochar, kraal manure, kraal manure and biochar, and cow manure and biochar. Results in Field A showed that sole biochar and kraal manure resulted in significantly better results than the control and other treatments for various soil chemical properties, while Field B showed inconsistent results. Sole biochar improved all physical soil properties in both fields. Despite no visible difference in growth traits, both co-applied biochar and manure treatments resulted in the highest yield and biofuel traits, followed by sole biochar. In terms of field comparisons, Field B was more productive than Field A with regard to yield and biofuel components. Field A's follow up trial was less productive than the primary trial, but both co-applied biochar and manure treatments increased sweet sorghum productivity. This study confirms that sole or co-applied biochar with manure can play a significant role in modifying soil fertility and sweet sorghum production.

Keywords: organic materials, biofuels, soil degradation, smallholder farming.

4.1. Introduction

The deterioration of soil fertility threatens agriculture's goal of providing food for the growing global population, which is projected to reach between 9.4 and 10.1 billion by the year 2050 (UN 2019). In agriculture, synthetic fertilisers and organic wastes are widely applied to counter soil deterioration (Agbede and Adekiya 2020). In particular, manure is typically used, over inorganic fertilisers, in smallholder farming systems because of its cost-effectiveness and ability to offer additional benefits to soil (Adekiya *et al.* 2019a). However, the rapid mineralisation of manure after its addition to soil compromises its long term sustainability on soil fertility and soil organic matter (SOM) due to its labile carbon (C) that can be utilised by microorganisms (Dzvene *et al.* 2019; Rasafi *et al.* 2021). Therefore, the inclusion of organic sources like biochar that decompose gradually due to recalcitrant organic carbon (OC), ensures a continuous supply of necessary functions to the longer-term and may improve agricultural efficiency.

Biochar is a black C, derived from the pyrolysis process through burning organic materials under elevated temperatures and partial oxygen conditions (Agbede and Adekiya 2020; Nyambo *et al.* 2020). Its richness in C makes biochar an exceptional soil conditioner due to elevated stability and gradual mineralisation (Burrell *et al.* 2016). Available evidence in literature suggests biochar can settle for more than 1 000 years, and primarily sequesters 50 % of its C, which equates to roughly 2.2 M ton year^{-1} of SOC (Nyambo *et al.* 2018), thereby contributing to sustainable long term soil functioning. Biochar remarkably supports soil physical, chemical and biological properties (Castellini *et al.* 2015; Agbede and Adekiya 2020), which is motivated by its intrinsic properties that arise during pyrolysis as well as the origin of biochar feedstock (Nyambo *et al.* 2018). As such, knowledge on the origin of biochar feedstock and pyrolysis conditions is important before the biochar is incorporated into the soil.

Biochar is reportedly known to directly supplement soil nutrients (Dzvene *et al.* 2019), while indirectly improving nutrient retention, which is attributed to its relatively high cation exchange capacity (Yu *et al.* 2019), increasing nutrient use efficiency. Biochar improves SOM mineralisation dynamics which ensures the gradual release of nutrients. It is also associated with important microorganisms involved in nutrient cycling (Rollon *et al.* 2020). Furthermore, biochar improves soil pH, which can be credited to its moderate pH which ranges between 6 and 9.6 (Agegnehu *et al.* 2017). This greatly enhances mineral nutrient availability such as soil P and K (Adekiya *et al.* 2019a), while reducing aluminium toxicity, especially under highly weathered soils (Agegnehu *et al.* 2017). Biochar undoubtedly also increases soil OC because of its internal recalcitrant OC (Dodor *et al.* 2019). This essentially improves diverse soil functions such as the provision of habitat and energy to soil fauna and nutrient preservation through its strong ability to hold soil aggregates (Nyambo *et al.* 2018).

Biochar can also significantly influence soil bulk density (BD), porosity (SP), moisture content and aggregate stability (AS) (Obia *et al.* 2016). This is because biochar consists of relatively low BD, below 0.6 g cm^{-3} (Agbede and Adekiya 2020), and is highly porous (Dodor *et al.* 2018), which can significantly decrease BD by 11-32.9 %, and increase SP by 15.4-46.5 % (Agbede and Adekiya 2020) through soil-biochar interaction mechanisms. This may enhance macropore formation which extensively facilitates other soil parameters like aeration, water holding capacity, volumetric water content, infiltration and permeability (Burrell *et al.* 2016). Moreover, biochar improves AS through the manner in which it manipulates other soil characteristics such as SOM, OC, CEC, surface area, and microbial support, which promotes soil binding and interaction (Obia *et al.* 2016), and can reduce soil loss by 27–70 % (Nyambo *et al.* 2018). This ultimately reduces soil erosion potential, while improving water and nutrient retention as well as creating a favourable environment for plant root growth.

Consequently, manipulation of soil properties following biochar incorporation heavily influences crop production. More prominently, biochar improves root morphology by modifying the rhizosphere (Lehmann *et al.* 2011). This enhances roots efficiency to secure nutrients, therefore improving plant growth and, ultimately, yield (Yu *et al.* 2019). In literature, biochar's influence on commercial crops such as maize (Dzvene *et al.* 2019), radish (Adekiya *et al.* 2019a), wheat (Castellini *et al.* 2015) and tomatoes (Githinji 2014) is well documented, notwithstanding heterogeneous results (Kavitha *et al.* 2018). A recent review by Palansooriya *et al.* (2019) observed that biochar rates of between 0.1 t ha^{-1} and 67.5 $t.ha^{-1}$ can increase yields by 2-143 %. However, the influence of biochar on traditional and neglected crops remains largely unknown. Traditional and neglected crops play major roles in food security, and the social and cultural systems of local communities. Moreover, they are versatile for cultivation under local climate and soil conditions (Tadele 2018). In this study our interest is on sweet sorghum.

Sweet sorghum (*Sorghum bicolor (L.)* Moench) is a crop native to sub-Saharan Africa (SSA) and offers multiple uses for food, forage, and biofuel (Oyier *et al.* 2017; Chattha *et al.* 2020). Currently, sweet sorghum is under the global spotlight as a promising biofuel feedstock, more so than traditional feedstocks such as maize, sugarcane and sugar beet (Zegada-Lizarazu and Monti 2012), due to the sweet sorghum's comparatively abundance of hexose sugars with considerable extraction and conversion efficiency to ethanol (Mengistu *et al.* 2016). In addition, sweet sorghum has tremendous adaptive features, making ease of cultivation under marginal environmental conditions, such as unreliable climate, flooding, salinity and depleted soil fertility possible (Malobane *et al.* 2018). These poor conditions are prevalent in smallholder farming systems, and simultaneous inclusion of sweet sorghum and biochar may offer a sustainable solution to optimise agricultural production.

Nonetheless, few studies have been conducted on the direct comparison between biochar and manure or biochar/manure combination. Convincing farmers to include biochar in their systems requires proper recommendations which desires rigorous comparison between the biochar and the manure that they use. Therefore, the aim of this study was to investigate the effects of amending soil with biochar, either sole or co-applied with cattle and kraal manure, on soil physicochemical properties and sweet sorghum growth, phenological, yield and biofuel components.

4.2. Methods and materials

4.2.1. Experimental sites

The experiment was conducted under two different fields which were named Field A and Field B, separated by a 200 m distance, and a follow-up trial was conducted in Field A only in the next season. The experiment was conducted at Welgevallen Experimental Farm (WEF), Stellenbosch University, Stellenbosch, South Africa (33°56'52.5"S, 18°52'19.9"E, altitude 119 m asl). Field A was previously under plastic growth tunnels which were removed, and the soil was characterised by high bulk density. Field B was previously under cannabis trials and the soil was characterised by high acidity. The WEF is characterised by a Mediterranean climate with dry summers, mean annual rainfall of 802 mm mostly in the winter months of June, July, and August and an average annual temperature of 16.4 °C (Loggenberg 2018). The soil on both sites are sandy and sandy loamy, categorised as Cambisol according to World Reference Base, and Oakleaf according to the South Africa Soil Classification system (Makeredza *et al.* 2013).

4.2.2. Biochar, cattle manure and kraal manure

Pinewood biochar, pyrolyzed at 500 °C, was used in this study and was supplied by Biomass Innovations (Pty) Ltd. Biochar production conditions and characteristics were provided by the manufacturer. Cattle manure was handpicked in paddocks at Mariendahl Experimental Farm (Stellenbosch University) and air dried. Kraal manure was purchased at Agrimark Hardware located in Stellenbosch Town and also air dried. Kraal manure consists of cattle dung which is mixed with other organic materials such as crop residues, tree and plant residues (Sileshi *et al.* 2017). Normally farmers put these materials in kraals to supplement their animals, and they mix with manure, thus this is how kraal manure differs from cattle manure, and the reason why it was included in this study. The chemical composition of all the treatments (biochar, manure, and combined) were determined before the start of the experiment.

4.2.3. Treatments and design

A complete randomised block design (CRBD) with 6 treatments, replicated 4 times, totalling 24 plots was used. The treatments were (i) untreated soil control (C), (ii) soil with cow manure (CM), (iii) soil with biochar (B), (iv) soil with kraal manure (KM), (v) soil with kraal manure and biochar (1:1) (KMB), and (vi) soil with cow manure and biochar (1:1) (CMB). All the treatments were applied at 10 t ha^{-1} application rate, also as per manufacturer's protocol for the biochar.

4.2.4. Soil physicochemical properties

4.2.4.1. Chemical properties

Initial soil samples (baseline) were collected before land preparation, and at harvest of sweet sorghum in Field A (2020/21) and Field B (2021/2022) only. Soil samples were not collected on the follow-up trial Field A (2021/2022) because the focus for the follow up study was on crop performance. In each plot, four samples were randomly taken at 15 cm depth using a soil auger and mixed to produce a composite sample. The samples were air dried and sieved using a 2 mm sieve prior to analysis. Soil analysis was outsourced at BemLab (Somerset West) and Elsenburg (Western Cape Department of Agriculture, Stellenbosch). The soil properties measured were as follows: available nitrogen (NH^{4+}-N and NO_{3-} -N), available P, available K, available S, available Na, soil pH, OC, cation exchange capacity (CEC), exchangeable bases (Ca and Mg), and available metal elements (Cu, Fe, Mn, and Zn).

4.2.4.2. Physical properties

Bulk density (BD) was determined as described by Okalebo *et al.* (2002). The soil (undisturbed) samples were taken from each plot using a core sampler to a depth of 15 cm and then weighed. The samples were subsequently oven dried at 60 °C for 5 days and weighed again to determine mass of dry soil. Bulk density, ρb ($g\ cm^{-3}$), was calculated as follows:

$$\rho b = \frac{Md}{Vs} \qquad (1),$$

where *Md* is the mass of dry soil and *Vs* is the volume of core sampler. Soil porosity, *SP* (%) was determined from ρb by assuming a particle density of 2.65 $g.cm^{-3}$ and 98 % saturation using the following equation:

$$SP = \left(1 - \left(\frac{\rho b}{\rho d}\right)\right) x\ 100\% \quad (2),$$

where ρb is the soil bulk density and ρd is the particle density. Gravimetric moisture content, U was determined using the following equation:

$$U = \frac{Mw - Md}{Md} \quad (3),$$

where *Mw* is the mass of wet soil, *Md* is the mass of dry soil. Volumetric water content, θ (cm^{-3} cm^{-3}) was derived from gravimetric water content, soil bulk and water density as follows:

$$\theta = U \frac{\rho b}{\rho w} \quad (4),$$

where *U* is the gravimetric water content, ρb is the bulk density and ρw is the density of water.

Aggregate stability was determined following the methods by Le Bissonnais (1996). Air dried soil samples (2 mm sieved) were initially oven-dried at 40 °C for 24 hours for ensuring uniform drying on all samples. Five grams of soil was weighed and cautiously submerged in a 250 mL beaker filled with 50 mL of deionized water for 10 minutes. A pipette was then used to siphon off the water, while the slaked aggregates remained. The aggregates were poured into a 53 µm sieve which was gently moved up and down in ethanol, five times, to separate the fragments (< 53 µm) from those (> 53 µm). The remaining > 53 µm fraction was oven dried at 105 ^{o}C for 24 hours and sieved on a stack of sieve fractions (2000, 1000, 500, 250, 106, and 53 µm) using an automatic sieve machine (Spartan 55743, Idar-Oberstein, Germany) for 10 minutes. The weight of each fraction was measured, and the weight of the soil fraction < 53 µm was calculated as the difference between the initial weight and the sum weight of the other six fractions and expressed as the mean weight diameter (MWD) using the following equation:

$$MWD = \sum_{n=1}^{i} w_i x_i \quad (5),$$

where w_i was the weight fraction of aggregates in i^{th} size range of the total dry weight of the sample analysed and x_i the mean diameter of the i^{th} size range of aggregates separated by sieving (Le Bissonnais 1996).

4.2.5. Sorghum cultivation

4.2.5.1. Agronomic practices

The experiment was established in the summer season of 2020/21 (Field A) and the second in the summer season of 2021/2022 (Field B) at WEF. Field A was replanted again as a follow-up trial in the summer season of 2021/2022 without re-incorporation of treatments. The ground was firstly tilled using a mouldboard plough and subsequently disked to attain fine tilth. Plot sizes of 9.2 m^2 with inter- and intra-row spacing of 44.5 cm and 15.0 cm respectively were used. Each plot accommodated seven rows. Data collection was excluded from the 2 outside rows and the first 15 cm for both sides, to evade border effects. All treatments were incorporated at a depth of 10 cm into soil 2 weeks before planting to initiate decomposition and proper mixing of soil and the treatments (Apori *et al.* 2021). Planting of sweet sorghum seeds was done on the 6th of January 2021 in Field A (2020/21 and) the 6th of October 2021 in Field B (2021/2022) and Field A's follow-up trial using a rate of 15 kg ha^{-1} and sowing depth of 25 mm. Four weeks after planting on all fields, the seedlings were thinned to the required spacing and targeted population of 148 148 plants ha^{-1}. No fertiliser was added, and weed control was done by hand and hoeing when essential. In addition, during week six in Field B and the follow-up trial of Field A, a severe fungal attack on plant leaves was observed, and a fungicide (Azoxystrobin, 40 L.ha^{-1}.) was applied. Sprinkler irrigation was used to supplement crop water needs by targeting about 25 mm per week. Weather data (at WEF) for both growing seasons was collected by- and obtained from the Department of Horticulture (Stellenbosch University). The sweet sorghum landrace used in this study was sourced from a smallholder farmer in Rustenburg (North-West Province).

4.2.5.2. Data collection

Crop growth

Crop growth parameters were collected at 2-week intervals after thinning, from 5 weeks after planting (WAP). Eight plants per plot were randomly chosen and tagged for data collection. Stem diameter was measured between 10-15 cm from the ground, using a digital vernier calliper (Tricle Brand, Shangai, China). Plant height was measured from the ground to the horizontal surface of the topmost grown leaf of the plant, and on the flag leaf, when it was visible, using a tape measure. Chlorophyll content index (CCI) was measured on the middle of the topmost grown leaf of a plant, and on the flag leaf when it was visible, using a digital chlorophyll meter, atLeaf CHL PLUS (FT Green LLC, Wilmington, Germany). Leaf Area Index (LAI) was determined using a ceptometer (ACCUPAR LP-80 2.50.3 METER, Group Inc. USA). The ceptometer was placed at a 45° angle adjacent to two rows and measured above and below canopy photosynthetically active radiation (PAR). Both CCI and LAI were measured within 1 hour of solar noon on clear days. Number of leaves per plant was enumerated on photosynthetically active (fully developed with a leaf collar) leaves (Hadebe *et al.* 2020).

In addition, due to the heavy winds which started during the 14th week (in April) after planting in Field A prior to the rain season, lodging scores were collected as the plants were affected from week 15 up to the termination of the experiment (week 25). Similarly, in Field B, lodging scores were recorded from the time lodging started. The scores were based on scale of 0 to 5, with 0 = no lodging, 1 = 20 % of plants lodged, 2 = 40 % of plants lodged, 3 = 60 % of plants lodged, 4 = 80 % of plants lodged, and 5 = plot completely lodged (Teetor *et al.* 2011).

Phenology

Days to 50 % flowering, were determined as the days taken from the sowing date to the day 50 % of the population in a plot commenced flowering, and days to 90 % physiological maturity, as the days taken from sowing day to the day 90 % of the population leaves changed to a predominantly yellow colour.

Yield and yield components

Harvesting was conducted as described by Teixeira *et al.* (2017) and Naoura *et al.* (2020) from week 21 to week 22, which was the period between soft-hard dough stages to physiological maturity. Fifteen plants per plot were randomly cut at 5 cm from the base with secateurs and separated into stalks, panicles, and leaves, and weighed to determine fresh stalk weight (FSW), fresh panicles weight (FPW) and fresh leaves weight (FLW) using a balance. Sub-samples were taken and subsequently oven dried at 60 °C for 5 days and dry biomass was recorded for dried stalk weight (DSW), dried panicles weight (DPW) and dried leaves weight (DLW). Moisture content was determined as the percent difference between fresh and dry weights. The fresh stalk yield (FSY) and dry stalk yield (DSY) were calculated as the average of FSW and DSW respectively multiplied by plant population per hectare. The dry panicle yield (DPY) and dry leaf yield (DLY) were calculated as the average of DPW and DLW, respectively, and multiplied by plant population per hectare. Total dry biomass yield (TDBY) was calculated as the summation of DSY, DPY and DLY. Fresh stalk yield was quantified from fresh stalks only without leaves and panicles. Grain yield (GY) was measured by choosing randomly 10 panicles and air dried to constant weight for 7 days. Panicles were thrashed manually using hands, and fresh grain weight (FGW) was measured. All the grains were oven dried at 60 °C for 3 days and dried grain weight (DGW) was measured. Moisture content was determined as the percent difference between FGW and DGW. The moisture percentage was adjusted at 14 % to determine the final GY (Ganesh *et al.* 2010). Thousand kernel weight was determined by counting 1

000 oven dry grains using a counting machine (Ikon InstrumentsC-241, Jhilmil Colony, New Delhi, Delhi, India, 110095) and weighing them.

Biofuel components

Biofuel properties of the sweet sorghum were quantified from 10 stalks of the 15 plants sampled for yield parameters. Juice from internodes number 2 and 3 of each sampled plant was squeezed using pliers or hands and brix (%) was measured using a digital refractometer (SCM-1000, HM Digital Inc. CA, USA). Brix (%) is highly influenced by the location of the internodes on the stalk, and the choice of internodes sampled in this study represents the brix for the whole plant during the soft to hard dough stages (Teixeira *et al.* 2017).

Juice and sugar yields were calculated according to (Naoura *et al.* 2020):

$$CSY = (FSY - DSY) \times Brix \times 0.75 \quad (6),$$

$$JCY\ (80\%\ extracted) = [FSY - (DSY - CSY)] \times 0.8 \quad (7),$$

$$SGY = JCY \times Brix \times 0.75 \quad (8),$$

where CSY is conservative sugar yield (t ha^{-1}), FSY is fresh stalk yield (t ha^{-1}), DSY is dry stalk yield (t ha^{-1}), JCY is juice yield (t ha^{-1}), and SGY is sugar yield (t ha^{-1}). Sugar concentration of juice (SCJ) was determined as 75 % of Brix expressed in g kg^{-1} sugar juice:

$$SCJ\ (g.kg^{-1}) = 0.75 \times Brix \quad (9),$$

Theoretical ethanol yield (TEY, L ha^{-1}) from extracted juice was calculated as sugar yield (kg ha^{-1}) multiplied by a conversion factor of 0.581 L kg^{-1} sugar:

$$TEY\ (L\ ha^{-1}) = CSY \times 0.581 \quad (10),$$

4.2.6. Data analysis

All soil physicochemical properties were analysed using a simple analysis of variance (ANOVA) and were analysed separately by field. A repeated measures ANOVA was used to determine the changes in growth, phenological, yield, and biofuel parameters of sweet sorghum across the treatments using the residual maximum likelihood (REML) approach, the growth, yield, and biofuel parameters being the dependent factors, while the treatments were the independent factors. The blocks (replications) and plants were treated as random factors in cases of growth parameters, while the blocks only were treated as random factors in cases of yield and biofuel parameters. Pearson's correlation coefficients were calculated to determine how the biofuel and yield characteristics are related. In, addition, homogeneity of variance using Bartlett's test was used to compare the growth, yield, and biofuel parameters of sweet sorghum between Field A (2020/21) and Field B (2021/2022), and Field A (2020/21) and the follow-up trial (Field A (2021/2022)). JMP version 14.0 statistical software (SAS Institute, Inc., Cary, NC, USA) was used for statistical analysis and mean separation techniques was tested using Tukey's HSD test.

4.3. Results

4.3.1. Initial soil properties and weather data

The initial soil properties for both sites (Field A and B) as well as the initial analysis of all organic materials used as treatments are shown in Table 4.1. The soil texture for Field A and B was sand and sandy loam respectively, while the pH was neutral and slightly acidic, respectively. Both the soils were high in bulk density, very low in OC and soil nutrients, but generally, soil from Field B had better fertility status than Field A. On the organic amendments, biochar had the highest pH, OC, CEC, and B. Kraal manure had the highest P, K, S, exchangeable Ca, exchangeable Mg, Cu and Zn. Combined kraal manure and biochar had the highest Fe, while the combined cattle manure and biochar had the highest Mn. Unfortunately, NH_4 and NO_3 could not be determined because of high organic matter. In addition, the biochar used in this study had high moisture content, volatile matter, fixed carbon, and ash.

The weather data for the season 2020/21 is represented in Figure 4.1b and Figure 4.1b, while Figure 4.2a and Figure 4.2b depict weather data for the season 2021/22. During the 2020/21 season, the max and min temperature and solar radiation were highest from January 2021 to February 2021 and thereafter started to decline in March 2021, whereas during 2021/22, they were low in October 2021 and reached the highest during January 2022 then decreased afterwards. Thus, max and min temperature and solar radiation were higher during the first two months of season 2020/21 than the first two months of season 2021/22. The total rainfall and irrigation received for the season 2020/21 were 173.6 and 290 mm respectively, while for the season 2021/22 it was 81.4 and 394 mm respectively, giving the total amount of water for seasons 2020/21 and 2021/22 to 463.3 and 476.5 respectively. The rainfall during 2020/22 was much skewed from mid-May onwards due to the Mediterranean climate of the location which receive winter rainfalls.

Table 4. 1:: Initial soil (0-15 cm depth) and treatment properties analysis used in this study before the beginning of the experiment. *

Properties	Unit	Field A Soil	Field B Soil	B	CM	KM	KMB	CMB
Clay	**%**	15	20	-	-	-	-	-
Silt	**%**	10	20	-	-	-	-	-
Sand	**%**	75	60	-	-	-	-	-
Type		Sand	Sandy loamy	-	-	-	-	-
pH	**H_2O**	7.28	6	7.74	7.49	7.31	7.27	7.58
OC	**%**	0.33	0.53	1.28	1.26	1.04	1.09	1.13
NH_4	**$mg.kg^{-1}$**	1.55	23.05	-	-	5.88	7.81	5.34
NO_3	**$mg.kg^{-1}$**	8.60	7.03	-	-	193.42	58.49	-
P	**$mg.kg^{-1}$**	161.00	167	273	193.00	410.00	239.00	171.00
K	**$mg.kg^{-1}$**	146.00	208	608	3704.00	10688.00	4628.00	1106.00
S	**$mg.kg^{-1}$**	4.5	6.1	44.6	116.00	300.00	100.00	192.00
Ex. cations (Ca)	**$cmol(+).kg^{-1}$**	9.20	6.18	29.39	19.07	53.22	42.70	17.96
Ex. cations (Mg)	**$cmol(+).kg^{-1}$**	0.62	0.72	6.24	16.73	24.30	13.68	3.88
CEC	**$cmol(+).kg^{-1}$**	2.73	14.04	21.66	13.67	13.67	4.32	1.80
Cu	**$mg.kg^{-1}$**	2.00	6.82	3.84	4.54	10.06	6.87	6.70
Zn	**$mg.kg^{-1}$**	8.50	13.45	31.26	29.69	162.70	77.35	48.78
Mn	**$mg.kg^{-1}$**	18.70	43.84	147.4	89.02	87.60	90.12	186.00
B	**$mg.kg^{-1}$**	0.35	0.3	0.68	0.45	0.43	0.23	0.14
Fe	**$mg.kg^{-1}$**	72.70	231.9	144.6	181.50		296.70	251.40
Moisture	**%**	-	-	4.44	-	-	-	-
Volatile Matter	**%**	-	-	19.61	-	-	-	-
Fixed Carbon	**%**	-	-	76.84	-	-	-	-
Ash	**%**	-	-	3.55	-	-	-	-

*B, Biochar; CM, Cattle Manure; KM, Kraal Manure; KMB, Kraal Manure and Biochar; CMB, Cattle Manure and Biochar

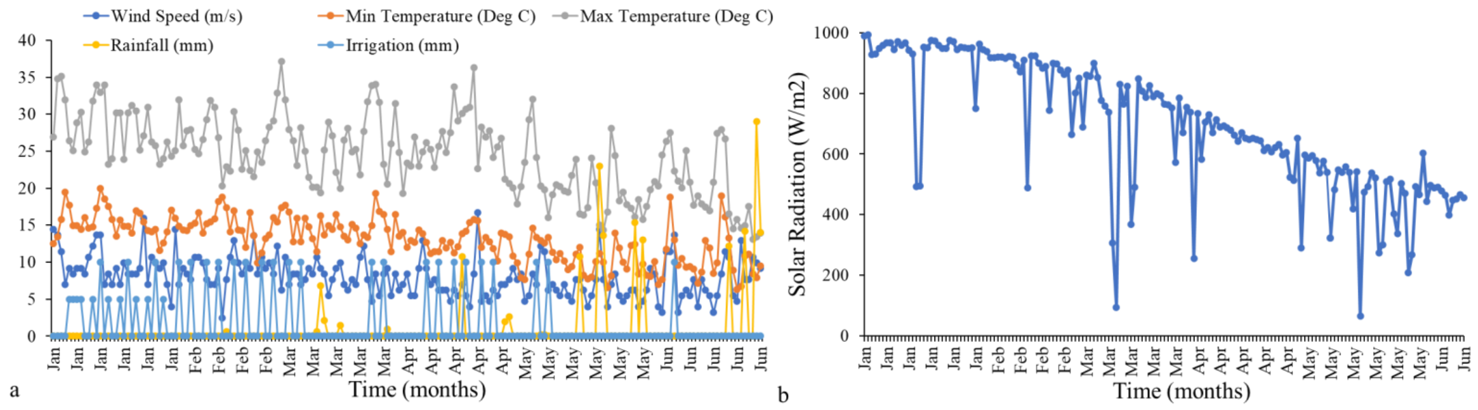

Figure 4. 1a-b:: The weather data for (a) rainfall, irrigation, min and max temperature, wind speed and (b) solar radiation for the 2020/21 trial.

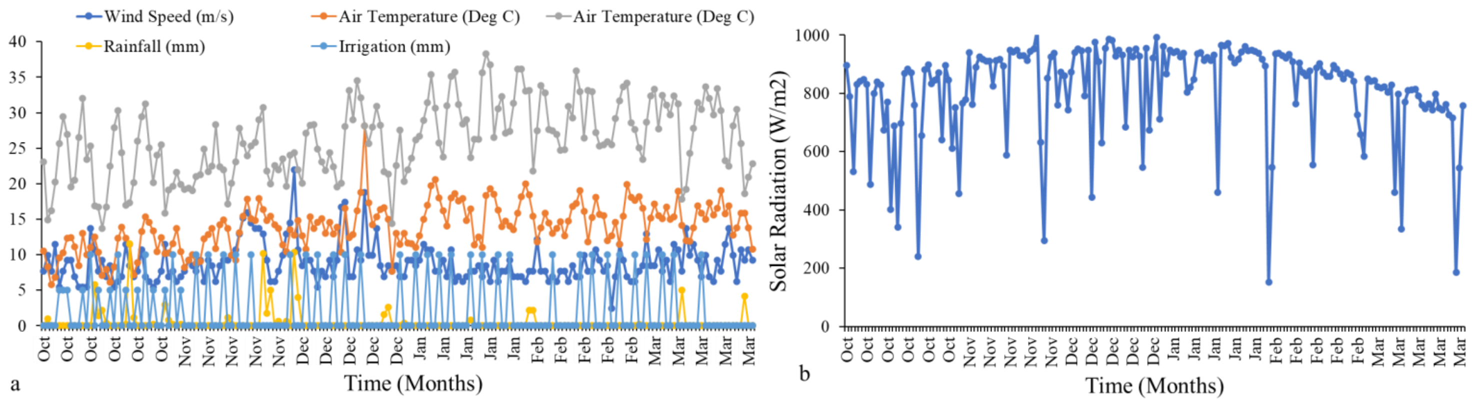

Figure 4: 2a-b. The weather data for (a) rainfall, irrigation, min and max temperature, wind speed and (b) solar radiation for the 2021/22 trial.

4.3.2. Soil physicochemical properties

The analysis of variance of treatment, during harvesting in Field A, showed significant differences for P and K ($p < 0.001$) and for Ca, Mg, Fe, Na, and Zn ($p < 0.0001$), while not significant for NH_4, NO_3, S, CEC, B, Cu and Mn ($p > 0.05$) (Table 4.2). Soil pH and OC were both significant at $p < 0.01$ and $p < 0.0001$, respectively. In Field B, the analysis of variance of treatment was significant on P, K, S, Ca at $p < 0.001$, and Mg, Na, and Zn were also significant at $p < 0.05$, $p < 0.0001$, and $p < 0.0001$, respectively; while NH_4, NO_3, CEC, B, Fe, Cu and Mn were not significantly affected. Soil pH and OC were also significantly different across Field B at $p < 0.001$ and $p < 0.0001$, respectively.

Both KM and B plots in Field A significantly increased P in comparison to other treatments, with an increase of 18.1 and 15.3 % respectively in comparison to the control plots, while no significant difference was observed between the CMB, KMB, CM plots and the control plots (Table 4.2). However, in Field B, the KMB plots were highest on P content, although it did not differ significantly from the control plots. In addition, the KM plots were significantly different in P (lower than the control), whereas the B, CM and CMB plots were not significantly different from the control (Table 4.3). Both the B and KM plots significantly increased K content by 26.9 and 22.1 % respectively in Field A than in the control plots, and were also significantly different from other treatment plots, except that the KM plots were similar to the KMB plots (Table 4.2). However, the CMB, KMB, CM and the control plots were not significantly different. In Field B, the KM plots were significantly higher than other treatment plots and increased by 26.5 % compared to the control plots on K content. In addition, the KMB plots contained significantly higher amounts of K compared to the CM and B plots, while not significantly different to the CMB and the control plots (Table 4.3).

There was an unexpected trend in exchangeable Ca on both Field A and Field B. Despite that the CM and KMB plots were highest in both Field A (Table 4.2) and Field B (Table 4.3), there was a decrease on the rest of all treatments in comparison to the control plots, with the largest decrease observed in the B (28.4 %) and KM (31.9 %) plots in Field A, and the KM (4.5 %) and CM (6.3 %) plots in Field B. However, Ca in the control plots was not significantly different from the KMB and CMB plots in Field A, and the B and CMB plots in Field B. Similarly, for exchangeable Mg, there was a decrease in the control plots in both Field A (Table 4.2) and Field B (Table 4.3). The highest decrease was observed in the B and KM plots in both Field A and Field B. However, the control plots were significantly different from the B, KM, KMB and CMB plots in Field A, and with the B plots only in Field B.

The highest Na content in Field A was observed on the control plots, implying that all treatment plots decreased Na (Table 4.2). The largest decrease was observed in the KM and CMB plots. However, in Field B, Na content was highest in the KM and KMB plots, which were significantly different from all other treatments and increased by 16 and 9.9 % respectively. In addition, no significant differences in Na were observed between the control, CM, B and CMB plots (Table 4.3). In Field B, the highest S content was observed in the KM and KMB plots, with an increase of 17.6 and 10.7 % respectively compared to the control (Table 4.3). In addition, the C, CM, B and CMB plots were not significantly different in S content.

The Fe content in Field A was highest in the B, KM and CMB plots at 74.4 %, 68.8 %, and 59.5 % respectively, compared to the control plots, but the CMB plots were not significantly different from the KMB plots (Table 4.2). In addition, no significant differences in Fe were observed between the control and the CM plots. The Zn content in Field A was highest in the B and KM plots, which were significantly different from all other treatment plots and increased by 43.1 and 26.9 % respectively from the control plots (Table 4.2). In addition, no significant differences were observed between the control, CM, KMB and CMB plots for Zn. Neither Fe nor Zn were significant in Field B.

Soil pH was highest in the B plots, which was only significantly different from the control plots in both Field A (Table 4.3) and Field B (Table 4.3). The pH in the B plots increased by 2.5 and 13.7 % on both Field A and Field B respectively. Furthermore, although the B plots did not differ significantly with other treatment plots in both fields, the control plots were not significantly different from all other treatment plots in Field A. The maximum OC was observed in the B and CMB plots in Field A (Table 4.2) and in the B and KMB plots in Field B (Table 4.3), which were significantly different from all other treatment plots in both fields, except where the KMB plots were not significantly different from the CMB plots in Field B.

Table 4. 2**.** Effect of soil organic treatments on soil fertility status at harvesting under sweet sorghum cultivation in Field A. Different letters indicate significant differences between treatments at $p \leq 0.05$.

Treatment plots	**NH4 (ug.l^{-1})**	**NO3 (ug.l^{-1})**	**P (mg.kg^{-1})**	**K (mg.kg^{-1})**	**S (mg.kg^{-1})**	**Ca (cmol(+).kg^{-1})**	**Mg (cmol(+).kg^{-1})**	**CEC (cmol(+).kg^{-1})**	
C	8.07±0.62	2.44±0.39	192.50±3.10b	74.50±3.22c	4.35±0.33	32.33±1.14ab	2.94±0.12a	9.22±0.35	
CM	8.17±0.62	2.44±0.39	196.25±3.10b	73.25±3.22c	4.37±0.33	36.32±1.14a	1.93±0.12b	9.02±0.35	
B	9.56±0.62	2.44±0.39	222.00±3.10a	94.00±3.22a	4.85±0.33	23.14±1.14c	1.10±0.12c	8.38±0.35	
KM	7.69±0.62	1.81±0.39	227.25±3.10a	91.00±3.22ab	4.70±0.33	22.03±1.14c	1.00±0.12c	8.13±0.35	
KMB	8.43±0.62	2.92±0.39	196.75±3.10b	77.33±3.22bc	4.47±0.33	29.58±1.14b	1.42±0.12bc	8.27±0.35	
CMB	6.36±0.62	2.44±0.39	201.00±3.10b	75.25±3.22c	4.37±0.33	26.29±1.14bc	1.22±0.12c	9.01±0.35	
	B (mg.kg^{-1})	**Cu (mg.kg^{-1})**	**Fe (mg.kg^{-1})**	**Mn (mg.kg^{-1})**	**Na (mg.kg^{-1})**	**S (mg.kg^{-1})**	**Zn (mg.kg^{-1})**	**pH**	**OC (%)**
C	0.31±0.02	2.18±0.29b	112.96±5.33c	33.30±2.32	167.33±7.21a	4.35±0.33	7.93±0.37b	7.58±0.03b	0.40±0.03d
CM	0.34±0.02	3.28±0.29ab	124.40±5.33c	35.45±2.32	102.00±7.21b	4.37±0.33	8.34±0.37b	7.68±0.03ab	0.91±0.03b
B	0.35±0.02	3.53±0.29a	197.00±5.33a	41.24±2.32	55.50±7.21c	4.85±0.33	11.35±0.37a	7.77±0.03a	1.23±0.03a
KM	0.33±0.02	2.24±0.29ab	190.70±5.33a	41.80±2.32	47.25±7.21c	4.70±0.33	10.06±0.37a	7.68±0.03ab	0.42±0.03cd
KMB	0.33±0.02	2.19±0.29ab	157.33±5.33b	36.79±2.32	69.75±7.21bc	4.47±0.33	7.70±0.37b	7.65±0.03ab	0.53±0.03c
CMB	0.36±0.02	2.56±0.29ab	180.17±5.33ab	40.09±2.32	54.25±7.21c	4.37±0.33	7.50±0.37b	7.69±0.03ab	1.13±0.03a

*B, Biochar; CM, Cattle Manure; KM, Kraal Manure; KMB, Kraal Manure and Biochar; CMB, Cattle Manure and Biochar

Table 4. 3:: Effect of soil organic treatments on soil fertility (nutrient composition) status at harvesting under sweet sorghum cultivation in Field B. Different letters indicate significant differences between treatments at $p \leq 0.05$.

Treatments plots	**NH4 (ug.l^{-1})**	**NO3 (ug.l^{-1})**	**P (mg.kg^{-1})**	**K (mg.kg^{-1})**	**S (mg.kg^{-1})**	**Ca (cmol(+).kg^{-1})**	**Mg (cmol(+).kg^{-1})**	**CEC (cmol(+).kg^{-1})**
C	4,59±0.14	3,71±0,57	154,00±3,10a	103,50±2,80bc	5,23±0,11c	7,61±0,05b	0,92±0,02a	7,40±0,20
CM	4,89±0.14	4,99±0,57	143,00±3,10ab	98,25±2,80c	5,42±0,11bc	7,13±0,05d	0,91±0,02ab	7,49±0,20
B	4,75±0.14	3,89±0,57	153,25±3,10a	92,00±2,80c	5,51±0,11bc	7,58±0,05b	0,83±0,02b	7,95±0,20
KM	4,87±0.14	4,80±0,57	134,25±3,10b	131,00±2,80a	6,15±0,11a	7,27±0,05	0,83±0,02ab	7,87±0,20
KMB	4,85±0.14	3,44±0,57	154,25±3,10a	114,00±2,80b	5,79±0,11ab	7,88±0,05	0,87±0,02ab	7,49±0,20
CMB	5,10±0.14	3,81±0,57	140,50±3,10ab	104,00±2,80bc	5,32±0,11bc	7,49±0,05bc	0,87±0,02ab	7,74±0,20

	B (mg.kg^{-1})	**Cu (mg.kg^{-1})**	**Fe (mg.kg^{-1})**	**Mn (mg.kg^{-1})**	**Na (mg.kg^{-1})**	**S (mg.kg^{-1})**	**Zn (mg.kg^{-1})**	**pH**	**OC (%)**
C	0,22±0,01	46,13±0,24	248,40±7,42	41,43±1.67	32,75±0,55b	5,22±0,11	13,11±1,37	6,59±0,08b	0,88±0,03d
CM	0,20±0,01	51,36±0,24	236,60±7,42	41,77±1.67	32,75±0,55b	5,41±0,11	12,08±1,37	7,34±0,08a	0,95±0,03cd
B	0,20±0,01	43,93±0,24	222,55±7,42	40,31±1.67	32,25±0,55b	5,50±0,11	14,45±1,37	7,49±0,08a	1,23±0,03a
KM	0,21±0,01	47,65±0,24	233,05±7,42	39,25±1.67	38,00±0,55a	6,14±0,11	14,73±1,37	7,24±0,08a	0,87±0,03d
KMB	0,23±0,01	46,55±0,24	239,82±7,42	43,17±1.67	36,00±0,55a	5,79±0,11	13,74±1,37	7,21±0,08a	1,12±0,03ab
CMB	0,20±0,01	45,10±0,24	234,77±7,42	40,36±1.67	32,25±0,55b	5,31±0,11	12,89±1,37	7,25±0,08a	1,08±0,03bc

*B, Biochar; CM, Cattle Manure; KM, Kraal Manure; KMB, Kraal Manure and Biochar; CMB, Cattle Manure and Biochar

Results from the analysis of variance of soil physical properties in Field A at harvest revealed that the treatments were significant on bulk density (BD) ($p < 0.05$) and mean weight diameter (MWD) ($p < 0.001$) and not significant ($p > 0.05$) on soil porosity (SP), gravimetric water content (GWC) and volumetric water content (VWC), whereas in Field B, all soil physical properties (BD, SP, GWC, VWC and MWD) were significant at $p < 0.05$.

The B plots significantly decreased BD by 16.4 % in comparison to the control plots, but not significantly different from all treatment plots in Field A (Table 4.4). Besides B plots, other treatment plots were not significantly different with the control plots. Also, MWD in Field A (Table 4.4) significantly increased on B plots (57.6 %) in comparison to the control plots. Like BD, all the other treatment plots were not significantly different from the B plots. In addition, the CM plots were not significantly different from the control plots. In Field B (Table 4.5), the lowest BD was observed in the B plots, with a decrease of 30.3 % from the control plots, while the B plots again had the highest SP, GWC, VWC and MWD with an increase of 9.1, 41.8, 26.6 and 25.6 % respectively in comparison to the control plots. However, the B plots were not significantly different from other treatments except with KM plots which were lower in MWD. Also, the CM plots did not differ significantly with the control plots on all physical parameters, which also applies to the KMB plots in VWC, and the KM, CMB and KMB plots in MWD.

Table 4. 4**.** The effect of treatments on soil physical properties at harvesting under sweet sorghum cultivation in Field A. Different letters indicate significant differences between treatments at $p = 0.05$.

Treatments (plots)	**BD ($g.cm^{-3}$)**	**SP (%)**	**GWC (%)**	**VWC (%)**	**MWD (mm)**
C	1.34±0.04a	49.35±1.15	15.32±0.85	14.64±1.32	0.33±0.02b
CM	1.23±0.04ab	55.83±1.15	14.86±0.85	17.44±1.32	0.42±0.02ab
B	1.12±0.04b	56.20±1.15	15.89±0.85	18.48±1.32	0.52±0.02a
KM	1.17±0.04ab	55.50±1.15	15.03±0.85	14.81±1.32	0.46±0.02a
KMB	1.23±0.04ab	53.49±1.15	14.61±0.85	18.07±1.32	0.45±0.02a
CMB	1.18±0.04ab	53.94±1.15	14.94±0.85	18.28±1.32	0.47±0.02a

BD, Bulk Density; SP, Soil Porosity; GWC, Gravimetric Water Content; Volumetric Water Content; MWD, Mean Weight Diameter. *B, Biochar; CM, Cattle Manure; KM, Kraal Manure; KMB, Kraal Manure and Biochar; CMB, Cattle Manure and Biochar.

Table 4. 5**.** The effect of treatments on soil physical properties at harvesting under sweet sorghum cultivation in Field B. Different letters indicate significant differences between treatments at p = 0.05.

Treatments (plots)	**BD** ($g.cm^{-3}$)	**SP** (%)	**GWC** (%)	**VWC** (%)	**MWD** (mm)
C	1,26±0.02a	52,45±0,73b	11,60±0,71b	14,72±0,69b	0,39±0,02b
CM	1,18±0.02ab	55,33±0,73ab	13,89±0,71ab	16,39±0,69ab	0,45±0,02ab
B	1,13±0.02b	57,22±0,73a	16,45±0,71a	18,64±0,69a	0,49±0,02a
KM	1,15±0.02b	56,73±0,73a	15,76±0,71a	18,06±0,69a	0,41±0,02b
KMB	1,15±0.02b	56,52±0,73a	15,29±0,71a	17,59±0,69ab	0,45±0,02ab
CMB	1,15±0.02b	56,71±0,73a	15,76±0,71a	18,03±0,69a	0,44±0,02ab

BD, Bulk Density; SP, Soil Porosity; GWC, Gravimetric Water Content; Volumetric Water Content; MWD, Mean Weight Diameter. *B, Biochar; CM, Cattle Manure; KM, Kraal Manure; KMB, Kraal Manure and Biochar; CMB, Cattle Manure and Biochar.

4.3.3. Sweet sorghum growth, yield and biofuel characteristics.

Repeated measures analysis of variance results on sweet sorghum growth parameters in Field A (2020/21) and Field B (2021/22) showed that treatment and time as independent factors significantly influenced LAI, AtLeaf chlorophyll content, stem diameter, plant height, leaf number and lodging at p < 0.001 (Table 4.6).

Table 4. 6 The repeated measure analysis of variance showing the effects of time, treatments, and treatment x time on sweet sorghum growth characteristics grown in Field A (2020/21), Field B (2021/22) and Field A (2021/22).

Variables	**Treatment**	**Time**	**Treatment x Time**
Field A (2020/21)			
LAI	F (5,215) = 113.65***	F (8; 215) = 2781.30***	F (53; 215) = 9.56***
ACC	F (5,215) = 114.15***	F (8; 215) = 225.95***	F (53; 215) = 6.64***
SD (cm)	F (5,215) = 19.15***	F (8; 215) = 773.36***	F (53; 215) = 2.80***
PH (cm)	F (5,215) = 74.41***	F (8; 215) = 36789.88***	F (53; 215) = 64.77***
LN	F (5,215) = 18.54***	F (8; 215) = 119.06***	F (53; 215) = 2.46***
Lodging	F (5;143) = 5.21, **	F (5; 143) = 191.7***	F (35; 143) = 0.16 ^{ns}
Field B (2021/22)			
LAI	F (5,215) = 124,70***	F (8; 215) = 2036,32***	F (53; 215) = 7,84***
ACC	F (5,215) = 263,73***	F (8; 215) = 564,6***	F (53; 215) = 8,4***
SD (cm)	F (5,215) = 489,53***	F (8; 215) = 3399,85***	F (53; 215) = 5,28***
PH (cm)	F (5,215) = 388,37***	F (8; 215) = 18453,80***	F (53; 215) = 16,50***
LN	F (5,215) = 470,44***	F (8; 215) = 3310,27***	F (53; 215) = 16,39***
Lodging	F (5;143) = 6,44***	F (5; 143) = 100,90***	F (35; 143) = 2,36 **
Field A (2021/22)			
LAI	F (5,215) = 124,70***	F (8; 215) = 2036,32***	F (53; 215) = 7,84***
ACC	F (5,215) = 69,20***	F (8; 215) = 163,70***	F (53; 215) = 2,93***
SD (cm)	F (5,215) = 256,33***	F (8; 215) = 1988,30***	F (53; 215) = 1,96***
PH (cm)	F (5,215) = 327,07***	F (8; 215) = 8954,39***	F (53; 215) = 3,29***
LN	F (5,215) = 215,69***	F (8; 215) = 1670,52***	F (53; 215) = 9,20***
Lodging	-	-	-

LAI, Leaf Area Index; ACC, AtLeaf Chlorophyll Content; SD, stem diameter; PH, plant height; LN, Leaf Number, *** significant at p < 0.001; ** significant at p < 0.01; * significant at p < 0.05 ns. = not significant at p > 0.05.

The results were similar to the follow-up trial of Field A (2021/22) in which all parameters were significant at $p < 0.001$, except for lodging which was not recorded (Table 4.6). The two-way interaction of treatment x time on both Field A (2020/21) and Field B (2021/22) was significantly influenced by LAI, AtLeaf chlorophyll content, stem diameter, plant height, leaf number and lodging at $p < 0.001$, except for lodging in Field A (2020/21) which was not significant at $p > 0.05$. Again, the follow-up trial of Field A (2021/22) was significantly affected by all growth parameters except for lodging which was not recorded. Both the phenology characteristics (days to 50% flowering and days to 90% physiological maturity) measured here did not show significant differences in all fields (Field A, Field B and Field A follow-up trial).

The control plots were significantly lower on leaf area index (LAI) throughout the growth period on both Field A (Figure 4.3a) and Field B (Figure 4.3b), while no remarkable differences were observed between treatment plots, except that the CM plots which were significantly lower than the KM, B, KMB and CMB plots during week 5 only, on both fields.

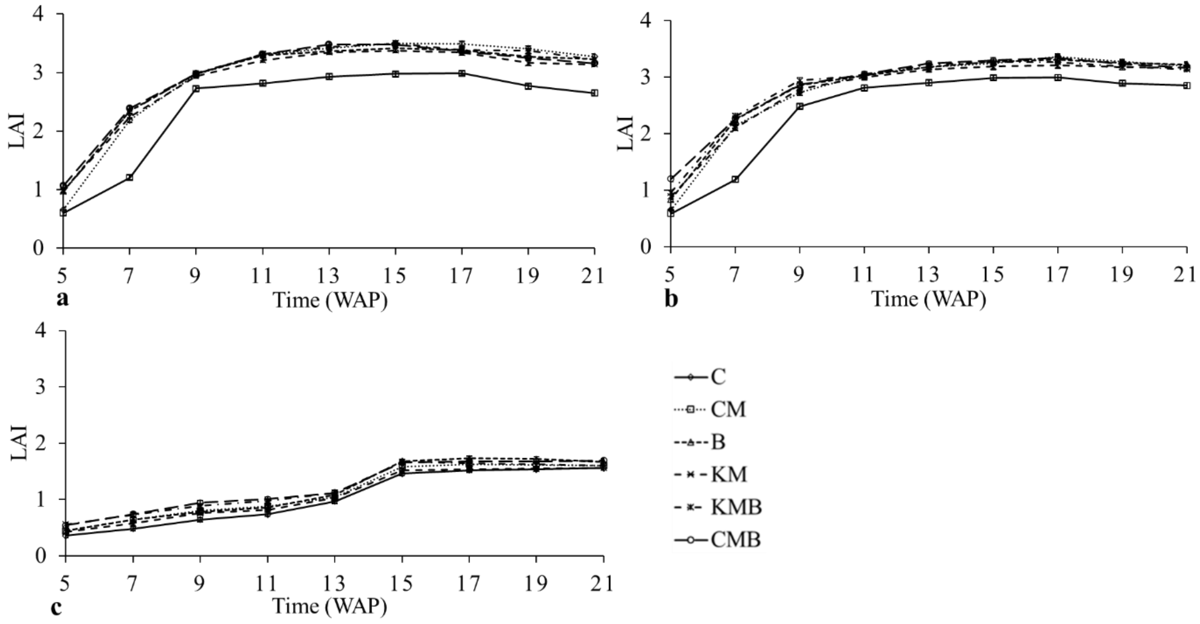

Figure 4. 3a-c. The effect of time and treatment interaction on LAI of sweet sorghum grown on (a) Field A (2020/21), (b) Field B (2021/22) and (c) Field A (2021/22). Error bars indicate standard error.

However, the CM plots LAI increased to the highest from week 15 and 17 in Field A and Field B respectively to week 21. Generally, LAI increased rapidly during the first 13 weeks on both fields (Field A and B) reaching the maximum, and afterwards, remained almost constant and declined from week 17 to 21. However, during the follow-up trial of Field A, the control plots were significantly lower than all treatment plots (Figure 4.3c).

All the treatment plots significantly outperformed the control plots on chlorophyll content (ACC) throughout the experiment on both Field A (Figure 4.4a) and Field B (Figure 4.4b).

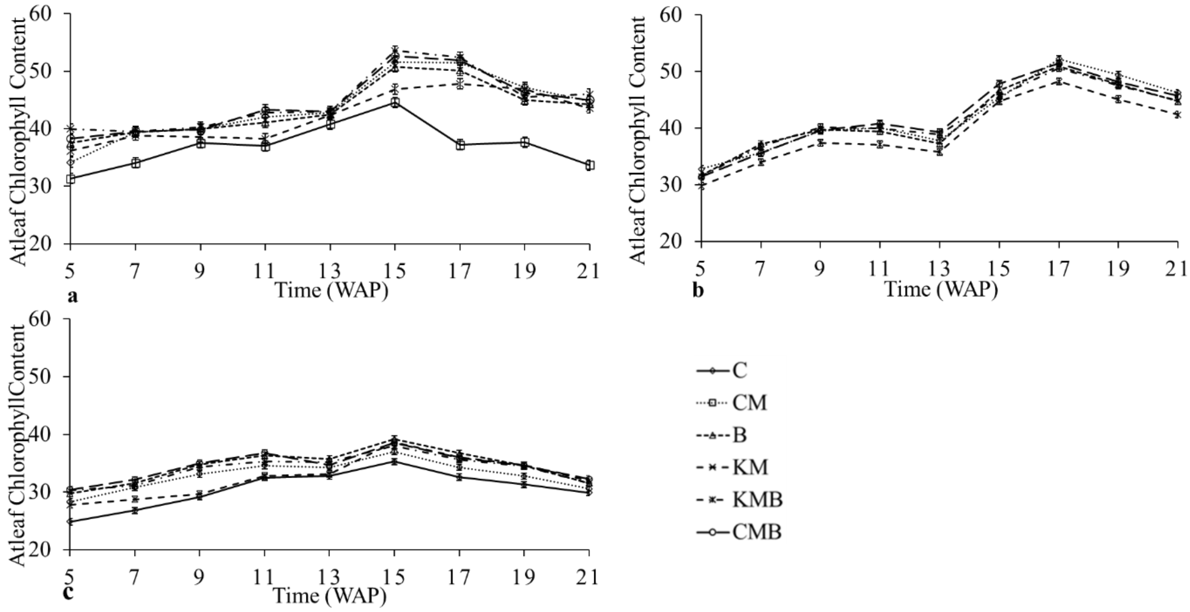

Figure 4. 4a-c**.** The effect of time and treatment interaction on chlorophyll content index of sweet sorghum (a) Field A (2020/21), (b) Field B (2021/22) and (c) Field A (2021/22). Error bars indicate standard error.

However, an exception was observed in Field A during week 5 in CM plots and during weeks 11, 15 and 17 in KM plots which did not significantly differ from the control plots (Figure 4.4a). Similarly, in Field B, KM plots did not significantly differ from the control plots during week 13 in Field B (Figure 4.4b). Additionally, in Field A, despite CM plots being relatively low during week 5, it improved to the peak over all the treatments in week 19, whereas in Field B, CM plots rose to thier peak in week 17. In general, the chlorophyll content gradually increased from week 5 to 15 in Field A and from week 5 to 17 in Field B, and thereafter declined up to the end of the experiment. During the follow-up trial in Field A, the control plots remained significantly lower than all treatment plots throughout the study, followed by the CM plots, which were relatively lower than other treatment plots.

The stem diameter was significantly lower on the control than treatment plots throughout the study on both Field A (Figure 4.5a) and B (Figure 4.5b).

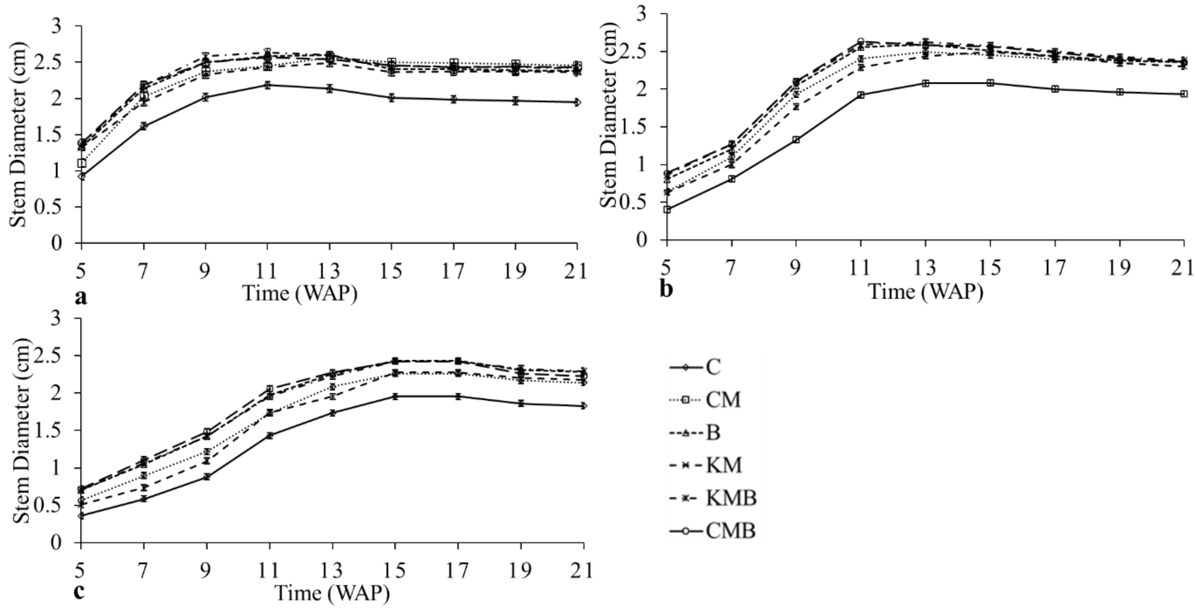

Figure 4. 5a-c. The effect of time and treatment interaction on stem diameter of sweet sorghum grown on (a) Field A (2020/21), (b) Field B (2021/22) and (c) Field A (2021/22). Error bars indicate standard error.

Among the treatments, the KM plot was significantly lower during week 9 and 11, while the CM plots were significantly lower during week 5, but increased to the highest from week 15 to 21 in Field A. In Field B, beside all treatments being significantly similar from week 13, both KM and CM plots where significantly lower than other treatments (B, KMB and CMB plots) from week 5 to 13. Generally, a sharp increase on stem diameter was noticed from week 5 to 9 in Field A and from week 5 to 11 in Field B and decreased between week 13 and 15 in both fields, and thereafter, remained constant up to the end of the experiment. Regarding the follow-up trial in Field A (Figure 4.5c), the control plots maintained the lowest stem diameter throughout the study, whereas the CM and KM plots were both significantly lower than the B, KMB and CMB plots. In general, the highest stem diameter was reached in week 13 and started decreasing in week 17.

All the treatment plots significantly increased plant height when compared to the control plots throughout the study on both Field A (Figure 4.6a) and B (Figure 4.6b), and increased rapidly from week 5 to week 15 and week 5 to 17 in both Field A and Field B respectively, and thereafter it was almost constant to the end of the experiment. In the follow-up trial of Field A (Figure 4.6c), the control plots maintained the lowest height and was not significantly different from the CM and KM plots during the first 13 weeks, whereas both CM and KM plots were relatively lower in comparison to the B, KMB and CMB plots.

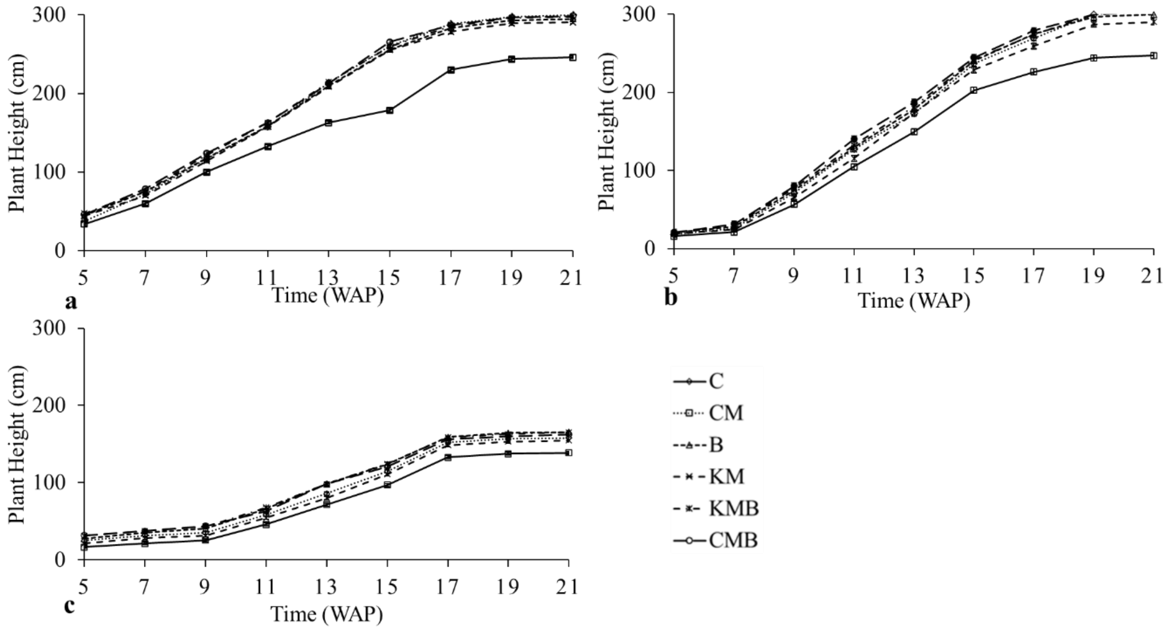

Figure 4. 6a-c**.** The effect of time and treatment interaction on plant height of sweet sorghum grown on (a) Field A (2020/21), (b) Field B (2021/22) and (c) Field A (2021/22). Error bars indicate standard error.

The control plots had significantly lower leaf numbers compared to treatment plots, while among the treatment plots no difference was observed both in Field A (Figure 4.7a) and Field B (Figure 4.7b). Moreover, the CM plots had significantly lower number of photosynthetically active leaves during week 5 than other treatment plots and increased to the peak in week 15 in Field A, while in Field B both the CM and KM plots had significantly lower number of leaves than the B, KMB and CMB plots during week 13 and 15. The highest number of leaves was reached in week 13 and 15 in Field A and Field B respectively, which then decreased afterwards. During the follow-up trial, the control plots maintained the lowest number of leaves throughout the study while both the CM and KM plots were relatively lower than the B, KMB and CMB plots from week 9 to the end of the study.

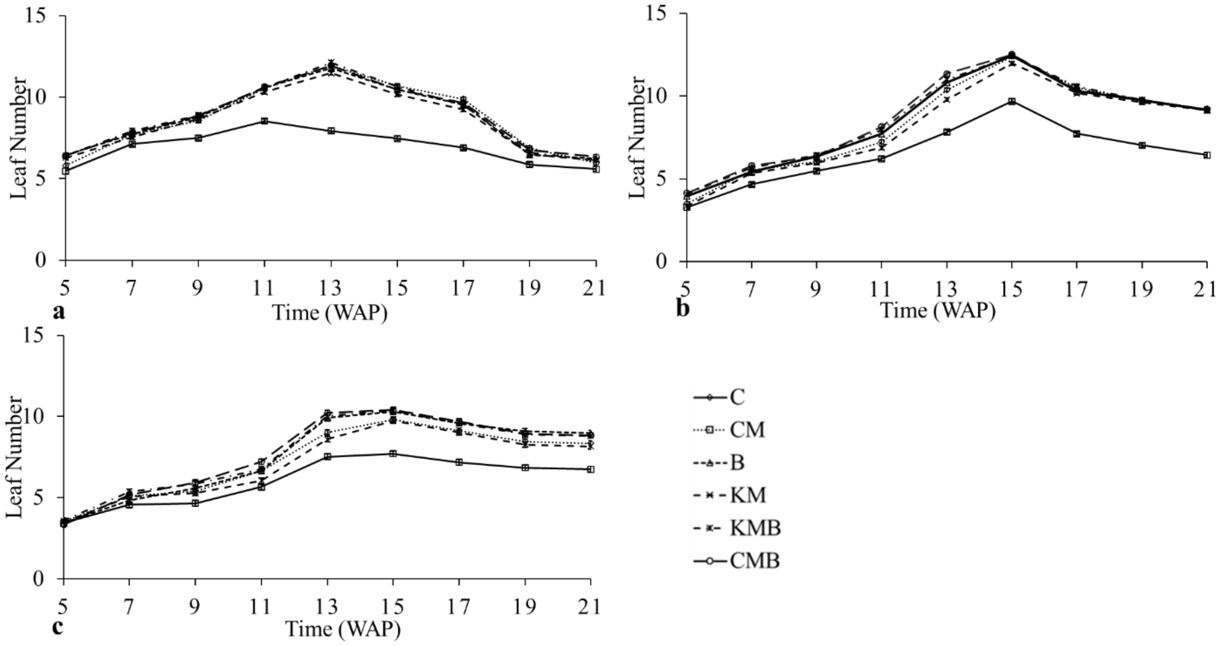

Figure 4. 7a-c**.** The effect of time and treatment interaction on leaf number of sweet sorghum grown on (a) Field A (2020/21), (b) Field B (2021/22) and (c) Field A (2021/22). Error bars indicate standard error.

Lodging was experienced from week 15 due to heavy rains that were accompanied by strong winds in Field A (Figure 4.8a). During week 17 in Field A, lodging decreased and rose again exponentially to the end of the experiment as the rains and winds becomes severe. The CMB plots were mostly affected with lodging, with no significant difference with KMB, KM and CM plots, while the control plots were the least affected followed by B plots. Lodging started in Field B from week 21 except for KMB and CMB plots which started during week 19 and both KMB and CMB plots continued to have the highest lodging, while the control plots was the lowest. During the follow-up trial in Field A, no lodging was experienced.

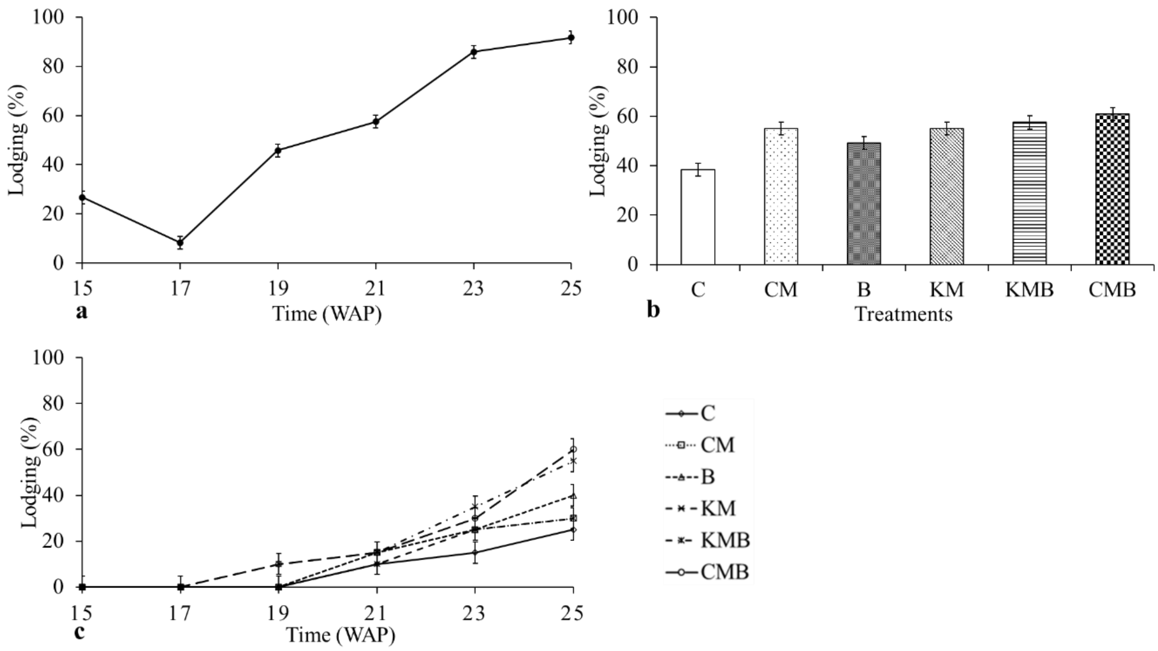

Figure 4. 8a-c**.** The effect of (a) time and (b) treatment on lodging of sweet sorghum grown in Field A (2020/21), and (c) the effect of time and treatment interaction on lodging of sweet sorghum grown in Field B (2021/22). Error bars indicate standard error.

4.3.4. Sweet sorghum yield and biofuel characteristics

Repeated measure analysis of variance results on sweet sorghum yield parameters in Field A (2020/21) and Field B (2021/22) showed that treatment and time as independent factors significantly influenced total dry mass yield, fresh stalk yield, grain yield and 1 000 grain weight at $p < 0.001$ (Table 4.7). Similarly, on the follow-up trial of Field A (2021/22) both treatment and time as independent factors were significant at $p < 0.001$. The two-way interaction of treatment x time on both Field A (2020/21) and Field B (2021/22) significantly influenced total dry mass yield, fresh stalk yield, grain yield and 1 000 grain weight at $p < 0.05$ (Table 4.7), which was similar as well during the follow-up trial in Field A (2021/22), except for 1 000 grain weight which was not significant at $p > 0.05$.

Table 4. 7**.** The repeated measure analysis of variance showing the effects of time, treatments, and treatment x time on sweet sorghum yield characteristics grown in Field A (2020/21), Field B (2021/22) and Field A (2021/22).

Variables	**Treatment**	**Time**	**Treatment x time**
Field A (2020/21)			
TDMY ($t.ha^{-1}$)	F (5; 95) = 13.39***	F (3; 95) = 29.55***	F (15; 95) = 2.15*
FSY ($t.ha^{-1}$)	F (5; 95) = 23.38***	F (3; 95) = 52.38***	F (15; 95) = 1.47*
GY ($t.ha^{-1}$)	F (5; 95) = 44.57***	F (3; 95) = 205.37***	F (15; 95) = 6.18**
1000 GW (g)	F (5; 95) = 4.59***	F (3; 95) = 72.61***	F (15; 95) = 2.20*
Field B (2021/22)			
TDMY ($t.ha^{-1}$)	F (5; 95) = 50,39***	F (3; 95) = 248,32***	F (15; 95) = 1,83*
FSY ($t.ha^{-1}$)	F (5; 95) = 116,69***	F (3; 95) = 151,53***	F (15; 95) = 2,34**
GY ($t.ha^{-1}$)	F (5; 95) = 53,23***	F (3; 95) = 194,82***	F (15; 95) = 2,25*
1000 GW (g)	F (5; 95) = 108,22***	F (3; 95) = 407,03***	F (15; 95) = 1,89*
Field A (2021/22)			
TDMY ($t.ha^{-1}$)	F (5; 95) = 28,79***	F (3; 95) = 163,02***	F (15; 95) = 2,3**
FSY ($t.ha^{-1}$)	F (5; 95) = 41,88***	F (3; 95) = 97,04***	F (15; 95) = 3,26**
GY ($t.ha^{-1}$)	F (5; 95) = 28,63***	F (3; 95) = 76,40***	F (15; 95) = 2,32**
1000 GW (g)	F (5; 95) = 103,52***	F (3; 95) = 15,39***	F (15; 95) = $0,59^{ns}$

Total Dry Biomass Yield, FSY; Fresh Stalk Yield, GY; Grain Yield; 1000 GW; 1000 Grain weight. *** significant at $p < 0.001$; ** significant at $p < 0.01$; * significant at $p < 0.05$; ns = not significant.

Total dry weight was significantly higher during the first harvesting week, with a gradual decline for the subsequent harvesting weeks on both Field A (Figure 4.9a) and Field B (Figure 4.9b). Among the treatments, generally the KMB and CMB plots had the highest total dry weight throughout the harvesting period, despite no significance with other treatment plots on week 23, 24 and 25 in Field A and week 25 in Field B, while the control plots were the lowest. In addition, the CM and KM plots were significantly lower than B during week 22 on both Field A and Field B. The KM plots were also significantly lower than the B plots during week 25 in Field B. Regarding the follow-up trial in Field A (Figure 4.9c), the total dry weight yield decreased with harvesting time. Both the KMB and CMB plots had the highest yield among the treatment plots while the control plots were the lowest.

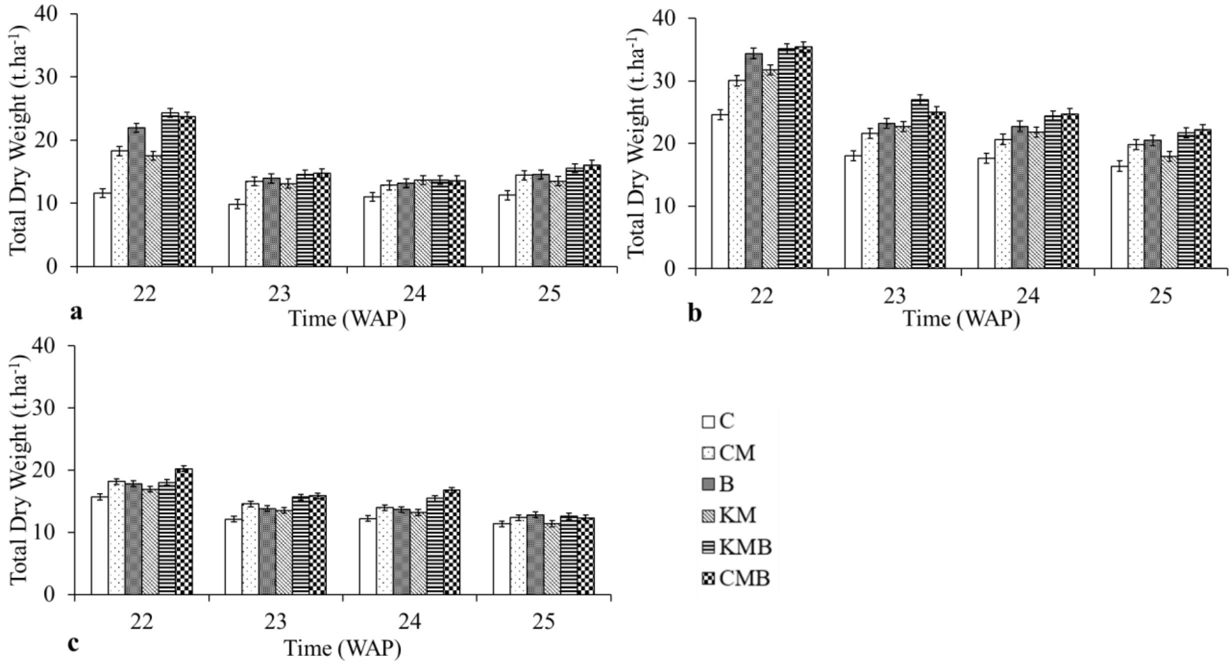

Figure 4. 9a-c**.** The effect of time and treatment interaction on total dry weight yield of sweet sorghum grown on (a) Field A (2020/21), (b) Field B (2021/22) and (c) Field A (2021/22). Error bars indicate standard error.

Like total dry weight yield, fresh stalk yield was highest during week 22 and declined towards the last harvesting week on both Field A (Figure 4.10a) and Field B (Figure 4.10b). The control plots had the lowest fresh stalk yield while the CMB and KMB plots were highest, although not different from other treatment plots in Field A. On the other hand, both the CMB and KMB plots were significantly different from other treatment plots in Field B. In addition, the KM plots was significantly lower than the CM and B plots during week 23 and 24 in Field B. In the follow-up study in Field A (Figure 4.10c), fresh stalk yield decreased with harvesting time and the CMB and KMB plots were both highest throughout the harvesting period, while the control was the lowest.

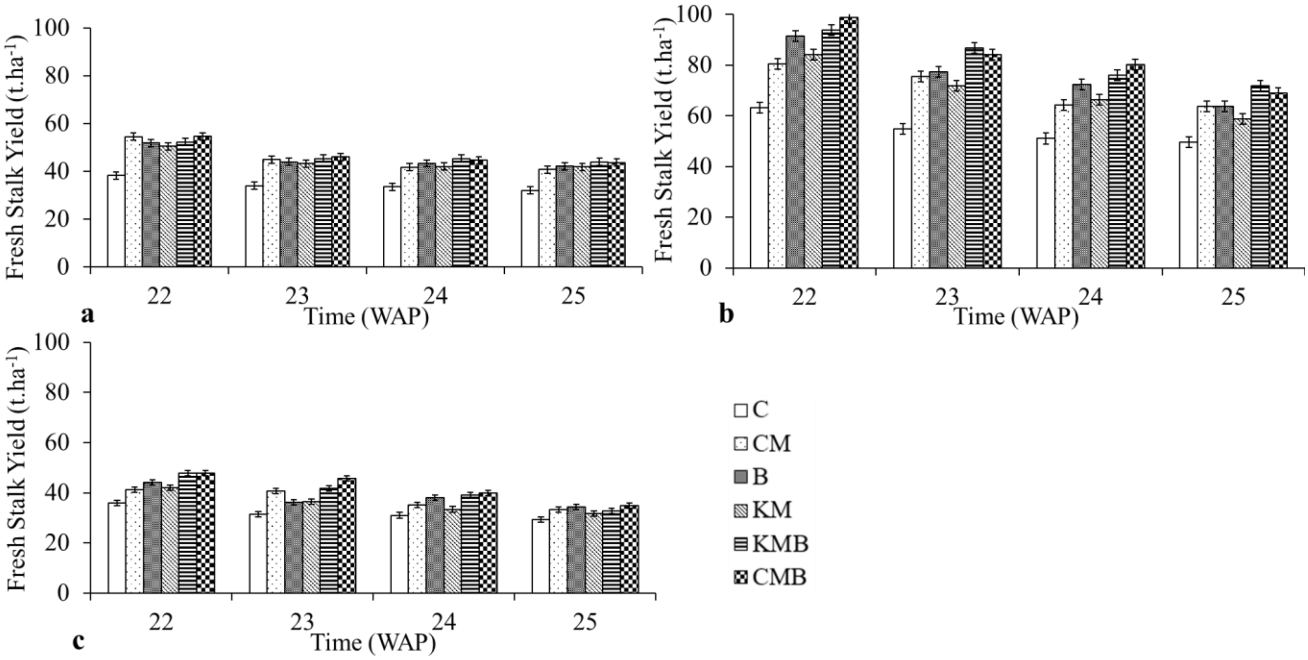

Figure 4. 10a-c. The effect of time and treatment interaction on fresh stalk yield of sweet sorghum grown on (a) Field A (2020/21), (b) Field B (2021/22) and (c) Field A (2021/22). Error bars indicate standard error.

Unlike total dry weight yield and fresh stalk yield, grain yield and 1 000 grain weight increased with harvesting time on both Field A (Figure 4.11a and Figure 4.12a) and Field B (Figure 4.11b and Figure 4.12b). KMB and CMB plots had the highest grain yield and 1 000 grain weight, while the control plots were the lowest in both Field A and Field B. Furthermore, B had significantly higher grain yield than in the CM and KM plots during the harvesting period in Field A, while in Field B, the B plots were only significantly higher than the KM plots during week 23 and 24. Regarding the follow-up trial in Field A, grain yield increased with harvesting time (Figure 4.11c). The control had the lowest grain yield throughout the study, while KMB and CMB plots were highest on grain yield. However, the most important observation on 1 000 grain weight was the control plots which were significantly lowest than other treatments (Figure 4.12c).

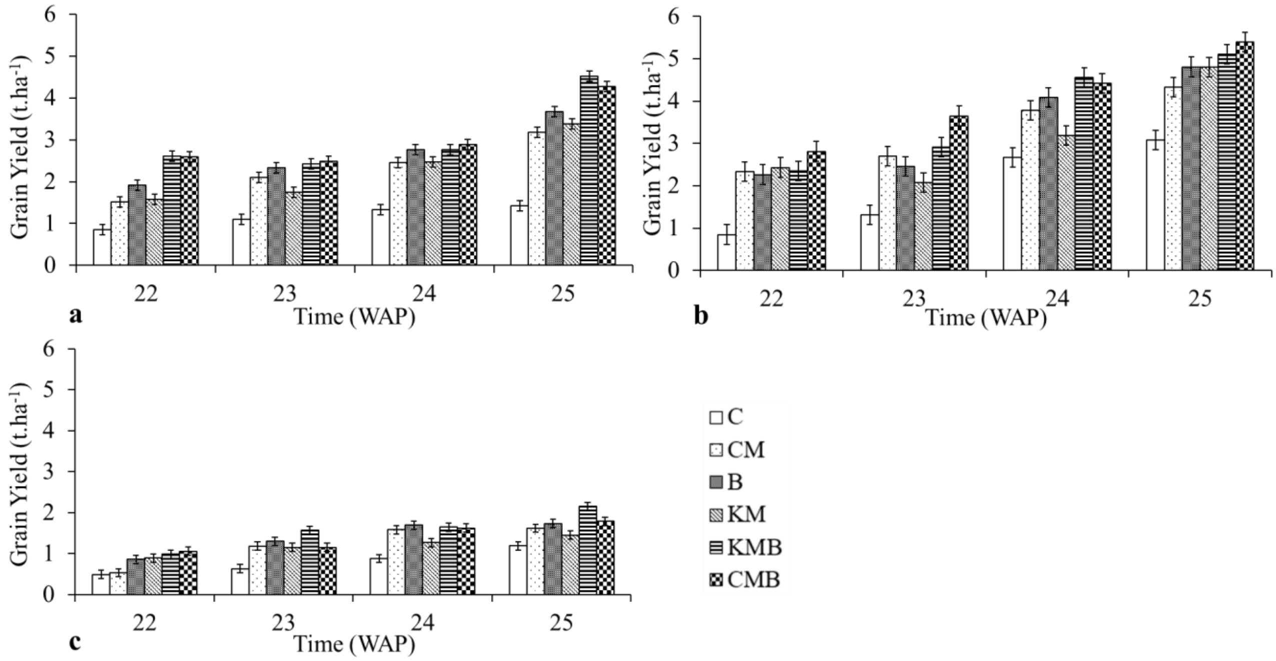

Figure 4. 11a-c. The effect of time and treatment interaction on grain yield of sweet sorghum grown on (a) Field A (2020/21), (b) Field B (2021/22) and (c) Field A (2021/22). Error bars indicate standard error.

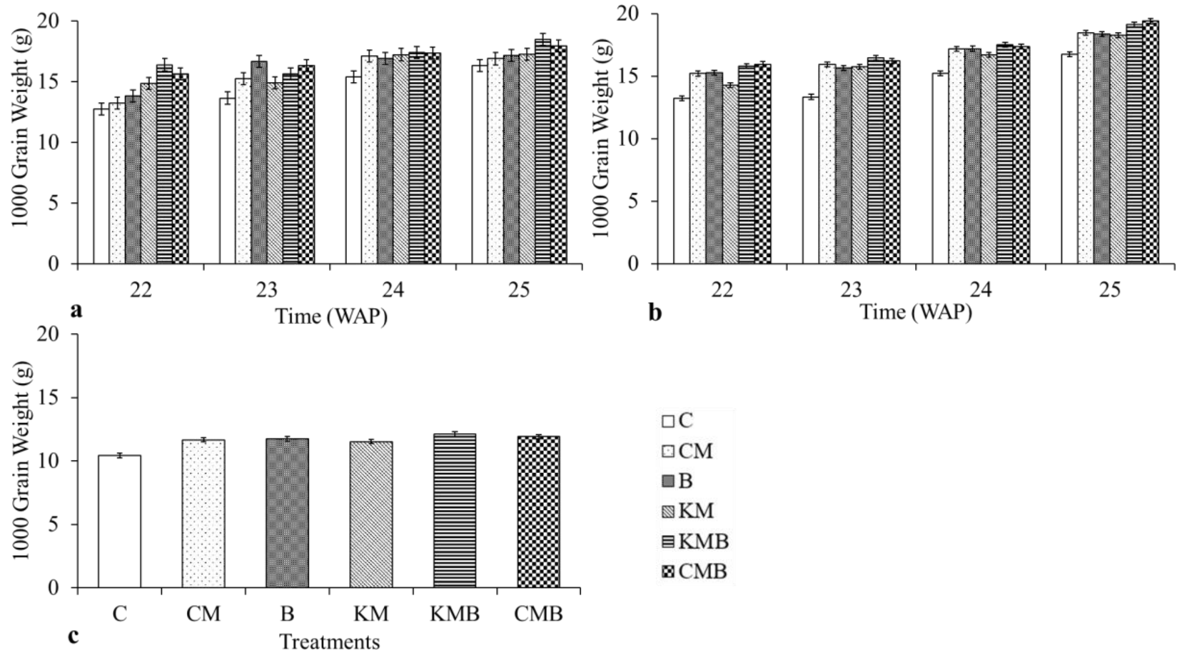

Figure 4. 12a-c. The effect of time and treatment interaction on 1000 grain weight of sweet sorghum grown in (a) Field A (2020/21), (b) Field B (2021/22) and (c) the effect of time on 1000 grain weight of sweet sorghum grown in Field A (2021/22). Error bars indicate standard error.

Results on sweet sorghum biofuel parameters repeated measure analysis of variance in Field A (2020/21) and Field B (2021/22) showed that treatment and time as independent factors significantly influenced brix, juice yield, sugar yield and theoretical ethanol yield at $p < 0.001$ (Table 4.8).

Similarly, in the follow-up trial in Field A (2021/22), both treatment and time as independent factors were significant at $p < 0.001$ (Table 4.8). The interaction of treatment x time significantly affected brix, juice yield, sugar yield and theoretical ethanol yield at $p < 0.05$. Regarding the follow-up trial of Field A (2021/22), the interaction of treatment x time significantly affected brix, juice yield, sugar yield and theoretical ethanol yield at $p < 0.001$ (Table 4.8).

Table 4. 8**.** The repeated measure analysis of variance showing the effects of time, treatments, and treatment x time on sweet sorghum biofuel characteristics grown in Field A (2020/21), Field B (2021/22) and Field A (2021/22).

Variables	**Treatment**	**Time**	**Treatment x time**
Field A (2020/21)			
Brix (%)	F (5; 95) = 18.84***	F (3; 95) = 30.07***	F (15; 95) = 2.21*
JY ($t.ha^{-1}$)	F (5; 95) = 27.00***	F (3; 95) = 28.32***	F (15; 95) = 2.12*
SY ($kg.ha^{-1}$)	F (5; 95) = 21.11***	F (3; 95) = 59.37***	F (15; 95) = 2.62**
TEY ($L.ha^{-1}$)	F (5; 95) = 20.79***	F (3; 95) = 58.71***	F (15; 95) = 2.56**
Field B (2021/22)			
Brix (%)	F (5; 95) = 40,61***	F (3; 95) = 343,79***	F (15; 95) = 2.21**
JY ($t.ha^{-1}$)	F (5; 95) = 103,67***	F (3; 95) = 52,30***	F (15; 95) = 2,17*
SY ($kg.ha^{-1}$)	F (5; 95) = 144,62***	F (3; 95) = 220,28***	F (15; 95) = 3,83***
TEY ($L.ha^{-1}$)	F (5; 95) = 128,20***	F (3; 95) = 205,05***	F (15; 95) = 3,60**
Field A (2021/22)			
Brix (%)	F (5; 95) = 14,37***	F (3; 95) = 207,71**	F (15; 95) = 5,97***
JY ($t.ha^{-1}$)	F (5; 95) = 29,41***	F (3; 95) = 41,64***	F (15; 95) = 2,86***
SY ($kg.ha^{-1}$)	F (5; 95) = 47,56***	F (3; 95) = 132,05***	F (15; 95) = 5,39***
TEY ($L.ha^{-1}$)	F (5; 95) = 41,85***	F (3; 95) = 111,95***	F (15; 95) = 5,03***

JY; Juice Yield, SY; Sugar Yield, TEY; Theoretical ethanol yield. *** significant at p<0.001; ** significant at p<0.01; * significant at p<0.05 ns = not significant.

The maximum brix was observed during the first week of harvest, and it generally declined with harvesting time on both Field A (Figure 4.13a) and Field B (Figure 4.13b). The control plots had the minimum brix throughout the harvesting stages on both fields, while the KMB and CMB plots had the highest brix except on week 25 in Field A. However, on the follow-up trial in Field A (Figure 4.13a), the control plots were only the lowest relative to other treatment plots during the first week of harvest and did not differ significantly afterwards. Additionally, the KMB and CMB plots were the highest only during the first week of harvest and did not differ significantly afterwards.

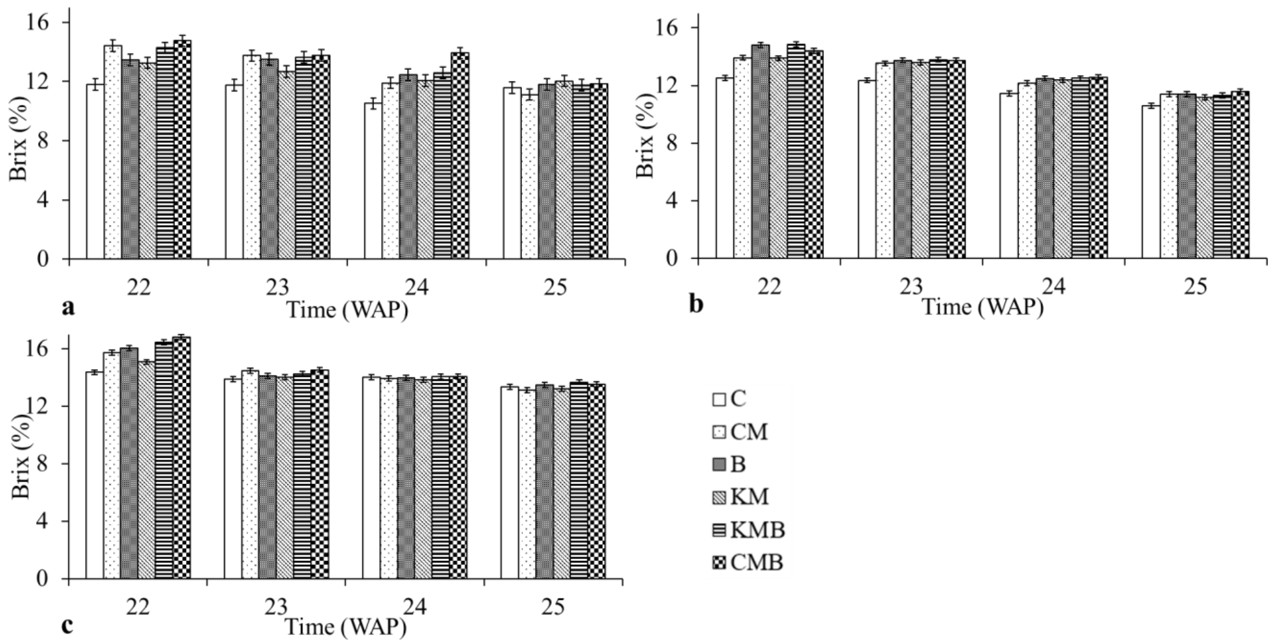

Figure 4. 13a-c. The effect of time and treatment interaction on brix of sweet sorghum grown on (a) Field A (2020/21), (b) Field B (2021/22) and (c) Field A (2021/22). Error bars indicate standard error.

Juice yield was highest during the first harvest and declines slightly with harvesting time on both Field A (Figure 4.14a) and Field B (Figure 4.14b). The control maintained its lowest juice yield throughout the harvesting period on both fields, while the CMB and KMB plots kept the highest juice yield throughout the harvesting period among all treatment plots. Similarly, during the follow-up trial (Figure 4.14c), juice yield was declining slightly from the beginning to the end of the harvesting period and both the CMB and KMB plots had higher juice yield than other treatments, except on the last harvesting week (week 25). The control plots were always the minimum.

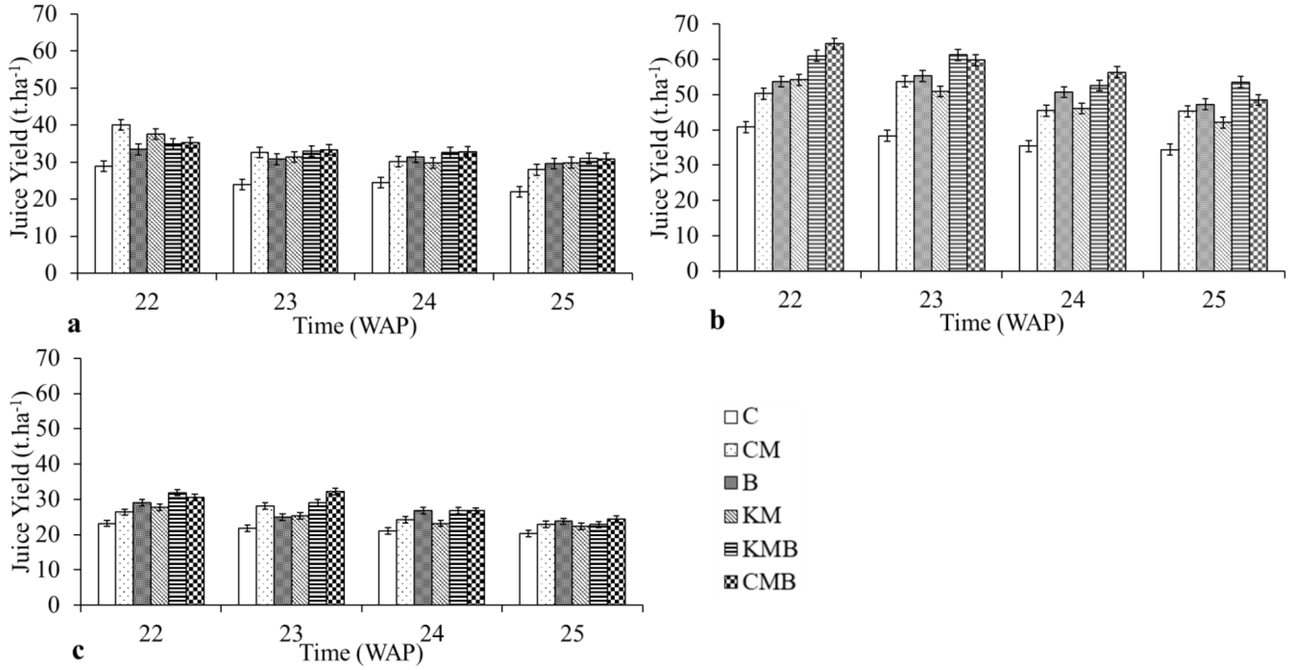

Figure 4. 14a-c. Effect of time and treatment interaction on juice yield of sweet sorghum grown on (a) Field A (2020/21), (b) Field B (2021/22) and (c) Field A (2021/22). Error bars indicate standard error.

The sugar yield was highest during the first week, and it decreased with time of harvest on both Field A (Figure 4.15a) and Field B (Figure 4.15b). The control plots had the lowest sugar yield throughout the harvesting period, while both the KMB and CMB plots were highest on both fields, except the CM plots in Field A, which was highest during the first harvesting week only. Similarly, sugar yield decreased with time of harvest in the follow-up trial; the control plots was lowest, while the KMB and CMB plots were both highest (Figure 4.15c).

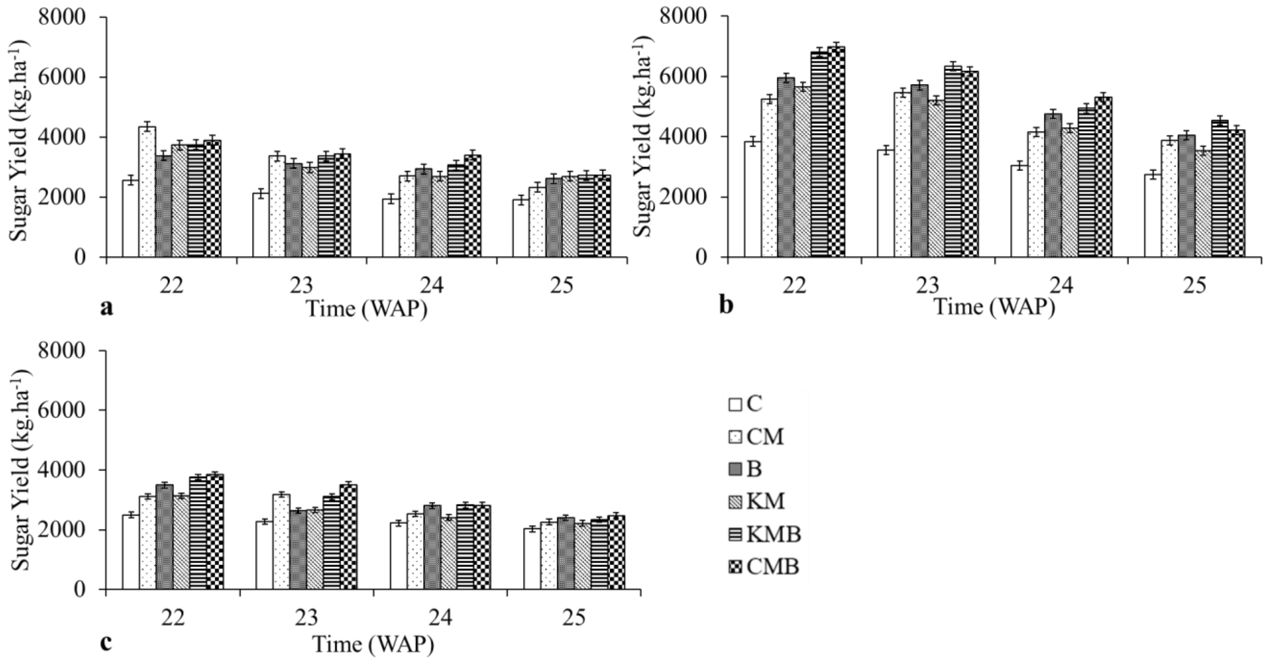

Figure 4. 15a-c. The effect of time and treatment interaction on sugar yield of sweet sorghum grown on (a) Field A (2020/21), (b) Field B (2021/22) and (c) Field A (2021/22). Error bars indicate standard error.

Lastly, theoretical ethanol yield diminished with time of harvesting on both Field A (Figure 4.16a) and Field B (Figure 4.16b). The lowest theoretical ethanol yield was observed on the control plots, while the KMB and CMB plots were both highest, except in Field A where the CM plots was highest during the first harvesting week only. During the follow-up trial in Field A, theoretical ethanol yield decreased with time of harvest from the beginning and the control plots were lowest, while the KMB and CMB plots were both highest (Figure 4.16c)

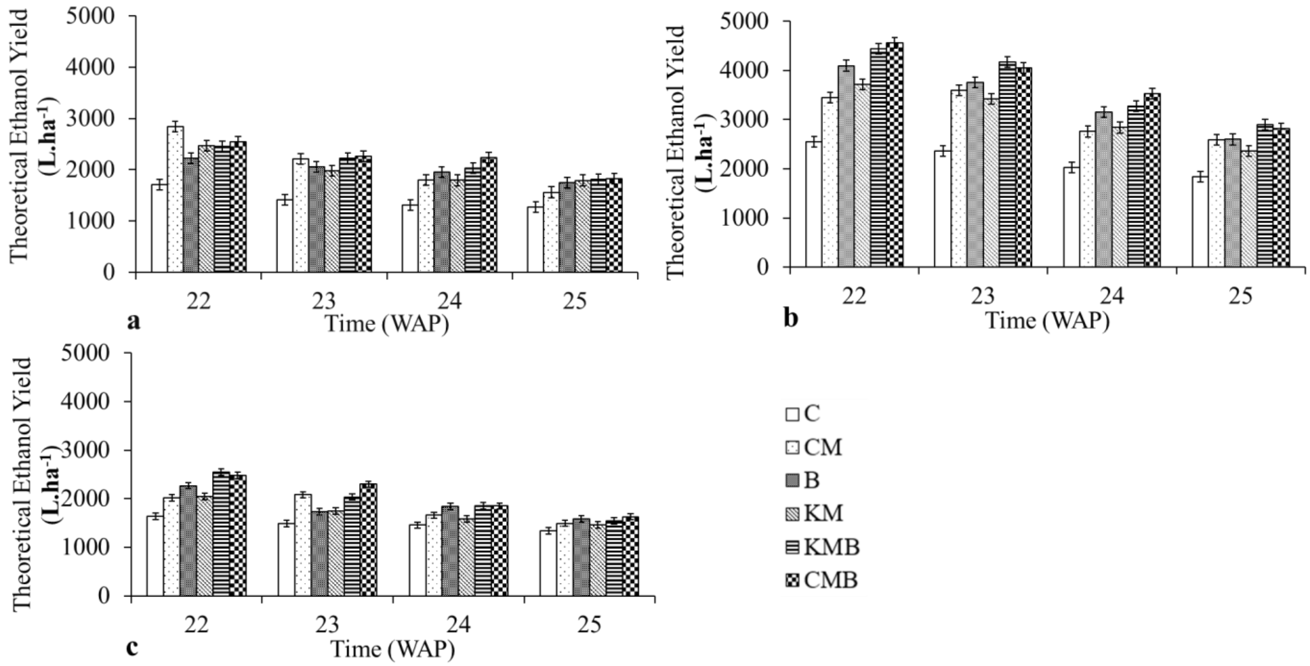

Figure 4. 16a-c**.** The effect of time and treatment interaction on theoretical ethanol yield of sweet sorghum grown on (a) Field A (2020/21), (b) Field B (2021/22) and (c) Field A (2021/22). Error bars indicate standard error.

Pearson's correlation relationships between sweet sorghum yield and biofuel characteristics are presented in Table 4.9. It was noted that brix, juice yield, sugar yield, theoretical ethanol yield, total dry biomass yield, and fresh stalk yield were all significantly ($p < 0.001$) and positively correlated ($r = 0.57$ to $r = 0.99$) to each other on both Field A and Field B. However, it was interesting to note that grain yield and 1 000 grain weight were only significantly and positively correlated to each other, while uncorrelated to other characteristics. The exception was on brix which was significantly and negatively correlated to 1 000 grain yield ($r = -0.23$, $p < 0.001$) in Field A, while both grain yield and 1 000 grain weight significantly and negatively correlated to brix in Field B. During the follow-up trial in Field A, brix, juice yield, sugar yield, theoretical ethanol yield, total dry biomass yield, and fresh stalk yield were all significantly ($p < 0.001$) and positively correlated to each other. The grain yield and 1 000 grain weight were significantly ($p < 0.001$) and positively correlated to each other only, while significant ($p < 0.05$) and negatively correlated to brix, sugar yield, theoretical ethanol yield, and total dry biomass yield although the relationships were weakly correlated. The correlation between both grain yield and 1 000 grain weight, juice yield and fresh stalk yield was not significantly correlated.

Table 4. 9**.** Pearson correlation analysis of sweet sorghum biofuel and yield characteristics grown in Field A (2020/21), Field B (2021/22) and Field A (2021/22).

	Brix (%)	JY ($t.ha^{-1}$)	SY ($kg.ha^{-1}$)	TEY ($L.ha^{-1}$)	TDBY ($t.ha^{-1}$)	FSY ($t.ha^{-1}$)	GY ($t.ha^{-1}$)	1000 GW (g)
Field A (2020/21)								
Brix (%)	1	0.63***	0.85***	0.84***	0.62***	0.69***	-0.11ns	-0.23*
JY ($t.ha^{-1}$)		1	0.94***	0.95***	0.57***	0.91***	0.13 ns	-0.02 ns
SY ($kg.ha^{-1}$)			1	0.99***	0.65***	0.90***	0.01ns	-0.13 ns
TEY($L.ha^{-1}$)				1	0.65***	0.91***	0.02 ns	-0.13 ns
TDBY($t.ha^{-1}$)					1	0.80***	0.20 ns	-0.06 ns
FSY ($t.ha^{-1}$)						1	0.19 ns	-0.03 ns
GY ($t.ha^{-1}$)							1	0.73***
1000 GW (g)								1
Field B (2021/22)								
Brix (%)	1	0,67***	0,87***	0,86***	0,82***	0,80***	-0,52***	-0,50***
JY ($t.ha^{-1}$)		1	0,95***	0,94***	0,69***	0,93***	0,07 ns	0,08 ns
SY ($kg.ha^{-1}$)			1	0,99***	0,81***	0,94***	-0,18 ns	-0,15 ns
TEY($L.ha^{-1}$)				1	0,81***	0,97***	-0,18 ns	-0,16 ns
TDBY($t.ha^{-1}$)					1	0,87***	-0,29 ns	-0,30 ns
FSY ($t.ha^{-1}$)						1	-0,10 ns	-0,09ns
GY ($t.ha^{-1}$)							1	0,89***
1000 GW (g)								1
Field A (2021/22)								
Brix (%)	1	0,63***	0,82***	0,81***	0,81***	0,75***	-0,48***	-0,53***
JY (($t.ha^{-1}$)		1	0,95***	0,96***	0,70***	0,97***	-0,05 ns	-0,18 ns
SY ($kg.ha^{-1}$)			1	0,99***	0,82***	0,98***	-0,21*	-0,33**
TEY($L.ha^{-1}$)				1	0,79***	0,97***	-0,20*	-0,31**
TDBY($t.ha^{-1}$)					1	0,84***	-0,34**	-0,47***
FSY ($t.ha^{-1}$)						1	-0,17 ns	-0,30 ns
GY ($t.ha^{-1}$)							1	0,78***
1000 GW (g)								1

JY; Juice Yield, SY; Sugar Yield, TEY; Theoretical ethanol yield, TDBY; Total Dry Biomass Yield, FSY; Fresh Stalk Yield, GY; Grain Yield; 1000 GW; grain weight. *, **, *** Significance at $p < 0.05$, $p < 0.01$, $p < 0.001$.

4.3.5. Comparison of sweet sorghum growth, yield and biofuel properties between Field A and Field B as well as between Field A first- and second year.

The general comparison between sweet sorghum growth parameters between Field A (2020/21) and Field B (2021/22) revealed that Field A (2020/21) was significantly higher than Field B (2021/22) on stem diameter, plant height, leaf number and lodging, while LAI and chlorophyll content were not significantly different between the fields. However, regarding the comparison of Field A (2020/21) and its follow-up trial in 2021/22, all sweet sorghum growth properties were significantly higher in Field A (2020/21) than the follow-up trial (Field A (2020/21)). The comparison of phenology between Field A (2020/21) and Field B (2021/22) was not significantly different, but the contrasts between Field A (2020/21) and its follow-up trial was significantly different, where both days to 50 % flowering and days to 90 % physiological maturity occurred earlier in the follow-up trial than Field A (2020/21).

Unlike the sweet sorghum growth parameters, all the yield and biofuel parameters between the two fields, showed that Field B (2021/22) was significantly higher than Field A (2020/21) except on brix and 1 000 grain weight, where both fields were not significantly different. The comparison of Field A (2020/21) and its follow-up trial in 2021/22 showed that all the yield and biofuel parameters in 2020/21 were significantly higher than the follow-up trial in 2021/22, except for brix which was the only one significantly higher in the follow-up trial than the first trial.

4.4. Discussion

This study aimed to evaluate the potential of sole or co-applied biochar on improving soil physicochemical properties and growth and performance of sweet sorghum. On the soil chemical properties, we found that on both fields (Field A and Field B), the control did not differ significantly from all treatments on NH^{4+} and NO^{3-}. In the case of biochar, Jones *et al.* (2012) similarly reported that neither long- nor short term effects were observed on NH^{4+} and NO^{3-} after biochar application over a three-year field study. Likewise, Angst *et al.* (2014) reported non-significant differences between the control and co-applied biochar and cattle manure on NH^{4+} and NO^{3-} over a year. Similar results were also recorded by Foster *et al.* (2016) who attributed the response to the feedstock used (wood derived); i.e. that the feedstock might have slightly influenced N mineralisation and nitrification, and slightly influenced prevention of NH^{4+} volatilisation and NO^{3-} leaching. In addition, other crops have reportedly facilitated biological nitrogen fixation which may increase N in control plots (Riziki *et al.* 2020), and sweet sorghum also apparently demonstrates N fixation abilities (Ceotto *et al.* 2014).

The increase in P in Field A following biochar addition corroborates findings by Riziki *et al.* (2020), who mentioned that 10 % biochar increased P compared to 10 % manure, while 20 % biochar increased P compared to combined 10 % biochar + 10 % manure, and 20 % biochar + 10 % manure and concluded that this increase was attributed to feedstock (wood) and elevated pyrolysis temperature. This contradicts some evidence that biochar organic matter pool does not easily decompose because of its high C:N ratios as well as high C:P ratios, which compromise P release dynamics (Lebrun *et al.* 2022). Additionally, a meta-analysis by Glaser and Lehr (2019) stated that wood-based biochar's had no influence on P bioavailability. Thus, other mechanisms such as facilitating native P mineralisation, protection of native P from erosion losses, enhancement of symbiotic mycorrhiza fungi, and soil pH alteration, which favours P availability by reducing Al and Fe fixation (Nguyen *et al.* 2018; Li *et al.* 2019; Riziki *et al.* 2020) might have contributed to the result found in Field B. Conversely, in Field B, biochar did not differ significantly from the control on P concentration, which may be the resultant from the soil texture. It has been argued that the effects of biochar are more pronounced in poor soils (Lusiba *et al.* 2017; Brtnicky *et al.* 2021). In this study, from a soil texture perspective, soil in Field A (sandy) can be considered as poor than Field B (sandy loam), which could be the reason why there was no difference between biochar and the control in Field B on P concentration. Lusiba *et al.* (2017) also found no significant difference between the control and biochar application rates of 5, 10 and 20 t ha^{-1} on both sandy loam and clay loam soils on P concentration.

Available K increase following biochar application (Field A) has previously been reported (Nguyen *et al.* 2018), and is explained by high presence of ash content in biochar and its high nutrient retention ability (Adekiya *et al.* 2020b). However, like available P, biochar and the control did not differ significantly in available K in Field B, which might arise from the sandy loam texture soil in this field, similar to the aforementioned explanation on P. The decrease in exchangeable Ca and Mg after soil treatments on both fields is uncommon, although consistent with findings by Miranda *et al.* (2017). Other studies found that organic materials undoubtedly increased exchangeable bases, attributing this to high ash content in the case of biochar (Nguyen *et al.* 2018). Miranda *et al.* (2017) observed similar results to this current study, and proposed that Ca and Mg could have discharged from biochar exchange sites resulting in leaching. Ashiq and Vithanage (2020) also suggested that elevated pyrolysis temperature can disorient functional groups which result in low biochar CEC reducing their ability to adsorb cations. Biochar and organic materials are known for increasing soil CEC, therefore, the relatively low cations, observed in the current study, could have correspondingly contributed to the insignificance of CEC, which corroborates results from other studies (e.g. Angst *et al.* 2014, Lima *et al.* 2021; Abagandura *et al.* 2021).

In Field A, all the organic materials reduced Na in comparison to the control and this was similar to results by Nguyen *et al.* (2018) who concluded that, although the mechanism behind this was unclear, Na adsorption under charged surfaces of organic materials could have been the cause. However, in Field B, the co-application of biochar (CMB and KMB) only significantly increased Na from the control while other treatments were not significantly different from the control. Biochar had a significant influence on Fe and Zn in Field A, which could possibly be resultant of direct release of readily accessible micronutrients as well as its ability to retain these micronutrients in its OM matrix. This similarly applies to manure (KM and CM plots) through its decomposition mechanisms. The increase in some nutrients in the CMB and KMB treatments may have resulted from the mutual consequence of combined biochar and manure (Lentz and Ippolito 2012). Lentz and Ippolito (2012) reported that combined application of biochar and manure yielded highest Fe, Zn, Mn, and Cu concentrations, although in this field, sole biochar was most effective.

The raised soil pH after biochar application on sole application or combined with manure (CMB and KMB plots) both fields is primarily consistent with high pH of biochar emanating from base cation accumulation during pyrolysis (Sukartono *et al.* 2011; Riziki *et al.* 2020; da Silva *et al.* 2021). Additionally, CEC of biochar may attract soil cations, enhancing soil pH. Hence, this facilitates nutrient availability, especially phosphorous, and reduces Al toxicity, particularly in highly weathered regions (Agegnehu *et al.* 2017). A similar trend was observed by Arif *et al.* (2016), where an increase in soil pH of 0.30–0.45 units in an alkaline soil after B addition. The slight increase reflects that biochar correspondingly influenced alkaline soils slightly, but relatively high in acidic soils. Therefore, pH highly depends on soil type and biochar properties.

The increase in OC following sole or co-applied biochar (CMB and KMB) in soil on both fields was demonstrated by previous studies (Ippolito *et al.* 2016; Nyambo *et al.* 2018, 2020; Abagandura *et al.* 2021). This systematically arises from the dominant recalcitrant aromatic C in biochar (e.g. 76.84% for biochar used in this study), rather than sole manure (KM and CM) which contains labile OC that decomposes rapidly (Dodor *et al.* 2019). Additionally, other dynamics like shielding native SOM/SOC from accelerated microbial decay (Ippolito *et al.* 2016), and presence of toxic compounds to microbes generated during pyrolysis (Dodor *et al.* 2018) may be contributing factors. Also, some authors have demonstrated that biochar enhanced aggregate stability and bulk density which ultimately facilitated OC in soil (Abagandura *et al.* 2021). This makes biochar a robust candidate for carbon sequestration and reduction of CO_2 emissions.

The decrease in bulk density following biochar application in the current study correspond with (Adekiya *et al.* 2020a) who reported a significant decrease in bulk density by 9 % after biochar addition. Similar results have been reported by Adekiya *et al.* (2019b) and Widowati *et al.* (2020). The lower biochar bulk densities, 0.3 – 0.43 $g.cm^{-3}$, correspondingly reduce bulk density after biochar incorporation (Agbede and Adekiya 2020b). In addition, the pore spaces in biochar enhance soil porosity, which reduces soil bulk density (Nyambo *et al.* 2018), and these pore spaces are enhanced by higher temperatures during pyrolysis (Xiu *et al.* 2019). Hence, low bulk density will potentially improve aeration, water and nutrient movement, and finally adequate root development, given that bulk densities above 1.54–1.56 $Mg.m^{-3}$ are detrimental in crop production (Agbede and Adekiya 2020).

Regarding soil physical properties, the soil porosity, gravimetric and volumetric water content were only significant in Field B. This might be attributed to addition of organic matter, which facilitates soil pore formation, improved aggregation, and easy water movement, as well as lowering bulk density. Additionally, biochar contains high porous surfaces which may increase soil porosity and enhance water retention (Agbede *et al.* 2020a), thus high water content. However, Field A did not demonstrate significant differences, which contradicts available literature, where increases in these properties were reported following application of either sole or combined biochar and manure (e.g. Agbede *et al.* 2020a ; Agbede *et al.* 2020b). In this field (Field A), the experiment was terminated in June when soil sampling was contacted during periods of heavy rainfalls, thus we suspect probably high rainfall could be the reason for no significance among the treatments.

Our results on both fields (Field A and Field B) undoubtedly demonstrated that amending soil with biochar significantly increased mean weight diameter (MWD) relative to the control, which corroborates findings by other studies (Nyambo *et al.* 2018; Xiu *et al.* 2019; Jin *et al.* 2020) . Moreover, Nyambo *et al.* (2018) demonstrated that increase in MWD after biochar application was influenced by time and application rates. Biochar acts as binding material because of charged surfaces which contain -COOH and -OH functional groups, and CEC which attracts chemical compounds, ions, and nutrients(El Rasafi and Haddioui 2020). Microorganisms also play a significant role on the binding ability of biochar. The labile portion of biochar provides energy for microorganisms, while its porosity and dense surface area provides shelter, thereby facilitating their activity (Agegnehu *et al.* 2017). Thus, high MWD after biochar addition is an indicator for good soil structure and strength which potentially reduce runoff and erosion threats.

It is undeniable that good soil quality is the fundamental ingredient for optimising crop productivity. Throughout the current study, treatments (CM, KM, B, KMB and CMB plots) significantly influenced all sweet sorghum growth parameters (LAI, chlorophyll content, plant height, stem diameter, and leaf number) relative to the control on both fields (Field A and Field B) and the follow-up trial in Field A. However, studies investigating both sole- and combined biochar and manure on sweet sorghum are scant in the literature. Nonetheless, there is some information on other crops, especially maize. For instance, Rollon *et al.* (2020) reported that maize height was maximum with biochar, manure, and their respective blends when compared to the control. Rasafi *et al.* (2021) observed that both biochar and manure significantly improved shoot length, stem diameter, leaf number, leaf elongation, and plant height of barley, either under contaminated or uncontaminated soils. Hindersah *et al.* (2018) stated that application of sole- and combined biochar with manure increased mung bean stem diameter, height, number of leaves, and number of root nodules. Other positive evidence of the effects of sole- and combined biochar and manure on plant growth parameters has been reported for radish (Adekiya *et al.* 2019a), rice (Singh *et al.* 2020), cocoyam (Agbede *et al.* 2020b), and common bean (Lima *et al.* 2021).

The improvement of plant growth characteristics following biochar and manure application is attributable to organic treatments which generally adds soil nutrients, organic matter, and improving other various soil chemical properties (El Rasafi and Haddioui 2020; Singh *et al.* 2020)Combining biochar and other organic materials facilitates availability of nutrients to plants by preventing their leaching or volatilization through biochar high CEC characteristic and negative surfaces charges (Roy *et al.* 2021). Biochar can shelter microorganisms responsible for OM decomposition which transform nutrients from organic to inorganic forms for plant roots absorption (Lebrun *et al.* 2022). Biochar and manure enhance soil water holding capacity which consistently improve plant-available water. Furthermore, biochar can extent its influence by its porous features which induce soil porosity and bulk density (Hindersah *et al.* 2018; Nyambo *et al.* 2018; Agbede *et al.* 2020b), allowing easy movement of water in the soil. Also, improvement in soil pH due to organic materials may improve availability of nutrients and creates a conducive environment for proper plant growth (Riziki *et al.* 2020; Rollon *et al.* 2020).

However, although all organic treatments significantly improved growth traits compared to the control, the KM treatment demonstrated to be inferior among the treatments, and this was most evident in the observed chlorophyll content, stem diameter, and leaf number. Initially, KM generally displayed highest composition of the various soil chemical properties compared to other organic materials (CM, B, KMB and CMB plots); therefore, we suspect that leaching may have caused loss of nutrients, resulting in poor performance of sweet sorghum growth characteristics as compared to other treatments. Additionally, sole CM treatment had some fascinating behaviour in comparison to other treatments in Field A and Field B. During the initial growth stages (first 7 weeks), generally all growth parameters on CM were relatively lower than other treatments and rose to the maximum with time to the end of the experiment although this was mostly visible in Field A. This was an exceptional case which may require deeper investigation, but normally delays in nutrient release from organic material may relate to high C:N ratio, which may drag initial crop growth. In addition, the highest increase in growth parameters was observed in the CM plots at the end of the season. Although not significantly different from other organic materials, the late stage increase can be related by the study of Riziki *et al.* (2020) on *Casuarina* seedlings and (El Rasafi and Haddioui 2020) on barley growth parameters.

Unlike plant height, LAI, chlorophyll content, stem diameter, and leaf number reached a certain maximum point and then decreased. Maximum LAI was reached between 13–17 WAP, which was later than the reported 7 WAP (Zegada-Lizarazu and Monti 2012), which indicates the period where highest carbon assimilation occurs. Chlorophyll content and leaf number reached their maxima at about 12 WAP, followed by a decline, indicating a decrease in photosynthetic activity as the plant approaches senescence (Teixeira *et al.* 2017). Similarly, stem diameter declined between 13–15 WAP, which is possibly because after flowering, stem sugars are translocated to carbohydrates in grains which becomes the primary sink (Tsuchihashi and Goto 2004; Oyier *et al.* 2017; Teixeira *et al.* 2017; Nur *et al.* 2019).

It was evident that plant height was not necessarily good for production because of severe lodging experiences in both fields. Lodging is one of the significant problems in sweet sorghum production. Lodging has been reportedly decreased sweet sorghum growth, yield and biofuel traits (Guo *et al.* 2018). It has been suggested that besides climatic factors (severe winds and heavy rains), aspects such as root knot disease, plant height, weak stems, high plant density, excessive nitrogen fertilization and susceptible cultivars can exacerbate lodging (Teetor *et al.* 2017; Briand *et al.* 2018). When lodging was first experienced in Field A, the plants recovered after two weeks indicating the possibility of recuperating. However, as the impact became severe, lodging worsened up until the end of the experiment. The control on both Field A and Field B, on the other hand, was significantly less affected than all organic treatments, which we suspect was due to the shorter height of the sweet sorghum in the control plots.

The current study evaluated the last four weeks to determine both the yield and biofuel qualities. In terms of sweet sorghum's yield and biofuel characteristics, plant growth parameters and addition of treatments (B, CM, KM, KMB and CMB) were significantly superior to the control on both fields, and the follow-up trial in Field A. As a rule of thumb, the growth performance of a plant will ultimately determine the fate of its yield. In this study we witnessed significant inferiority of plant growth characteristics in the control plots relative to organic treatments, which is eventually the reason why yield was minimized, and biofuel characteristics were poor. The initial nutrients of the sites could directly express that, without supplementing nutrients, limited soil and crop productivity was guaranteed. As similarly explained on plant growth characteristics, organic materials could have added nutrients and manipulated other soil properties for the benefit of increasing yield and biofuel characteristics. Despite scarcity of studies investigating sole- and combined application of biochar and manure on sweet sorghum, studies that have investigated other crops show significant yield increases compared to the control (Nguyen *et al.* 2018; Adekiya *et al.* 2019b; Riziki *et al.* 2020; Rollon *et al.* 2020; Widowati *et al.* 2020; Lebrun *et al.* 2022).

In addition, in the current study, soil analysis at the end of the experiment showed high Na content in control plots, which is indicative of possible salinity stress that the sorghum may have been subjected to, especially in Field A. This was also reported by Nguyen *et al.* (2018), who stated that the presence of excess Na concentration in control than biochar and manure plots was the reason for yield decline of rice.

Among the organic treatments, combined application of biochar and manure (KMB and CMB plots) treatments generally maximised both yield and biofuel traits throughout the harvesting periods than individual manure and biochar, except for few cases were combined mixtures could not differ statistically with their sole counterparts. This interactive effect of biochar and manure reflects the ability to improve efficient utilisation of nutrients by plants (Rollon *et al.* 2020), leading to elevated yield and biofuel characteristics. It has been suggested that combination of biochar and manure treatments potentially decrease leaching of essential nutrients and improve nutrient retention of soil (Hindersah *et al.* 2018; Nguyen *et al.* 2018; Adekiya *et al.* 2019a), thus improving sweet sorghum yield and biofuel. This occurs through the high CEC, presence of negative surface charges, pore spaces and surface area of biochar (Dodor *et al.* 2018), which can hold nutrients released with manure, since some authors proposed that manure nutrient release could be earlier than biochar, but when manure is applied alone, nutrients are vulnerable to leaching and volatilisation than when applied as a mixture with biochar (Adekiya *et al.* 2020a; Lebrun *et al.* 2022).

Numerous studies have observed similar trends on crop yield and quality characteristics when biochar was combined with manure. Recently, Lebrun *et al.* (2022) reported that combined application of biochar and manure increased leaf and tuber biomass of sugar beet than when applied alone (see also Hindersah *et al.* (2018), for similar findings for mung bean. Comparably, Adekiya *et al.* (2019a) also found that biochar and manure co-application had highest number of rhizomes and fresh rhizome yield in ginger compared to individual application of biochar and manure, notwithstanding that biochar and inorganic fertiliser combination had the overall highest yield. On the contrary, Nguyen *et al.* (2018) reported that highest rice biomass was observed when two different biochar types were added on their own than when co-applied with manure. Dodor *et al.* (2018) proposed that dynamics such as shielding of organic substances from microbial utilization, trapping of microbial enzymes and reduction in soil porosity may probably explain why combining biochar and manure reduced organic matter decomposition, which influenced nutrient release patterns and ultimately crop yield.

On the yield characteristics, total dry biomass and fresh stalk biomass were more pronounced on the first week of harvest and subsequently decreased for the next three harvesting times, which is in line with findings by Almodares *et al.* (2006) and Oyier *et al.* (2017). Conversely, grain yield and 1 000 grain weight increased with harvesting time and was more pronounced at the last harvesting stage as also reported by (Oyier *et al.* 2017). However, all biofuel traits decreased from the start of harvesting to the end, and this was in contradiction to some studies that observed increases in biofuel traits with time of harvest (Oyier *et al.* 2017; Chattha *et al.* 2020). Thus, for our study, we deduce that the optimum time of harvest can be confusing because ethanol yield was highest at the beginning of harvest, while grain yield was highest on the last day of harvest. Therefore, increasing the harvesting times beyond those used in this study may assist for a robust investigation of these findings. Also, harvesting of both yield and biofuel characteristics should begin from the flowering period and extend to some few weeks after hard dough stage.

The comparison of correlation results corroborate Naoura *et al.* (2020), who observed that brix and yield (i.e., sugar, juice, theoretical ethanol, fresh stalk, and total dry matter) were all positively correlated. However, brix was negatively corelated with 1 000 GW. The increase in dry matter accumulation represents high carbon accumulation during photosynthesis. This carbon is then utilised for stem sugar and carbohydrates production in the sweet sorghum and is thus positively correlated with biofuel traits. Additionally, dry matter accumulation increases with stem elongation, both height and diameter (Oyier *et al.* 2017). However, although grain yield and 1 000 GW did not reveal any statistical difference with biofuel traits in the current study apart from brix and 1 000 GW, other studies have demonstrated negative correlations (Adams *et al.* 2015; Naoura *et al.* 2020). The plausible reason being that sugars in stems are transformed and transferred to grains during the grain filling period reducing the biofuel traits yield, while increasing grain yield (Teixeira *et al.* 2017; Nur *et al.* 2019).

In this study we found that growth, yield and biofuel properties between Field A and Field B were significantly different between the two fields, where Field A was significantly higher than Field B. The discrepancy found between Field A and Field B on sweet sorghum growth characteristics were an anomaly in relation to other studies. Previous studies have reported higher growth rate when sorghum is planted early than late (Teetor *et al.* 2011; Pagire *et al.* 2021). The differences observed in this study might be attributed to the temperatures during the period Field B was planted, which were relatively lower compared to the time Field A was planted, thus after emergence, there was rapid growth in Field A than Field B. Usually plants that initially grow faster from emergence have greater advantage in terms of growth rate than plants which grow slower after emergence. In addition, Field B was attacked by a leaf disease in week 5, which might have decelerated its growth rate initially.

The yield and biofuel were negatively correlated to growth characteristics, whereby Field B dominated Field A entirely, except for few characteristics which did not differ significantly. In literature, it is documented that planting sweet sorghum earlier in the season increases all yield and biofuel characteristics than planting late (Sollenberger and Gilbert 2011; Teetor *et al.* 2011; Han *et al.* 2012; Pagire *et al.* 2021). This is further correlated with sunshine hours and temperature received in this area which both are highest during the period of October to March (growth period of Field B), and sweet sorghum as a C4 crop maximised photosynthetically active radiation throughout the growth period and ultimately yield (Pagire *et al.* 2021). Nevertheless, in Field A, plants received high sunshine hours and temperature only from January to March, because from April the sunshine hours and temperature start to decrease.

Lodging might have also played a significant role in reducing productivity in Field A as described by other authors (Teetor *et al.* 2017; Guo *et al.* 2018). In Field A, lodging started earlier (in April) and progressively became severe, especially during critical periods such as flowering and grain filling stages, which may have ultimately affected both yield and biofuel characteristics. In Field B, lodging was witnessed later towards the end, and had limited consequences on both yield and biofuel characteristics. Regarding the comparison of Field A first season and the follow up trial, all growth, yield and biofuel characteristics where significantly high in Field A first season than second season, except for brix. This was because of decrease in residual effects of nutrients on the follow-up trial from the first trial, which resulted lower crop productivity.

4.5. Conclusion

This study generally verified that biochar and manure either applied individually or combined are valuable organic materials in modifying soil fertility and sweet sorghum production. Even though those organic treatments did not differ significantly on various chemical properties, sole B and KM had much dominance, while on physical properties B dominated, showing biochar potential in promising soil stability. However, sweet sorghum plant growth parameters generally did not differ significantly, but for yield and biofuel characteristics, combining minimally processed manure and biochar (CMB and KMB plots) seemed to yield the best results. This indicates the promising effects of synergising biochar and manure on yield and biofuel provisions of sweet sorghum. In addition, the influence of biochar and other organic materials highly depends on climate, soil conditions, and biochar pyrolysis temperature and feedstock. Also, validations on biochar effects in agricultural systems may require long term studies to give appropriate recommendations. Additionally, our judgement on the appropriate harvesting time for optimizing both ethanol and grain yield was inconclusive, and we suggested further investigation with additional dates of harvest more than the ones evaluated in this study.

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CHAPTER 5. General discussions, limitations and recommendations for future research

5.1. General discussion

Soil degradation is a concern that is limiting crop productivity in smallholder farming due to its depletion of nutrients and SOM and increase in soil acidity. Although manure application is commonly applied, crop productivity improvements are negligible in smallholder farming. This might be related to either improper utilisation of manure or its associated shortcomings mainly rapid mineralisation. Biochar has been hypothesised to have better amendment effects on alleviating soil degradation than just manure, which is due to its significant structural changes that occur during pyrolysis, especially the formation of recalcitrant C with prolonged half-life. Thus, in this thesis, we firstly evaluated manure application practices which are best in improving crop productivity; and secondly, conducted field trials to assess the potential of biochar in improving soil and crop productivity. The overall thesis aim was to evaluate the best manure application management practices and to investigate the potential of biochar either sole or co-applied with manure (cattle and kraal) in improving marginal soils functioning and crop productivity of sweet sorghum.

5.1.1. Objective 1

On the first objective, manure application practices that can best improve crop yields and soil fertility in smallholder farming systems were evaluated by conducting a meta-analysis (Chapter 3). All systematic guidelines of conducting a meta-analysis were applied to determine how manure application rate, time, method, and type affects crop yields and soil fertility. Generally, it was evident that edition of manure improved crop yields and soil fertility irrespective of any application practice. Regarding application rates, the highest crop yields and biomass yields were highest on low and high application rates respectively, while all soil fertility properties were highest on medium application rate. Incorporating manure outperformed broadcasting on crop yields, biomass yields and all soil fertility properties. We found no significant differences on application of manure before and after planting on crop yields, but application before planting increased biomass yields more than application after planting. Additionally, all soil properties were highest when manure was applied before planting. Lastly, the highest crop and biomass yield was found on cattle and poultry manure respectively, whereas total nitrogen and pH were highest on goat manure, and soil organic carbon, available P, and K were highest on poultry manure.

Results from the meta-analysis demonstrated how significant yields and soil functioning can be improved in smallholder farming by following proper manure application practices rather than the unguided practices currently done by farmers. This may also reduce unpleasant environmental consequences which arise from unsystematic manure application practices. Thus, this information will be critical in guiding farmers to efficiently utilise manure for optimising crop yields sustainably, which significantly enhance food security and poverty alleviation. In addition, the meta-analysis can be used to impart beneficial knowledge for researchers, extension officers and policy makers to draft better refined decisions on the utilisation of manure in smallholder farming.

5.1.2. Objective 2

The aim of the second objective was the evaluation of biochar's potential either applied as sole or co-applied with manure (cattle and kraal) on soil physicochemical properties and crop growth, phenology, yield, and biofuel traits of sweet sorghum (*Sorghum bicolor* (L.) Moench). In addition, yield and biofuel components were harvested under different periods to determine the optimum harvesting time. This objective addressed the prevailing soil degradation challenges which continue to challenge smallholder farmers in optimising yields. Also, the objective addressed the potential of sweet sorghum as an underutilised and under researched crop which has broad advantages in smallholder systems.

As the first part of this objective, biochar was evaluated on how it improves soil chemical and physical properties under two fields. It was observed that the effects of biochar either applied sole or combined with manure was inconsistent on how it affected soil nutrients and was also variable under different fields. In Field A, sole biochar and kraal manure were significantly higher than the control and other treatments on various soil nutrients. In Field B, all treatments, nutrient concentrations were interchangeably high or lower depending on a particular nutrient. This can be explained by mineralisation dynamics, of soil-biochar and soil-organic materials interactions, which are easily influenced by a range of environmental factors such as temperature, moisture, and soil texture. Under this study, the soil textures from the two fields were different, and the period of the year both the experiments conducted was different, which could differ on how temperature and moisture influence soil mineralization dynamics. Additionally, the inconsistency of nutrients availability due to biochar application can also be explained by the proportions of nutrients at specific pyrolysis temperatures in which some nutrients will be high while others low.

However, it was important to note that pH and OC in biochar plots were significantly higher than the control. This stemmed from absolute high pH of biochar, which is increased during the pyrolysis process due to loss of acidic functional groups, leaving behind the alkaline groups with higher liming effects. This similarly applies to OC which is high in biochar because of the pyrolysis process. In addition, woody feedstock biochar is known to yield high C content due to high lignocellulose content. The outcomes of this study on pH and OC further highlight the significance of biochar in reducing soil acidity and its priming effects on SOC and SOM. For instance, Field B had higher soil pH increase because the soil was highly acidic than in Field A. Regarding soil physical properties, biochar was significantly higher than the control, although no significant observations on porosity, GWC, and VWC. Improvement in soil physical properties following biochar application is attributable to high porosity of biochar which are happens during pyrolysis.

This objective also evaluated crop productivity potential of biochar application using sweet sorghum as a test crop. The outcome clearly shows that enriching soil with organic amendments has a significant influence on sweet sorghum growth, yield, and biofuel performance. Among organic amendments, there were no visible differences on growth performance, but on yield and biofuel characteristics, we can generalize that combining biochar and manure (CMB and KMB plots) produced high yields and biofuel characteristics of sweet sorghum, although in some instances there were no differences in comparison to sole amendments. Also, biochar alone performed better than cattle and kraal manure applied on its own. The increase in crop performance due to biochar and manure combinations arises from the synergistic effects of both biochar and manure which enhances the efficiency of soil functioning, therefore improving crop productivity.

The other part of this study was to determine an appropriate harvesting stage for achieving optimum yield and biofuel components especially grain and ethanol yield. We therefore evaluated the last four weeks of growth to determine both the yield and bioethanol qualities. It was observed that total dry biomass and fresh stalk biomass were highest at the start of the four weeks and decreased with harvesting time as the plants began to senesce, while grain yield and 1 000 grain weight increased with harvesting time. All biofuel components declined with time of harvest because more photosynthates are directed to grain formation and sugars in stalks is converted to carbohydrates for grains at this stage of plant development. However, these outcomes could not direct us to a conclusion on when we can optimize both grain and ethanol yield. Therefore, we suggest that future studies may need to extend harvesting stages from flowering to post harvesting maturity.

The comparison between the fields shows that Field B was more productive than Field A in terms of yield and biofuel components of sweet sorghum. This was mainly due to difference in planting dates as Field A was planted three months later in the season than Field B. This shows how temporal variations may influence crop development and yields. Additionally, the factor of lodging cannot be ignored on decreasing yield and biofuel components of sweet sorghum in Field A, which was exacerbated by strong winds occurring towards the commencement of winter season in this location. Possibly, if earlier planting was done, chances of heavy winds interception were likely to be reduced, but discrepancies in planting were due to unavoidable delays caused by the Covid-19 restrictions and lockdowns. Nevertheless, despite the fact that yield and biofuel results obtained from Field A were significantly lower than Field B, the results are comparable to other findings reported in literature. On the follow-up trial of Field A, it was evident that repeating the experiment reduced the residual effects of treatments and it was fascinating that the patterns between the treatments remains almost the same from the initial experiment. For instance, the blended treatments (KMB and CMB) remained high on the follow-up trial which was the same on the initial trial.

The outcome of this study illustrates how amending soil with biochar either sole or combined may be significant in managing soil functioning and crop productivity. Also, it creates the basis for future research on sweet sorghum as an underutilized and under researched crop, and how it can be grown sustainably using biochar. Evaluation of different harvesting dates is crucial because sweet sorghum is a multipurpose crop in which farmers benefit grains for food security and ethanol for energy, while the remaining stover is utilised as animal feed. Its significance may not only be relevant to smallholder farmers but to commercial farmers. Therefore, this study is significant to wide range of stakeholders in agriculture and beyond.

5.2. Limitations

In terms of Objective 1, several studies did not mention summary of statistics (standard errors and standard deviations) which may be required to increase the statistical power of a meta-analysis by weighting effects sizes, although one can procced without their consideration, like this study. Inadequate experimental studies from other regions of SSA especially Central Africa was another limitation because it was important to have at least all regions of SSA included. There was insufficiency of other crops or group of crops for crop yields and biomass evaluation, which was vital in evaluating how certain crops or group of crops are specifically affected by manure practices. Lastly, other categories of explanatory factors had far less observations in comparison to others. For instance, sheep manure had very fewer observations than other types of manure, which was its exclusion reason, despite that it is also commonly used by smallholder farmers and worth evaluation.

The main limitation for Objective 2 was the delay to start the field trials because of Covid 19 outbreak. I came to the University during mid November 2020 rather than February 2020. I was already late for the season, and I had to prepare and start my experiment from that time. Thus, I was able to plant in January 2021 for Field A rather than earlier, and the logistics for me to use another field (Field B) were not yet finalised, which is the reason I was unable to utilise that field on the first year and could not have a follow-up trial. The biochar used in this study was supplied by a company which produce it industrially, and one type of biochar produced at one pyrolysis temperature was used. Therefore, outcomes of this study are more relevant in describing biochar effects in mind of the production condition used because biochar is mainly affected by production conditions. The study was conducted under one location which has same climate conditions. Thus, the results are more relevant in this location. Lodging of Field A was high and made it difficult for data collection because at the end and was the reason data collection for growth characteristics ended on week 21 as most of the plants were down.

5.3. Future Research

Future field studies must include summary statistic in their results, which will be vital in future meta-analyses in improving their statistical power. There is need for more experimental studies of manure practices in Central Africa specifically. Even though some regions had fewer datasets, it was because some studies could not meet the inclusion criteria, but studies are available. More experiments are required on manure effects on other crops besides maize, especially indigenous crops which are adapted to the changing environmental settings and their wide socio-economic advantages.

Future research addressing the effects of biochar on soil nutrients, should prioritise both greenhouse and field studies in parallel. One of the major contributions to the inconsistence in understanding biochar effects on soil nutrition in field studies is because of difficulties in tracing biochar. Thus, under greenhouse conditions, biochar is manageable. Since the effects of biochar on soil and crop productivity are long term, evaluation of long-term field experiments is essential in exposing numerous dynamics associated with changes in soil and crop productivity as biochar ages. Studies like this will require multiple sites which possess different agroclimatic conditions and soil types, as soil productivity and crop yields are random under different conditions. Increasing the sweet sorghum harvesting times beyond those assessed in this study may assist a robust investigation of the findings in this research. Thus, harvesting of both yield and bioethanol characteristics should begin from the flowering period and extend some few weeks after maturity stage. It is worth evaluating the proper planting date of sweet sorghum in this location. In this study, as we unintendingly plant the fields on different seasonal time, we observed that Field A which was planted later dominated Field B on growth characteristics, whereas Field B which was planted earlier dominated Field A on yield and biofuel characteristics. Lastly, the variety of sweet sorghum used in this study was unimproved and sourced from a smallholder farmer, therefore future studies in this region may require evaluation of improved varieties.