Synergistic effects of biochar-compost blends on soil fertility and bioethanol sweet sorghum productivity in marginal South African soils

by

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DECLARATION

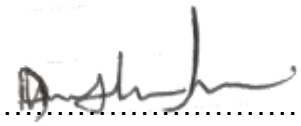
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PREFACE

This dissertation is composed of five chapters. The first chapter contextualizes the background and states the study purpose and objectives. Chapter two offers a comprehensive analysis of literature on biofuel sweet sorghum feedstock, production constraints on South African marginal soils, and the integration of biochar, compost, and their blends as a sustainable production strategy. Chapters three and four consist of interrelated experimental studies; therefore, some degree of repetition was unavoidable. The fifth chapter of the study synthesises the overall results and summarises the general conclusions and recommendations.

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GENERAL ABSTRACT

The sustainable production of biofuel feedstocks on marginal soils in South Africa is a major challenge. This is due to the low soil fertility and dependency on rainfed agriculture which limit crop productivity. This study compared the performance of biochar, compost, and a 1:1 biochar-compost blend with inorganic fertiliser in improving sweet sorghum (*Sorghum bicolor L. Moench*) productivity under marginal soil and rainfed conditions. Specifically, SUPASWEET 2 was used as a cultivar in this study.

Field experiments were conducted at Fine Living Farm in Cullinan, Gauteng Province, South Africa (25°38′59.0″ S, 28°26′31.9″ E). An integrated assessment was done to determine the effects of the different soil amendments on soil physicochemical properties, sweet sorghum fresh biomass yield, brix content, estimated ethanol yield, soil nutrient availability, and soil pH. Biochar, compost, and a 1:1 biochar-compost mixture were each applied at a rate of 7 Mg of carbon per hectare in each growing season. In addition, inorganic fertilisers were applied as basal dressing of 300 kg ha^{-1} of 2:3:4 (30), followed by top dressing of 400 kg ha^{-1} limestone ammonium nitrate. The effects of treatments were evaluated using analysis of variance (ANOVA) in JMP Student Edition version 18. Treatment means were separated using the Least Significant Difference (LSD) test at the 5% level of significance ($P \leq 0.05$).

The findings of this study demonstrated that organic amendments significantly increased sweet sorghum fresh biomass by 27 to 50%, brix content by 13.9 to 48.4% and estimated ethanol yield by 58 to 100% as compared to inorganic fertiliser. The biochar-compost blend consistently produced the highest biomass, brix content, and estimated ethanol yield amongst all treatments.

In addition, the application of biochar, compost, and their 1:1 mixture improved chemical properties which included soil organic carbon (SOC), pH, electrical conductivity (EC), ammonium (NH4+-N), nitrate (NO3--N), available phosphorus (AvP), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), and the capacity of the soil to cation exchange capacity (CEC). The biochar-compost blend significantly enhanced soil fertility parameters by 4.8 to 67.4% as compared to inorganic fertiliser.

In the short term, the biochar-compost blend improved the fertility status of the marginal soil cultivated with bioenergy sweet sorghum. Generally, the findings of this study demonstrated the ability of a 1:1 biochar-compost blend to serve as a sustainable soil management strategy for enhancing soil health, rehabilitating marginal soils and enhancing bioenergy sweet sorghum productivity. This short-term study further indicated the potential contribution of organic amendments to climate-smart biofuel production systems that support soil restoration, reduce reliance on inorganic fertilisers and promote inclusive participation of resource constrained farmers in former homeland areas.

Nevertheless, future long-term studies are crucial for the integration of organic nutrient amendments with conservation practices on South Africa's marginal soils and for evaluating their socio-economic feasibility for sustainable and scalable bioenergy feedstock production.

Keywords: Biochar, Compost; Marginal soils; Soil fertility; Brix content, Biomass yield, Bioenergy production; and chemical properties.

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CHAPTER 1: OVERALL INTRODUCTION

1.1 Introduction.

Utilization of fossil fuels to produce energy is unsustainable and contributes to significant environmental harm (Dell'ariccia et al., 2020). South Africa's greenhouse gas (GHG) emissions are expected to increase drastically by 2050 (Creecy, 2024). In 2022, a large proportion of GHG emissions in South Africa originated from the energy (78%) and agriculture (10.7%) sectors (Creecy, 2024). To support the objectives of lowering GHG emissions by the energy and agricultural sectors (Creecy, 2024), sustainable and renewable energy sources must be adopted (Malobane et al., 2020). For this reason, biofuels are widely recognised as sustainable, clean, renewable and environmentally friendly sources of energy (Munonye et al., 2023).

Biofuels which fall within the category of renewable energy can assist in offsetting the adverse environmental impacts associated with fossil fuel consumption (Chowdhury et al., 2025). Beyond their capacity to reduce dependence on fossil fuels (Cabrera-Jiménez et al., 2022), sustainable biofuel production can contribute to an inclusive circular economy for rural communities and promote the sustainable utilisation of marginal soils (Malobane et al., 2020). The South African Biofuels Industrial Policy has approved the use of first-generation crops for biofuel feedstock (Malobane et al., 2020). However, these approved crops are primarily food crops and their use for energy production creates a food-fuel conflict (Cabrera-Jiménez et al., 2022). Since only approximately 14% of South Africa's land is arable and predominantly dedicated to food production (Kgaphola et al., 2023), biofuel initiatives should prioritise drought-tolerant crops that can perform well in marginal conditions (Malabadi et al., 2022).

Therefore, sweet sorghum is a suitable feedstock to sustainably produce biofuel (Kgaphola et al., 2023). Sweet sorghum is well suited to marginal soils, where the productivity of first-generation biofuel feedstocks is typically constrained (Velmurugan et al., 2019; Xiao et al., 2021). It also requires less fertiliser and water compared to maize and sugarcane (Mengistu et al., 2016), making it highly attractive as a versatile biofuel crop with the capacity to produce high levels of fermentable sugars and biomass (Fu et al., 2024; Pulighe et al., 2019). Furthermore, sweet sorghum is recognised for its multipurpose nature, providing fermentable sugars and grain (Velmurugan et al., 2019). As a lignocellulosic crop, it produces biomass suitable for diverse applications in food, feed, and biofuel industries (Malabadi et al., 2022).

Sweet sorghum is resilient to harsh environmental conditions (Zhang et al., 2024) and can produce renewable energy on marginal soils while safeguarding food security (Malobane et al., 2018). Despite these advantages, successful sweet sorghum production for bioenergy also requires rigorous agronomic management practices (Mangena et al., 2018), which ultimately enhance soil quality with limited environmental impact (Kgaphola et al., 2023). Therefore, developing sustainable and effective management strategies to enhance the quality of degraded marginal soils in South Africa for biofuel-oriented sweet sorghum production is crucial (Kgaphola et al., 2023). South African communal lands are degraded with reduced water availability, vegetation carrying capacity and low fertility status (Kgaphola et al., 2023). Hence, inorganic fertilisers which are negatively impacting the environment continue to be used to increase and maintain productivity in marginal soils (Jote, 2023). Inorganic fertilisers are also expensive for resource-constrained smallholder farmers (Jote, 2023; Sher et al., 2022). Thus, environmentally friendly and sustainable methods that increase soil fertility and productivity in agriculture are needed to assist and uplift rural communities to participate in agriculture and biofuel sectors (Sher et al., 2022).

Organic nutrient amendments enhance key soil functional attributes, including those associated with overall soil quality (Mikajlo et al., 2024). Biochar, compost and biochar-compost blend improve soil properties (Mikajlo et al., 2024; Tazebew et al., 2024) and the quality status of marginal soils for poor rural farmers to participate in the biofuel economy (Kgaphola et al., 2023; Russo et al., 2025). Thus, agricultural systems that conserve and enhance the quality of marginal soils for sweet sorghum-based biofuel production are needed (Fu et al., 2024). Accordingly, this study evaluates the effectiveness of organic amendments in improving marginal soil quality in South Africa to sustainably support sweet sorghum biofuel production.

The subsequent objectives serve to define the scope of the current study:

1. To determine the effects of organic nutrient amendments (biochar, compost, and a biochar-compost blend) on sweet sorghum biomass and estimated ethanol production.

2. To assess the ameliorating influence of organic amendments on nutrients availability and pH under biofuel sweet sorghum.

Furthermore, the research was guided by the following hypotheses:

1. Compost, biochar and biochar-compost blend increase sweet sorghum biomass and ethanol yields.

2. Compost, biochar and biochar-compost blend improve soil nutrients availability and pH under biofuel sweet sorghum.

1.2 Definition of key concepts

The following key terms are defined to provide common understanding of the terminology used throughout this dissertation. This is done to improve conceptual clarity and provide context in this study.

1. **Marginal soils**

   Marginal soils are inherently constrained by biophysical and chemical limitations that are restrictive to agricultural productivity and require appropriate management interventions to sustain crop production (Kgaphola et al., 2023).

2. **Biochar**

   Biochar is a stable, carbon-rich material produced from biomass through the pyrolysis process of under limited oxygen conditions (Gross et al., 2025).

3. **Compost**

   Compost is a stabilised organic rich material produced through a controlled an aerobic decomposition of organic residues (Mikajlo et al., 2024).

4. **Biochar–compost blend**

   Biochar-compost blend is a mixture of biochar and compost applied at the same time as an organic soil amendment.

5. Sweet sorghum

Sweet sorghum (*Sorghum bicolor (L.) Moench*) is a C4 crop rich in fermentable surgars, cultivated for food, animal feed and biofuel production (Fu et al., 2021).

6. Soil organic carbon (SOC)

Soil organic carbon (SOC) is a carbon component of soil organic matter which plays a key role in soil fertility, soil quality and carbon sequestration (Cheng et al., 2025).

7. Cation exchange capacity (CEC)

Cation exchange capacity (CEC) is the capacity of soil to adsorb, retain and exchange positively charged nutrient ions (cations) (Sebahire et al., 2024).

8. Brix

Brix is the concentration of total soluble solids primarily sugar in plant juice (Elhawat et al., 2025).

9. Estimated ethanol yield

Estimated ethanol yield is a calculated potential volume of ethanol produced from sweet sorghum biomass based on its biomass and sugar content (Nazli et al., 2024).

10. Soil pH

Soil pH is a measure of the acidity or alkalinity of the soil solution which is important for nutrient availability, microbial activities and plant growth (Ding and Yu, 2024).

11. Electrical conductivity (EC)

Electrical conductivity (EC) is a measure of the concentration of soluble salts and an indicator of soil salinity (Meng et al., 2025).

CHAPTER 2: LITERATURE REVIEW

2.1 Sustainable alternative energy and biofuel in South Africa

Pressure to reduce fossil fuel use and greenhouse gas (GHG) emissions is increasing (Pulighe et al., 2019). In Africa, the largest emitter of carbon dioxide (CO_2) is South Africa, due to its industrialized economy (Pulighe et al., 2019). Consequently, there is a pressing need for alternative renewable, clean and environmentally friendly energy sources to support industrialization (Gielen et al., 2019). In response, the South African government has prioritized access to sustainable and clean bioenergy to support a resilient economy primarily through policies such as the National Biofuels Industrial Strategy (Malobane et al., 2020). This strategy focuses on addressing poverty and promoting economic development (Creecy, 2024).

The current chapter examines the utilisation of sweet sorghum as a feedstock for biofuel production. It further assesses compost, biochar and their blend for sustainable agricultural productivity, improvement of soil status, and environmentally friendly production methods. Sustainable production methods, in this context refer to agricultural practices that produce crops in a manner that protects the environment, preserves natural resources, and promotes soil quality (Pulighe et al., 2019).

2.2 Sweet Sorghum

2.2.1 The role of sweet sorghum in sustainable bioenergy production

Cultivating biofuel feedstock leads to land-use conflicts between energy and food crops, indicating the need to implement sustainable agricultural practices (Creecy, 2024; Shukla et al., 2023). In response, the National Biofuels Industrial Strategy prohibits the use of basic staple food crops, mainly maize (*Zea mays*) for biofuel production, while prioritising support for farmers in former homeland communities (Malobane et al., 2018). However, approved crops currently permitted for biofuel production are considered as first-generation biofuel feedstock (Westhuizen et al., 2022). These crops are cultivated primarily for food, raising concerns about their long-term sustainability compared to second-generation biofuel alternatives (Kgaphola et al., 2023). The cultivation of first-generation biofuel crops requires arable land that is best suited for food production, thereby intensifying the food-fuel conflict (Mathur et al., 2017). Therefore, the National Biofuels Industrial Strategy encourages the use of land in the former homeland areas to produce biofuel (Malobane et al., 2018). However, former homelands are characterized by marginal soils with poor fertility, severe degradation, high erodibility, and inherently low organic matter (Kgaphola et al., 2023).

Marginal soils are unsuitable for cultivating first-generation crops as recommended in the National Biofuels Industrial Strategy (Malobane et al., 2018). Moreover, first-generation crops generally require high agronomic inputs to achieve optimal yields (Russo et al., 2025), which presents a major challenge for resource-poor smallholder farmers in these areas (Nenciu et al., 2022). For example, sugarcane as a first-generation crop requires high water inputs, making it unsuitable for South Africa’s water-scarce conditions (Dodo et al., 2017).

Therefore, biofuel production depends on a reliable supply of biomass that can be cultivated with minimal inputs on marginal soils, without competing with arable land used for food production (Russo et al., 2025; Shukla et al., 2023). Crops that require fewer agronomic inputs, use limited water, and are adapted to marginal soils are suitable biofuel feedstocks for South Africa (Russo et al., 2025).

Lignocellulosic crops, particularly sweet sorghum have relatively low agronomic input requirements, environmental adaptability, and are well suited for sustainable biofuel production (Beluhan et al., 2023). Furthermore, crops with diverse applications, capable of yielding food, livestock feed, and biofuel precursors, are seen as more suitable than crops dedicated only to energy production (Malabadi et al., 2022). As a multipurpose crop (Figure 2.1), sweet sorghum provides edible grains, livestock feed, and stalks containing sugars that can be processed into bioethanol (Malabadi et al., 2022). For these reasons, sweet sorghum is a well-suited crop for the sustainable production of biofuels in South Africa (Mengistu et al., 2016).

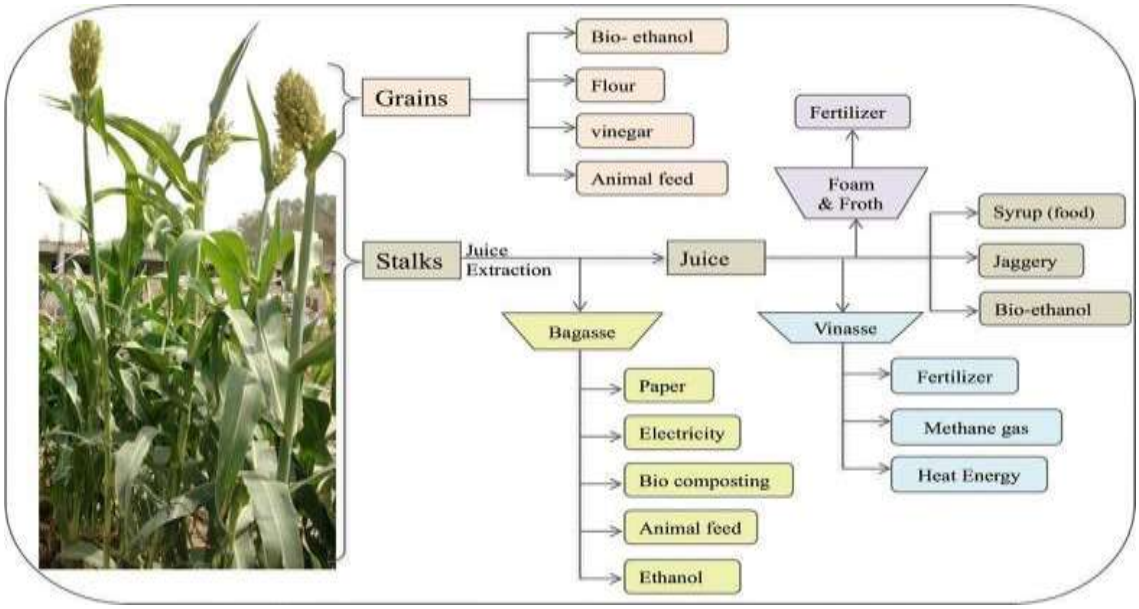


Figure 2.1: Various uses of multipurpose sweet sorghum (Mathur et al. 2017).

2.2.2 Agronomic and bioenergy potential of Sweet Sorghum

Sweet sorghum is a C_4 plant with agronomic traits that enable tolerance to several biotic and environmental stresses (Fu et al., 2021). Sweet sorghum is characterized by efficient water use and minimal impact on surrounding water resources (Mengistu et al., 2016). Furthermore, sweet sorghum stalks produce more soluble sugars under marginal conditions where sugarcane and other lignocellulosic biomass crops are less productive (Nenciu et al., 2022). Sweet sorghum can produce 6-8 $t.ha^{-1}$ of sugar and approximately 3,000 $L.ha^{-1}$ of ethanol with low agronomic input (Mangena et al., 2018; Nazli et al., 2024). Sugarcane cultivated under high input management yields 7-8 $t.ha^{-1}$ of sugar and 3,000–5,000 $L.ha^{-1}$ of ethanol (da Costa et al., 2021; Dodo et al., 2017).

Although sugarcane generally produces higher bioethanol yields (Dodo et al., 2017), sweet sorghum's annual bioethanol output can exceed that of sugarcane in warmer climates (Nenciu et al., 2022), which characterise most parts of South Africa (Brown et al., 2024). Moreover, sweet sorghum has similar biochemical composition and biomass recalcitrance to sugarcane (Brown et al., 2024). Consequently, existing sugarcane ethanol processing infrastructure can be utilized for sweet sorghum without requiring major technical modifications (Beluhan et al., 2023; Yudina et al., 2021). This represents a practical benefit for biofuel production using sweet sorghum (Yudina et al., 2021). Thus, producing sweet sorghum for biofuel presents a favourable return on investment (Zhang et al., 2024).

2.2.3 Limitations in biofuel sweet sorghum production

Although sweet sorghum offers considerable benefits for bioenergy production in South Africa, adoption of appropriate management approaches is crucial for optimal production (Mengistu et al., 2016). Generally, sustainable management practices for sweet sorghum production are lacking (Chowdhury et al., 2025; Oueld Lhaj et al., 2024). A knowledge gap persists regarding the development of appropriate agronomic practices essential for improving sweet sorghum productivity (Chowdhury et al., 2025). To achieve higher ethanol yields in South African marginal soils, the development of sustainable cultivation practices that incorporate the application of organic amendments in sweet sorghum production systems is important (Fu et al., 2024).

2.3 Amelioration of the soil with organic amendments

High quality soils are essential for sustainable agricultural productivity in South Africa (Westhuizen et al., 2022). For many years, agricultural productivity has been maintained using inorganic fertilisers (Jote, 2023). Continuous application of inorganic fertilisers without organic inputs can accelerate soil organic matter mineralisation, potentially resulting in a decline in soil organic carbon (Jote, 2023). The implementation of practices that depend less on inorganic fertilisers is critical in conserving and improving soil quality (Jote, 2023). Incorporating organic fertilisers alongside inorganic fertilisers represents a vital alternative management practice (Sher et al., 2022). It maintains optimum levels of soil organic matter (Shamrikova et al., 2022), thus enhancing soil quality and agricultural productivity (Lucchetta et al., 2023). Compost and biochar strengthen soil biochemical properties, raise nutrient levels, and promote higher crop yields (Suvendran et al., 2025).

2.3.1 Compost as an organic soil ameliorator

Compost is produced through the aerobic decomposition of plant and animal residues (Mikajlo et al., 2024). With its rich humus, it supports soil health, increasing nutrient content and boosting agricultural productivity (Sayara et al., 2020, Suvendran et al., 2025). Moreover, compost improves chemical properties by increasing soil organic carbon (Lucchetta et al., 2023), which enhances the ability to exchange cation and retain nutrients in marginal soils (Sun et al., 2025). It also supplies essential macro and micronutrients that are gradually released through mineralisation (Agegnehu et al., 2017), enhancing availability of nutrients and reduce leaching (Sun et al., 2025). Beneficial microbes break down organic matter, thereby facilitating nutrient turnover, and crop yield (Xu et al., 2023).

Compost buffers soil pH by supplying base cations and combining with exchangeable aluminium to lower soil acidity (Xu et al., 2023). In addition, organic acids and humic substances in compost enhance the availability of phosphorus by preventing the fixing of iron and aluminum oxides (Sun et al., 2025; Xu et al., 2023). These processes improve fertility and chemical stability, supporting sustainable sweet sorghum production under low input conditions typical of marginal soils of South Africa (Agegnehu et al., 2017).

2.3.2 Utilization of biochar to ameliorate soil conditions

Biochar is characterized by high porosity and carbon content (Gross et al., 2025) which are important for fertility (Fernández-Ugalde et al., 2020). It also provides habitat for micro-organisms that drive nutrient cycling and enhance nutrients availability for plants (Pokharel et al., 2025). Previous research has shown that biochar improves soil biochemical characteristics and fertility (Zhu et al., 2025).

The process supplies organic carbon, negatively charged sites, and oxygenated moieties (Adhikari et al., 2024). These improve nutrients retention and exchange of cations (Izilan et al., 2022). Biochar can sorb dissolved nutrients through adsorption and physicochemical interactions to minimize losses while promoting more efficient use of nutrients and water (Gao et al., 2025). Compost and biochar individually improve soil properties on marginal lands (Gross et al., 2025) and assist in biofuel feedstock production (Izilan et al., 2022). Nevertheless, compost applied on its own is prone to nutrient losses through leaching (Gao et al., 2025), while biochar supplies limited readily available nutrients (Izilan et al., 2022). A biochar-compost blend is a suitable intervention that harnesses the strengths of the two organic amendments (Harrison et al., 2024).

2.3.3 Biochar-compost blend as organic soil ameliorator

The biochar-compost blend is an organic soil enhancer that integrates pyrogenic carbon with decomposed organic input (Umair Hassan et al., 2024). These amendments are applied jointly to the soil to harness the complementary benefits of the two (Harrison et al., 2024). Compost contains readily available nutrients and biologically active (labile) organic matter (Cheng et al., 2025) while biochar contributes stable carbon, improves biochemical properties and enhance nutrients (Gross et al., 2025). This combination provides synergistic effects that increase soil organic carbon (SOC), available phosphorus, total nitrogen exchangeable bases, water retention and micro-organism activities to improve crop productivity (Adhikari et al., 2024). The combined effect makes the biochar-compost mixture a promising strategy to restore fertility (Khan et al., 2024) and sustain productivity in marginal and degraded soils for bioenergy sweet sorghum (Suvendran et al., 2025).

2.4 Modulating soil greenhouse gas emissions by biochar-compost amendments

Carbon dioxide (CO_2), methane (CH_4) and Nitrous oxide (N_2O) are produced naturally through Earth's environmental processes (Palansooriya et al., 2025), but anthropogenic activities exacerbate their discharge into the ambient air (Harrison et al., 2024). By absorbing and re-emitting infrared radiation, these gases amplify the greenhouse effect, leading to climate change and rising global temperature (Shrestha et al., 2023).

Agricultural soils function as both sources and reservoirs of greenhouse gases (GHGs) (Palansooriya et al., 2025), with emissions generally regulated by microbial processes (Umair Hassan et al., 2024). These microbial processes include soil respiration which releases CO_2 (Gao et al., 2025), methanogenesis and methanotrophy which releases CH_4 (Harrison et al., 2024), and nitrification–denitrification which releases N_2O (Palansooriya et al., 2025). In addition, soil GHG emissions are influenced by soil moisture, aeration, temperature, availability of organic matter, and utilisation of inorganic and organic fertilisers (Palansooriya et al., 2025).

Understanding how different soil amendments affect these gas producing processes is essential for developing climate-smart agricultural strategies aimed at reducing GHG emissions and enhancing soil sustainability (Umair Hassan et al., 2024). Biochar-compost amendments regulate the generation and uptake of CO_2, CH_4 and N_2O in soils, influencing greenhouse gas fluxes (Shrestha et al., 2023). Mixing compost with biochar positively affects soil by increasing aeration, maintaining nutrients, and promoting microbial processes (Baizán et al., 2021). Biological and physico-chemical impact of biochar and compost collectively influence microbial pathways which are responsible for GHG fluxes (Baizán et al., 2021). The process limits climate change by storing carbon in the soil (Umair Hassan et al., 2024).

The slow decomposition and long stay in the soil of biochar also assist in removing CO_2 from the atmosphere by storing plant derived carbon (C) in a stable form (Gamage et al., 2023). Biochar-compost amendments can further stabilise soil organic carbon (SOC) by adsorbing labile compounds and reducing mineralisation, thereby lowering CO_2 emissions relative to compost alone (Zulfiqar et al., 2021). This stabilisation effect, together with enhanced soil aeration and reduced availability of mineral nitrogen, can suppress N_2O emissions by limiting denitrification (Baizán et al., 2021), while improving gas diffusivity which reduces CH_4 production in anaerobic microsites (Harrison et al., 2024). Thus, applying biochar-compost blend in the cultivation of sweet sorghum represents a promising climate-smart approach for rehabilitating marginal lands (Gamage et al., 2023), advancing renewable energy goals, and lowering agricultural impact on the environment (Xiao et al., 2021).

CHAPTER 3

Sweet sorghum biomass, brix content and estimated ethanol yield as affected by inorganic fertiliser, biochar, compost, and biochar-compost blend in marginal soils under rainfed conditions.

Abstract

Sustainable cultivation of bioenergy crops like sweet sorghum is fundamentally important in biofuel production as part of clean energy. Thus, the impact of organic fertilisers on biomass, brix content and estimated ethanol productivity compared to inorganic fertiliser requires evaluation.

The current research aimed to evaluate the impact of biochar, compost, and a biochar-compost blend, relative to inorganic fertiliser, on sweet sorghum fresh biomass, brix content and estimated ethanol yield in marginal soils under rainfed conditions. Organic amendments were applied at 7 Mg C ha−1 in each growing season. Inorganic fertilisers were applied at 300 and 400 kg ha−1 (2:3:4 (30) and limestone ammonium nitrate) as basal and topdressing, respectively. The application of organic amendments increased sweet sorghum fresh biomass by 27-50%, brix content by 13,89-48,43% and estimated ethanol yield by 58-100% compared to inorganic fertiliser, respectively. In the short term, the biochar-compost (1:1) blend emerged as the most promising sustainable practice for bioenergy sweet sorghum production. This treatment outperformed other organic amendments across all evaluated parameters. However, future research should explore the integration of additional conservation practices to develop holistic sustainable production systems for bioenergy crops under rainfed and marginal soils.

Keywords: Sustainable production, bioenergy, ethanol, biofuels, organic amendments.

3.1 Introduction

Sustainable implementation of the South African Biofuel Industrial Strategy will require continuous biomass production at low agronomic inputs in marginal soils (Malobane et al., 2018). Therefore, sweet sorghum is considered one of the leading bioenergy crops that can be produced in marginal soils at low agronomic inputs (Xiao et al., 2021). Additionally, sweet sorghum doesn't contribute to the food-fuel conflict (Sumberg and Giller, 2022). Sweet sorghum tolerates drought and waterlogging, requires minimal water and fertiliser inputs, and performs effectively in moderately acidic to alkaline soils (pH 5.0–8.5) with high salinity conditions (Dewi et al., 2023). Nonetheless, its sustainable production as a bioenergy crop remains under-researched in South African marginal soils (Malobane et al., 2018). Energy crops are conventionally cultivated under intensive production systems that rely on chemical fertilisers and involve the complete removal of aboveground biomass (Malobane et al., 2018).

Continuous use of chemical amendments in bioenergy crop production negatively impacts soil health (Sumberg and Giller, 2022). The South African former homelands which are recommended to produce bioenergy crops (Malobane et al., 2020), are already poor and highly degraded (Sepuru and Dube, 2018). Thus, implementation of traditional practices can worsen the soil quality and lead to reduction in bioenergy crop yields (Sepuru and Dube, 2018). Application of agricultural methods that don't deteriorate soil quality through inorganic fertiliser are vital to produce bioenergy crops sustainably (Bhatia and Sindhu, 2024). Organic fertilisers are reported to be sustainable production in enhancing crop yields while minimizing land degradation (Bhatia and Sindhu, 2024; Gamage et al., 2023).

Compost and biochar are amongst organic amendments which were reported to enhance crop yield under different soils (Kebede et al., 2023). For example, the use of compost improved productivity of tomato by 12.7% whereas biochar application resulted in 30% improvement of tomato yield relative to inorganic fertilizers (Zulfiqar et al., 2021). Additionally, biochar-compost blend enhanced maize biomass and grain yields by 22.22% and 8.46%, respectively, in comparison to inorganic fertilizers (Wu et al., 2023). Furthermore, biochar substantially improved winter wheat height by 15.74% and grain yield by 13.19% relative to inorganic amendments (Zulfiqar et al., 2021).

Moreover, organic nutrient amendments enrich soil properties and plant development (Sepuru and Dube, 2018). Despite advantages of organic nutrient amendments, less is known about their impact on bioenergy crops and ethanol yields. Accordingly, the current research investigated the influence of organic nutrient amendments on biomass production and potential ethanol yield of bioenergy sweet sorghum.

3.2 Experimental Materials and Methods

3.2.1 Trial site: description and management

The trial was conducted at Fine Living farm in Gauteng Province of South Africa. The farm is situated east of Pretoria in Cullinan at latitude of 25º38’59.0” S and longitude 28º26’31.9’ E. The area is characterized by warmer summer temperatures between September and March with cold winter temperatures starting from May to August. The average summer and winter temperatures are 28ºC and 17ºC respectively.

In addition, Cullinan is a semi-arid area with a mean annual rainfall of approximately 625 mm with January being the wetter month while May to August is dry (Knight and Elbasit, 2024). Hutton soils, classified as Rhodic Ferralsols under the World Reference Base for Soil Resources, are the dominant soil form at the study site. These soils are typically deep and well drained (Soil Classification Working Group, 1991).

3.2.2 Field experiment set up

The experiment was established during the 2023/2024 growing season and concluded following harvest in the 2024/2025 growing season. Planting for the first growing season commenced on 5 January 2024 and concluded with harvest and data collection on 9 May 2024. The second growing season commenced on 17 November 2024 and ended with harvest and data collection on 1 March 2025. Treatments were applied to plots measuring 1.8 m x 3.6 m, with each treatment replicated three times in a randomized complete block design (RCBD). The total experimental area was 0.008 ha, accommodating a total plant population of 1,404 plants. The four treatments consisted of: (i) a control with no organic amendment, (ii) compost, (iii) biochar, and (iv) a 1:1 biochar-compost blend.

The organic amendments were applied at a rate of 7 Mg C ha^{-1} in each growing season (Gao et al., 2025). All the twelve plots received a basal application of 300 kg ha^{-1} of 2:3:4 (30) fertiliser at planting and a topdressing application of 400 kg ha^{-1} limestone ammonium nitrate (LAN) during crop growth (Mengistu et al., 2016). Sweet sorghum (*Sorghum bicolor (L) Moench*), commercially available biochar and compost were used in the study. In addition, the cultivar used for this study was ‘SUPASWEET 2’ (Agricol, South Africa).

Seed was procured from Agricol while biochar and compost were procured from Organics Matter SA (PTY) Ltd in Pretoria, South Africa. Furthermore, the biochar used was derived from pine wood feedstock and produced through a pyrolysis process at 1000°C, while the compost consisted of a blend of wood chips, cattle manure, and grass residues. Sprinkler irrigation was used to supplement rainfall during the first growing season. However, during the second growing season, rainfall was sufficient to meet the crop water requirements.

3.2.3 Soil sampling

For measuring the impact of the treatments on the availability of nutrients after 2 planting seasons, soils were sampled after the harvesting of sweet sorghum in March 2025. Aboveground plant and animal materials were cleared. This was followed by soil sampling which was carried out with a soil auger. Twelve core samples were randomly collected from the top (0–20 cm) of the soil profile and transported to the laboratory in paper soil bags. For analysis of soil chemical attributes, samples were oven-dried and subsequently passed through a 2 mm sieve.

3.2.4 Characterization of compost and biochar

To prepare homogeneous samples for initial characterization, both biochar and compost were oven-dried at 60°C and subsequently passed through a <2 mm sieve. The concentrations of Nitrogen (N), Magnesium (Mg), Potassium (K), Calcium (Ca), Sodium (Na), Sulphur (S), Phosphorus (P), Manganese (Mn), Zinc (Zn), Iron (Fe), Copper (Cu), Molybdenum (Mo), and Boron (B) were analysed with Coupled Plasma- Optical Emission Spectrum.

Walkley-Black method was used for total organic carbon (ToC) (Zineb et al., 2023). Biochar, compost and selected soil were characterised (Table 3.1 and 3.2).

Table 3. 1: Physicochemical characterisation of biochar and compost

Parameters	N	Ca	Mg	K	Na	S	P	Fe	Mn	Cu	Zn	Mo	B	pH	ToC
	%	%	%	%	mg/kg	%	%	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	pH units	%
Biochar	0.01	0.29	0.1	0.32	807	0.02	0.04	461	480	13	4	0.23	16	8.5	83.47
Compost	0.67	3.96	0.4	1.43	1805	1.38	0.4	7862	396	117	177	1.53	13	7.3	28.1

Table 3. 2 : Selected soil characteristics in the experiment site

Variables	Unit standards	Figures
Sand	%	84
Silt	%	4
Clay	%	12
Textural class	-	Sandy loam
pH	-	7.08
Soil organic carbon	g/kg	9.3
Electrical conductivity	mS/m	51.8

3.2.5 Management of experimental variables

In each growing season, land preparation was done using a disc plough. In addition, the organic amendments were applied on the surface two weeks before planting sweet sorghum in each growing season. Sweet sorghum was sown at 0.9 m row spacing and 0.3 m plant spacing to ensure even distribution of plants.

Weeds were controlled manually as required to maintain clean plots. Lambda-cyhalothrin (50 g L^{-1}) was applied to control Melanaphis sacchari, Rhopalosiphum maidis, Spodoptera frugiperda, Busseola fusca and Chilo partellus which are common pests of sorghum in South Africa (Imoloame and Osunlola, 2017).

3.2.6 Determination of Bioethanol Yield

Brix content was measured at hard dough stage using portable refractometer. The brix content measurements were taken from the 3rd internode from the plant base (da Costa et al., 2021). Biomass yield was collected during brix measurement. Total ethanol yield ($L \cdot ha^{-1}$) was calculated as follows:

Ethanol yield = fresh stalk Brix (%) × fresh stalk biomass (t/ha) × 10 × 0.511 × 0.85 × 0.90 × (1.00/0.79) (Fu et al., 2021).

Where:

- 0.511 is the conversion factor of sugar to ethanol,
- 0.85 represents the fraction of fermentable sugars,

- 0.90 is the process efficiency for ethanol production, and
- 1.00/0.79 accounts for the specific gravity of ethanol ($g \cdot mL^{-1}$) (Fu et al., 2021).

3.2.7 Statistical analysis

The effects of treatments were evaluated using analysis of variance (ANOVA) in JMP Student Edition version 18. Differences among treatment means were evaluated with the LSD test at $P \leq 0.05$.

3.3 Results and Discussion

3.3.1 Results

The results presented in Table 3.3 indicate that inorganic fertiliser (control) and organic nutrient amendments significantly ($P < 0.05$) influenced sweet sorghum fresh biomass, brix content, and estimated ethanol yield. Fresh biomass and ethanol yield were significantly ($P < 0.05$) affected in both growing seasons, while brix content was significant ($P < 0.05$) only in the second season (Table 3.3).

Table 3. 3: Effect of different treatments (inorganic fertilisers, biochar, compost and biochar-compost blend) on sweet sorghum fresh biomass, brix content, and estimated ethanol yield.

Measured variable	Fresh Biomass		Brix %		Estimated Ethanol	
	S1	**S2**	**S1**	**S2**	**S1**	**S2**
F-value	26.88	18.44	2.59	34.16	42.61	51.88
df	3,6	3,6	3,6	3,6	3,6	3,6
P-value	0.0007*	0.0020*	0.1480^{NS}	0.0004*	0.0002*	0.0001*

S1: season 1; S2: season 2; *: Significant at P<0.05; NS: Not significant, df: degrees of freedom:

3.3.1.1 The impact of inorganic fertiliser and organic nutrient amendments on sweet sorghum fresh biomass yield.

Organic amendments significantly (P < 0.05) enhanced fresh biomass yield relative to the control in both season 1 and season 2 (Figure 3.1). Fresh biomass was greatest in biochar-compost blend treatments (Figure 3.1). In season 1, the compost-biochar blend yielded significantly higher fresh biomass (P < 0.05) than biochar, while showing no significant difference from compost (Figure 3.1 S1). Furthermore, during the second season, no significant variances (P < 0.05) were observed among the organic amendment treatments (Figure 3.1 S2). In season 1, biochar-compost blend, compost and biochar had 50,07%, 38,81% and 35,8% fresh biomass higher compared to control, respectively. In addition, in season 1, biochar-compost blend had 8,11% and 10,51% higher fresh biomass yield compared to compost and biochar, respectively.

On the other hand, in season 2, biochar-compost blend, compost and biochar had 38,72%, 37,20% and 27,02% higher fresh biomass yield in comparison to control, respectively. Moreover, biochar-compost blend had 1,95% and 9,21% higher fresh biomass yield compared to compost and biochar, respectively.

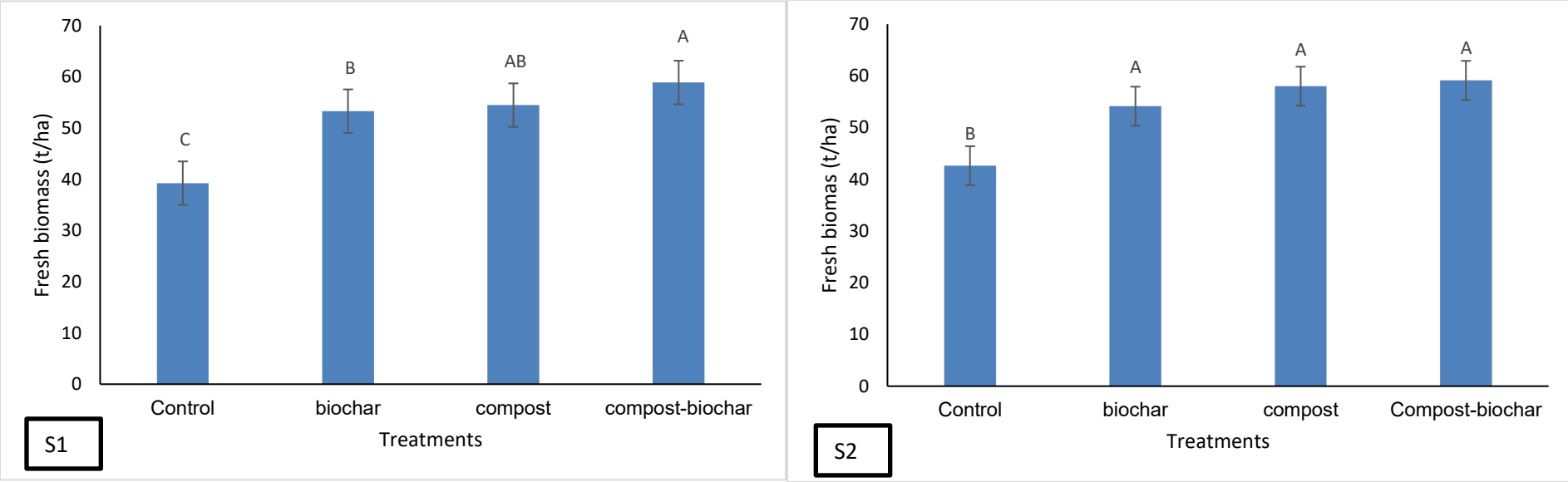


Figure 3.1: Total fresh biomass as influenced by different fertilisers. Bars sharing the same letters are not significantly different (P<0.05). S1: Season 1, S2: Season 2.

3.3.1.2 Effect of inorganic fertiliser and organic nutrient amendments on sweet sorghum brix.

Brix content did not differ significantly ($P < 0.05$) among treatments in season 1 (Table 3.3; Figure 3.2 S1). However, in season 1, biochar-compost blend, compost and biochar had 16,67%, 16,67% and 13,89% higher brix content than control, respectively. In season 2, organic amendments had a significantly high ($P<0.05$) brix content relative to inorganic fertiliser treatment (Figure 3.2 S2). The brix content was not significant ($P<0.05$) amongst all organic amendment's treatments (Figure 3.2 S2). In season 2, biochar-compost blend, compost and biochar had 48.43%, 44.29% and 43,91% higher brix content in comparison to control, respectively.

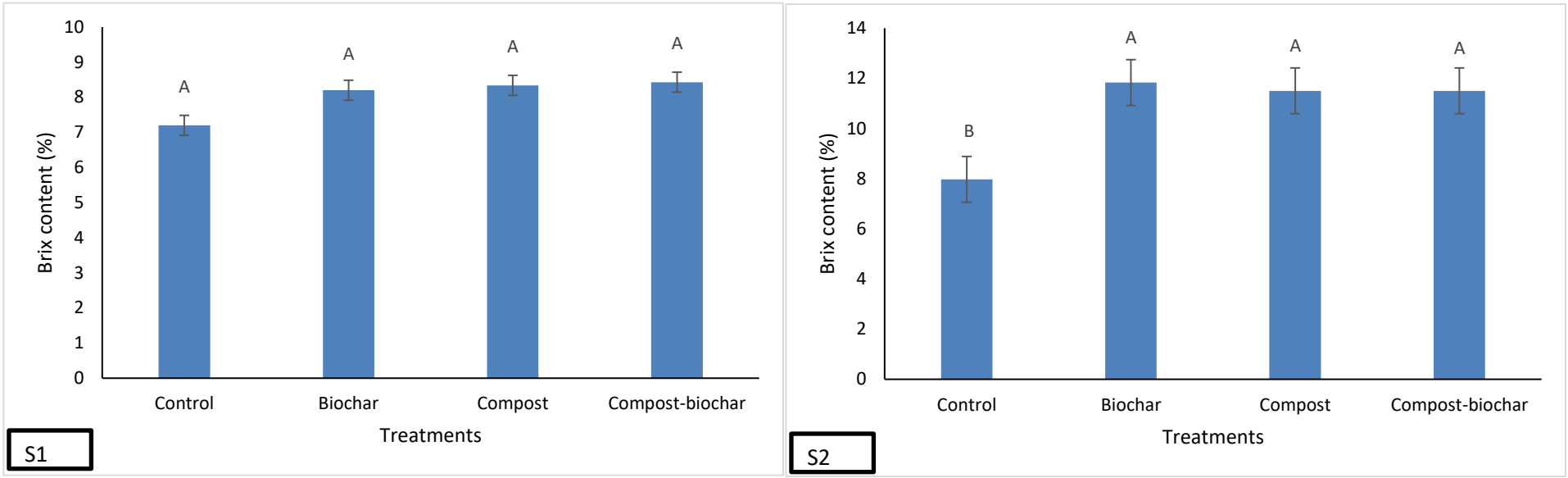


Figure 3.2 : Total brix content as influenced by different fertilisers. Bars sharing the same letters are not significantly different (P<0.05).

Season 1 = S1, Season 2 = S2.

3.3.1.3 The impact of control (inorganic fertiliser) and organic nutrient amendments on sweet sorghum estimated ethanol yield.

In both growing seasons, estimated ethanol yield was significantly ($P<0.05$) greater under organic nutrient amendments as compared to inorganic fertiliser treatment (Figure 3.3). During the first season, estimated ethanol yield was significantly ($P<0.05$) greater under biochar-compost blend than all other treatments (Figure 3.3 S1). In contrast, organic amendments did not differ significantly ($P<0.05$) in season 2 (Figure 3.3 S2). Biochar-compost blend, compost and biochar had 75,4%, 58,71% and 58,05% estimated ethanol yield higher compared to control in season 1, respectively. Furthermore, in season 1, biochar-compost blend had 10,52% and 10,98% higher estimated ethanol yield compared to compost and biochar, respectively. On the other hand, in season 2, biochar-compost blend, compost and biochar had 100%, 96.54% and 88.67% higher estimated ethanol yield compared to the control, respectively.

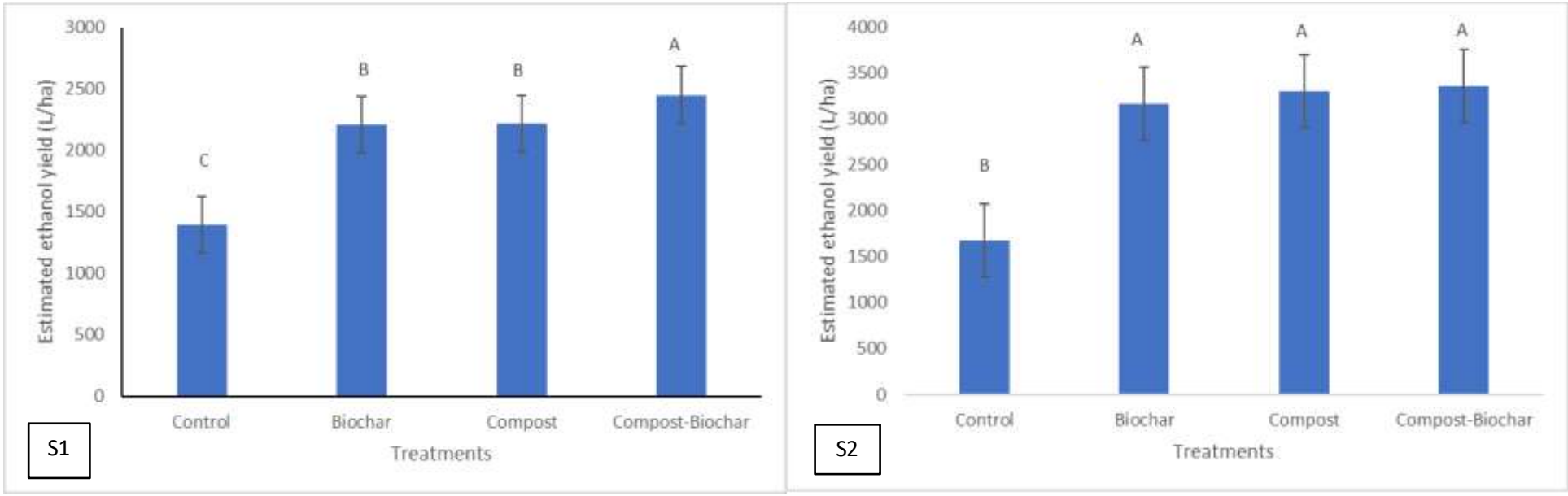


Figure 3.3: Estimated ethanol yields as influenced by different fertilisers. Bars sharing the same letters are not significantly different (P<0.05). S1: Season 1, S2: Season 2.

3.3.2 Discussion

The production of bioenergy from plant biomass remains one of the promising innovations to offset the reliance on fossil fuel resources (Nair et al., 2022). However, sustainable production of biofuel feedstock biomass remains a research interest (Malobane et al., 2020). This research assessed the effect of biochar, compost, and a biochar-compost blend (organic amendments) and inorganic fertiliser (control) on sweet sorghum biomass, brix content, and estimated ethanol yield. The results of this research are vital for sustainable production of biofuel feedstock without negatively impacting the soil. Marginal soils are at the center of biofuel feedstock biomass production, and they should be protected (Chowdhury et al., 2025). These results demonstrate that organic amendments, particularly the biochar-compost blend, are suitable for ethanol production in rainfed systems.

Biochar-compost blend resulted in high sweet sorghum biomass yield, brix content and estimated ethanol yield relative to other treatments in this study. Previous studies also found that biochar-compost blend yielded more biomass as compared to the individual use of compost, biochar and inorganic amendments (Shifa et al., 2024). The improvement in sweet sorghum biomass yield after using biochar-compost relative to other treatments under rainfed conditions could have been attributed to the mixture's effect on soil property. Biochar-compost mixture is known to enhance the retention of water and availability of nutrient than the use of biochar, compost, and inorganic fertiliser alone (Ho et al., 2022). The observed response is because of the complementary properties in both biochar and compost when co-applied. Biochar contributes to improved moisture retention through its porous structure (Kallenbach et al., 2018), while compost provides nutrients needed for crop productivity (Ho et al., 2022).

Increased water use efficiency and nutrient availability are directly linked to plant biomass yields (Elhawat et al., 2025; Kallenbach et al., 2018). Furthermore, soil moisture content is important for crop growth particularly under rainfed conditions (Schreiner-McGraw and Baffaut, 2023). Organic fertilisers were reported to improve brix content of crops compared to inorganic fertilizer (Elhawat et al., 2025). This aligns with findings of this current study in which biochar, compost, and biochar-compost mixture increased sweet sorghum brix content. However, research on the influence of organic amendments compared to inorganic fertiliser on crop brix content remains limited. The increase in brix content because of organic amendments compared to inorganic fertiliser in this study is associated with enhanced use of water and nutrients. Improved use in water and nutrients is directly linked to crop brix content under rainfed conditions (Sher et al., 2022).

Organic amendments also increased estimated ethanol yield in this study compared to inorganic fertiliser treatment because of enhanced sweet sorghum fresh biomass yield and brix content. Biomass yield and fermentable sugars are important in production of bioethanol (Petropoulos et al., 2020; Morales et al., 2021). Therefore, biomass and brix content have direct relationship with bioethanol yield (Amaefule et al., 2023; Nazli et al., 2024). The brix content which serves as a proxy for sugar concentration was reported to have a positive correlation with bioethanol yield (Nazli et al., 2024). Moreover, biomass offer structural carbohydrates for lignocellulosic ethanol pathways fermentation in ethanol production (Broda et al., 2022). The findings of this study highlight the potential of organic amendments to support sustainable bioenergy feedstock production. However, certain limitations should be acknowledged. The study evaluated only one sweet sorghum cultivar (SUPASWEET 2) and a single biochar-compost blend ratio (1:1).

Consequently, the response of other sweet sorghum cultivars and biochar-compost amendment ratios remains unknown. Furthermore, the study assessed the short-term effects of the amendments and therefore may not have fully captured their cumulative impacts on soil quality and crop productivity. Future research should investigate the long-term effects of biochar, compost, and biochar-compost blends across a wider range of sweet sorghum cultivars and amendment ratios to identify optimum combinations for enhancing biomass yield, brix content and bioethanol yield for sustainable production of biofuel feedstock under marginal soil conditions.

3.4 Conclusion

This study showed that organic fertilisers enhance bioenergy sweet sorghum biomass yield and brix content under rainfed, and marginal soils compared to inorganic fertiliser. Such positive increase in biomass and brix lead to an improved estimated ethanol yield. Biochar-compost (1:1) has a higher potential to be a sustainable fertiliser production practice to enhance production of bioenergy sweet sorghum under rainfed and marginal soils. More studies on biochar-compost blend under bioenergy crops are recommended. The research should also look at the introduction of other conservation practices to develop wholistic sustainable production of bioenergy crops under rainfed and marginal soil conditions.

CHAPTER 4

Moloto LA, Malobane ME and Motlhalamme T (2026). Nutrient availability and pH level as influenced by inorganic fertiliser, biochar, compost, and biochar-compost blend in bioenergy sweet sorghum under marginal soils in Cullinan, Gauteng, South Africa. Front. Agron. 8:1857927. doi: 10.3389/fagro.2026.1857927.

Nutrients availability and pH level as influenced by inorganic fertiliser, biochar, compost, and biochar-compost blend in biofuel sweet sorghum under marginal soils.

Abstract

Marginal soils are very important in producing bioenergy crops. Thus, sustainable production systems are paramount to avoid worsening the conditions of the marginal soils. The current study therefore aimed to assess the influence of organic amendments on pH and soil nutrient availability in comparison with inorganic fertilisers for biofuel sweet sorghum production on marginal soils. The current study determined the influence of biochar, compost, a 1:1 biochar-compost blend and inorganic fertilisers.

Key soil chemical attributes assessed under biofuel sweet sorghum cultivation on marginal soils included total nitrogen (TN), pH, electrical conductivity (EC), total organic nitrogen (TON), ammonium (NH4+-N), nitrate (NO3--N) nitrogen, available phosphorus (AvP), soil organic carbon (SOC), Calcium (Ca), Magnesium (Mg) and cation exchange capacity (CEC).

The use of organic fertilisers was associated with improvements in available phosphorus, soil pH, soil organic carbon, electrical conductivity, potassium, calcium, magnesium, and cation exchange capacity compared with inorganic fertiliser applications. The biochar-compost blend significantly enhanced the measured variables more than biochar, compost, and inorganic fertiliser treatments. Relative to inorganic fertiliser, the biochar-compost blend resulted in increases ranging from 4.76% to 67.35% in soil pH, TN, EC, TON, AvP, SOC, K, NO_3^-–N, Ca, NH_4^+–N, Mg, and CEC. The biochar-compost blend also had the least sodium (Na+) concentration compared to other treatments.

The biochar-compost blend treatment enhanced marginal soil fertility status while reducing Na+ in the short-term in bioenergy sorghum grown on marginal soils. Future studies should include long-term experiments alongside other sustainable practices under different bioenergy crops.

Keywords: organic amendments, Soil fertility, soil quality, soil organic carbon, bioenergy, sustainable production systems.

4.1 Introduction

South African marginal soils are predominantly degraded with low nutrient availability (Mengistu et al., 2016), which threatens sustainable biofuel sweet sorghum production (Malobane et al., 2018). Despite their low fertility status, marginal lands have recently received much interest in the cultivation of bioenergy crops as an option to enhance food security for rural farmers (Zahra et al., 2021). In addition, smallholder farmers are heavily dependent on these marginal lands to enhance their livelihood and generate income (Mathur et al., 2017). Hence, advancing the implementation of sustainable agricultural methods to increase nutrients and fertility on marginal soils in South Africa is important (Kallenbach et al., 2018). Furthermore, environmentally friendly and sustainable agricultural methods which use less inorganic fertiliser, increase soil available nutrients and improve soil nutrient use efficiency are imperative to produce biofuel (Kallenbach et al., 2018).

In the South African context, utilization of marginal soils to increase bioenergy crop production has intensified concerns about accelerated soil degradation (Mengistu et al., 2016). Therefore, effective bioenergy crop production will need the utilization of organic fertilisers to enhance soil quality while facilitating soil nutrient availability to produce biofuel feedstock like sweet sorghum on marginal soils (Mathur et al., 2017). Soil organic amendments like compost and biochar have shown the ability to influence the availability of nutrients by altering chemical and physical properties, and microbial activities (Zahra et al., 2021). For instance, soil pH increased by 6.7% and 5.3% after coconut husk and bamboo biochar were applied, respectively, relative to inorganic fertiliser (Mengistu et al., 2016).

In addition, coconut husk biochar increased nitrogen by 7.6% as compared to 2.1% for sawdust biochar and 0.8% for the control (Mengistu et al., 2016). Moreover, bamboo biochar increased phosphorus (P) to 35.4 kg/ha in comparison to the control at 31.5 kg/h (Domingues et al., 2020). A biochar-compost blend was shown to lower EC from 59.23 mS/m to 25.1 mS/m (Goldan et al., 2023). Coffee husk biochar was proved to enhance CEC by 47.5% in comparison to the control without biochar (Domingues et al., 2020).

Biochar influences soil properties through several factors, namely, feedstock, pyrolysis and the intrinsic soil properties (Domingues et al., 2020). For this reason, some authors have reported contradicting results following the use of biochar. In one study, biochar from wheat straw was reported to decline phosphorus sorption in alkaline soils while enhancing phosphorus sorption in acidic soils. (Goldan et al., 2023). In contrast, other studies found corn stover and switchgrass biochar to enhance phosphorus sorption in alkaline soils while decreasing phosphorus sorption in acidic soils (Novak et al., 2021; Domingues et al., 2020). Although compost and biochar were reported to improve soil functionality and agricultural productivity, inconsistent findings from literature suggest that their impact on soil properties under bioenergy crop systems is not entirely understood. Accordingly, this study was undertaken to determine how biochar, compost, and their 1:1 blend influence soil pH and nutrient availability on marginal soils planted with biofuel sweet sorghum.

4.2 Materials and Methods

4.2.1 Characteristics, location, and management of the study site

Trial site, field experiment set up, soil sampling, characterisation of compost and biochar, and management of experimental variables are explained in sections 3.2.1, 3.2.2, 3.2.3,

3.2.4 and 3.2.5 of chapter 3. In March 2025, soil sampling was conducted after sweet sorghum harvesting to assess soil chemical properties.

4.2.2 Soil chemical properties analysis

4.2.2.1 Available Phosphorus analysis

Bray and Kurtz P-1 method was used to analyse available Phosphorus (P) whereas ICP-OES analysed P concentration (Westhuizen et al., 2022). Equation 4.1 was used to calculate Bray and Kurtz P-1 phosphorus:

$$P\ (mg\ kg^{-1}) = Cp \times (0.020\ L) / 0.002\ kg \quad \text{.....4.1}$$

Where: CP is P concentration in mg/L.

4.2.2.2 Nitrogen analysis

Kjeldahl method was utilized to analyse nitrogen (N) (Hicks et al., 2022), where N content was calculated using equation 4.2.

$$N = \frac{(V1 - V0) \times c(H+) \times MN}{m} \quad \text{.....4.2}$$

Where:

- N is the soil nitrogen concentration in mg/g;
- V1 is the H2SO4 volume in mL;

- V0 is blank test volume of H_2SO_4 in mL,
- c(H+) is H+ concentration in H_2SO_4 solution (mmol mL^{-1});
- MN is the molar mass of N (mg $mmol^{-1}$) and
- m is the mass of test sample (g).

4.2.2.3 Extractable Bases and Cation Exchange Capacity

Ammonium acetate method was used to analysed CEC and extractable bases (Hossi et al., 2023).

4.2.2.4 pH and Electrical Conductivity

pH and EC of the soil were determined using electrode meters. The ration for the soil and was 1:25 (Fu et al., 2024).

4.2.2.5 Soil Organic Matter (SOC) analysis

SOM was evaluated using the Walkely-Black method (Shamrikova et al., 2022). Organic matter percentage was calculated using equation 4.3.

$$\text{Organic matter \%} = \frac{(B - S) \times N}{Wt.} \times 0.67 \quad \text{.....4.3}$$

Where:

- B is titrant volume for blank (mL),
- S is titrant volume for sample (mL),
- N is $FeSO_4$ normality,

- Wt. is air-dried soil sample weight (g) and
- 0.67 is conversion factor from organic carbon to organic matter.

4.2.2.6 Statistical analysis

The effects of treatments were evaluated using ANOVA in JMP Student Edition version 18. Differences among treatment means were evaluated with the LSD test at $P \leq 0.05$.

4.3 Results and Discussion

4.3.1 Results

Nutrient availability and pH under inorganic fertiliser and organic amendments (biochar, compost, and a biochar-compost blend) are shown in Table 4.1 and 4.2. Treatment effects were significant ($P < 0.05$) for all measured variables.

Table 4. 1: Effects of inorganic fertiliser and organic amendments on pH, Electric Conductivity (EC), Total Nitrogen (TN), Total Organic Nitrogen (TON), Ammonium ion (NH4+), Nitrate ion (NO3-), Available Phosphorus (AvP).

Measured variable	**pH**	**EC (mS/m)**	**TN (mg/kg**	**TON (mg/kg)**	**$NH4^+$ (mg/kg)**	**$NO3^-$ (mg/kg)**	**AvP (mg/kg)**
F- values	11.95	8.44	53.6	54.9	16.98	19.66	16.71
df	3,6	3,6	3,6	3,6	3,6	3,6	3,6
P-values	0.0053*	0.0140*	<0.0001**	<0.0001**	0.0020*	0.0012*	0.0021*

*: Significant at P<0.05.**: Highly significant at P<0.001. df: degrees of freedom

Table 4. 2: Effects of inorganic fertiliser and organic amendments on Soil Organic Carbon (SOC), Cation Exchange Capacity (CEC), Potassium (K), Calcium (Ca), Magnesium (Mg) and Sodium (Na).

Measured variable	SOC (g/kg)	CEC (cmol/kg)	K (cmol/kg)	Ca (cmol/kg)	Mg (cmol/kg)	Na^+ (cmol/kg)
F- values	53.53	20.42	21.53	14.09	36.53	21.53
df	3,6	3,6	3,6	3,6	3,6	3,6
P-vales	<0.0001**	0.0015*	0.0013*	0.0040*	0.0031*	0.0013*

*: Significant at P<0.05.**: Highly significant at P<0.001. df: degrees of freedom

4.3.1.1 The influence of inorganic fertiliser and organic amendments on pH and electrical conductivity (EC) under biofuel sweet sorghum.

pH and EC were greatly significant (P<0.05) in organic amendments treatments than in inorganic fertiliser treatment (Table 4.3). The pH in all treatments ranged from 7.3 to 7.82 while EC ranged from 53.3 mS/m to 59.5 mS/m.

Table 4. 3: Mean separation (P<0.05) findings of pH and Electric Conductivity (EC) as influenced by the inorganic fertilisers, biochar, compost and compost-biochar blend under bioenergy sweet sorghum production.

Treatments	pH	EC (mS/m)
Inorganic fertiliser	7.3^{b} [±0.11]	53.3^{c} [±1.60]
Biochar	7.5^{b} [±0.11]	58.4^{b} [±1.20]
Compost	7.6^{ab} [±0.13]	58.8^{b} [±1.05]

Compost- Biochar	7.82[a] [±0.13]	59.5[a] [±1.44]

Standard deviation []. The superscripted lowercase letters show significant difference amongst the mean values of measured variables as influenced by treatments.

Biochar-compost blend showed significantly higher soil pH ($P < 0.05$) relative to the biochar and inorganic fertiliser, whereas the difference from the compost treatment was not statistically significant (Table 4.3). Furthermore, there was no significant ($P<0.05$) variance in pH between compost, biochar and inorganic fertiliser (Table 4.3). Biochar-compost blend, compost and biochar had 7.12%, 4.1% and 2.74% higher pH value compared to inorganic fertiliser treatment, respectively. In addition, biochar-compost blend had 2.89% and 4.27% higher pH value in comparison to compost and biochar, respectively.

Compost-biochar blend had significantly ($P<0.05$) the highest EC relative to compost, biochar and inorganic fertiliser treatments (Table 4.3). However, EC did not differ significantly ($P > 0.05$) between compost and biochar treatments (Table 4.3). Biochar-compost blend, compost and biochar had 11.49%, 10.17% and 9.48% higher EC compared to inorganic fertiliser, respectively. Amongst the organic amendments the application of biochar-compost blend resulted in 1.19% and 1.83% higher EC in comparison to compost and biochar, respectively.

4.3.1.2 The effect of inorganic fertiliser and organic amendments on soil nitrogen fractions under biofuel sweet sorghum.

The treatments had a significant ($P<0.05$) effect on TN, TON, NO_3^-–N, and NH_4^+–N (Table 4.4). Organic amendment treatments showed greater concentrations of these nitrogen forms than the inorganic fertiliser (Table 4.4).

Table 4. 4: Mean separation (P<0.05) findings of TN, TON, NH4+-N and NO3--N as influenced by the inorganic fertilisers, biochar, compost and compost-biochar blend under bioenergy sweet sorghum production.

Treatments	**TN (mg/kg)**	**TON (mg/kg)**	**NH4+-N (mg/kg)**	**NO3--N (mg/kg)**
Inorganic fertiliser	911.9^{d} [±3.12]	887.95^{c} [±6.25]	10.2^{c} [±0.10]	13.7^{d} [±0.43]
Biochar	1004.9^{c} [±3.88]	979,2^{bc} [±3.70]	11b^{c} [±0.15]	14.7^{c} [±0.39]
Compost	1031.6^{b} [±7.20]	1004,16^{b} [±6.70]	11.8^{ab} [±0.49]	16^{b} [±0.16]
Compost- Biochar	1063.2^{a} [±4.30]	1033^{a} [±4.87]	12.4^{a} [±0.34]	17.7^{a} [±0.25]

Standard deviation []. The superscripted lowercase letters show significant difference amongst the mean values of measured variables as influenced by treatments.

Amongst the organic amendments, compost-biochar blend had significantly (P<0.05) the highest nitrogen forms relative to compost, biochar and inorganic fertiliser treatments (Table 4.4). In comparison to inorganic fertiliser treatment, total nitrogen (TN) in biochar-compost blend, compost, and biochar treatments were 16.49%, 13.13%, and 10.19% higher, respectively. On the other hand, biochar-compost blend treatment had 3.06% and 5.8% higher TN compared to compost and biochar, respectively. With respect to TON, application of biochar-compost blend, compost and biochar treatments had 16.33%, 13.1% and 10.28% higher TON compared to inorganic fertiliser treatment, respectively. Additionally, biochar-compost blend treatment had 2.87% and 5.49% higher TON in comparison to compost and biochar treatments, respectively.

Ammonium nitrogen (NH4+ -N) was 21.27%, 15.29% and 7.75% higher in biochar-compost blend, compost and biochar as compared to inorganic fertiliser treatment, respectively. Amongst the organic amendments, biochar-compost blend had 5.19% and 12.56% higher NH4+ -N relative to compost and biochar, respectively. Lastly, biochar-compost blend, compost and biochar had 29.21%, 13.82% and 6.92% higher NO3- -N relative to inorganic nitrogen treatment, respectively. On the other hand, biochar-compost blend had 10.8% and 20.84% higher NO3- -N relative to compost and biochar, respectively.

4.3.1.3 The impact of inorganic fertiliser and organic amendments on Available Phosphorus (AvP) under biofuel sweet sorghum.

AvP was greatly significant (P<0.05) in organic amendment treatments relative to inorganic amendment (Figure 4.1). Biochar-compost blend, compost and biochar had 29.47%, 24.34% and 20.65% higher AvP in relation to inorganic fertiliser, respectively. Amongst the organic amendments, compost-biochar blend significantly (P<0.05) influenced AvP relative to compost, biochar and inorganic fertiliser (Figure 4.1). Application of biochar-compost blend had 4.13% and 7.31% higher AvP compared to compost and biochar, respectively.

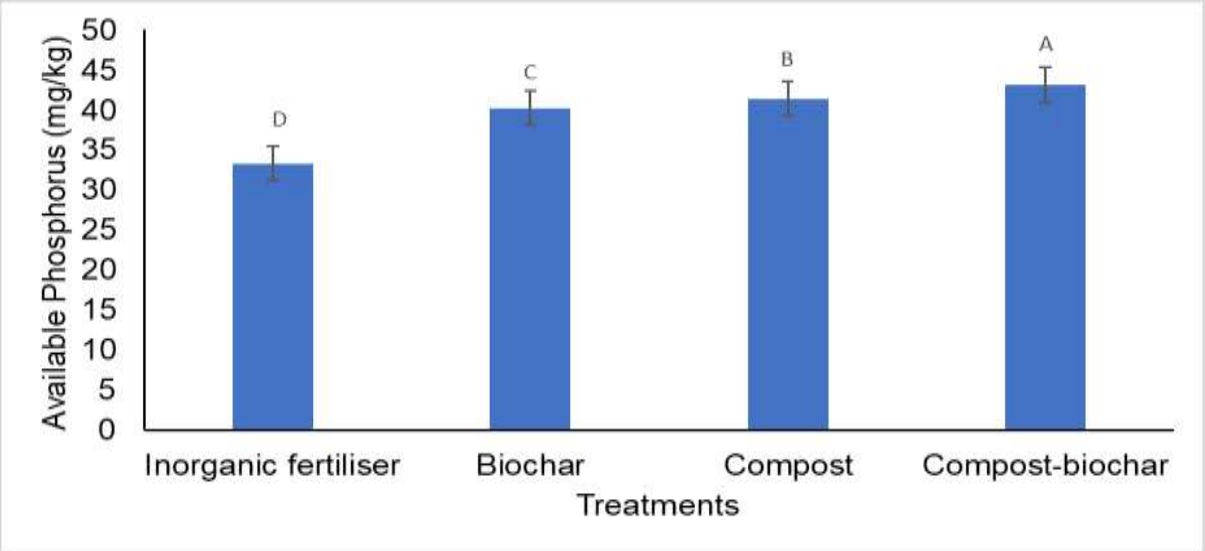


Figure 4. 1: Available Phosphorus as influenced by different fertilisers. Bars with unrelated letters implies significant different at P<0.05.

4.3.1.4 The ameliorating effect of inorganic fertiliser and organic amendments on Soil Organic Carbon (SOC) under biofuel sweet sorghum.

Organic nutrient amendments significantly (P<0.05) influenced SOC relative to inorganic fertiliser (Figure 4.2). SOC was greatly (P < 0.05) influenced by compost-biochar blend among the treatments. Nonetheless, no significant (P < 0.05) variance was observed between compost and biochar (Figure 4.2). Biochar-compost blend, compost and biochar had 17.01%, 9.14% and 6.88% higher SOC compared to inorganic fertiliser treatment, respectively. Additionally, biochar-compost blend had 7.21% and 9.48% higher SOC compared to compost and biochar, respectively.

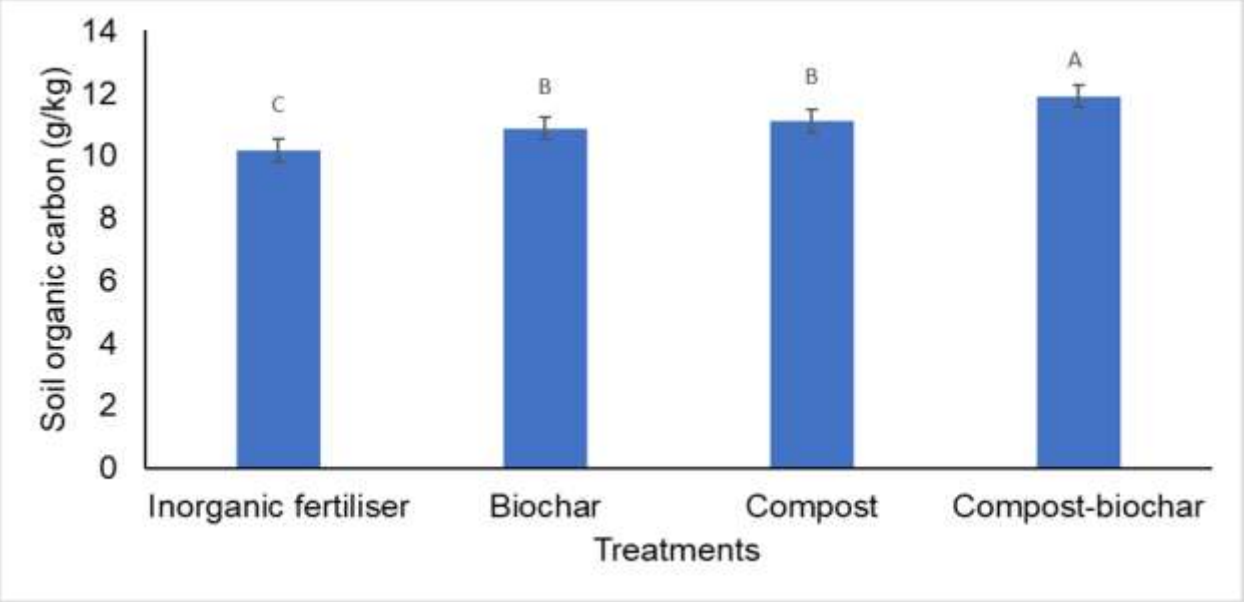


Figure 4. 2: SOC as influenced by un-alike fertilisers. Dissimilar letters imply significant differences at P<0.05.

4.3.1.5 The influence of inorganic nitrogen and organic nutrient amendments on cation exchange capacity (CEC) and extractable bases under biofuel sweet sorghum.

Organic fertilisers significantly (P<0.05) had higher CEC, K, Ca and Mg relative to inorganic nitrogen treatment (Table 4.5). However, inorganic fertiliser treatment significantly (P<0.05) had higher sodium (Na+) in comparison to organic amendments (Table 4.5).

Table 4. 5: Mean separation (P<0.05) results for CEC, K, Ca, Mg and Na+ as affected by the inorganic fertilisers, biochar, compost and compost-biochar blend under bioenergy sweet sorghum production.

Treatments	CEC (cmol/kg)	K (cmol/kg)	Ca (cmol/kg)	Mg (cmol/kg)	Na+ (cmol/kg)
Inorganic fertiliser	9.9^{c} [±0.21]	0.29^{c} [±0.02]	6.19^{c} [±0.18]	3.15^{c} [±0.07]	0.12^{a} [±0.008]
Biochar	$10.8b^{c}$ [±0.85]	0.35^{c} [±0.01]	6.84^{b} [±0.13]	3.33^{b} [±0.08]	0.07^{bc} [±0.006]
Compost	11.4^{b} [±0.20]	0.41^{b} [±0.03]	7.19^{b} [±0.20]	3.57^{b} [±0.07]	0.09^{ab} [±0.006]
Compost-Biochar	12.6^{a} [±0.51]	0.49^{a} [±0.01]	8.03^{a} [±0.50]	3.74^{a} [±0.08]	0.07^{c} [±0.008]

Standard deviation []. The superscripted lowercase letters show significant difference amongst the mean values of measured variables as influenced by treatments.

Biochar-compost blend, compost, and biochar increased cation exchange capacity (CEC) by 26.01%, 15.42%, and 8.67%, respectively, in relation to inorganic fertiliser. Furthermore, the biochar-compost blend resulted in 9.17% and 15.96% higher CEC than compost and biochar treatments, respectively. Similarly, biochar-compost blend, compost, and biochar increased potassium (K) by 67.35%, 42.27%, and 19.56%, respectively, relative to the inorganic fertilizer treatment. The biochar-compost blend also had 17.63% and 39.94% higher K compared with compost and biochar treatments, respectively.

Calcium (Ca) concentrations were 29.73%, 16.16%, and 10.5% higher in the biochar-compost blend, compost, and biochar in relation to inorganic nitrogen treatment, respectively. Additionally, biochar-compost blend treatment resulted in 11.69% and 17.4% higher Ca compared to compost and biochar treatments, respectively. Lastly, magnesium (Mg) concentrations were 18.73%, 13.33%, and 5.71% higher in biochar-compost blend, compost, and biochar in relation to inorganic fertiliser treatment. Furthermore, biochar-compost blend treatment had 4.76% and 12.31% higher Mg in comparison to compost and biochar treatments, respectively. Application of inorganic fertiliser treatment, compost and biochar had 74.24%, 39.39% and 19.70% higher sodium (Na+) as compared to biochar-compost blend treatment, respectively. In addition, inorganic nitrogen treatment had 25% and 45.57% higher Na+ as compared to compost and biochar, respectively.

4.3.2 Discussion

Marginal lands are fundamentally important to produce bioenergy crops (Fu et al., 2024). This will ensure minimal competition of land and avoid food-fuel conflict (Fu et al., 2024).

Generally marginal soils are predominantly fragile (Ding and Yu, 2024), thus, the continuous application of inorganic fertilisers to produce high biomass for bioenergy might worse their conditions (Chowdhury et al., 2025). Sustainable production methods are strongly advocated in bioenergy crop production to reduce negative environmental impacts (Chowdhury et al., 2025). Therefore, this short-term study assessed the potential benefits of biochar, compost, and their 1:1 blend on availability of nutrient, relative to inorganic fertiliser, under bioenergy sweet sorghum production on marginal land. Application of organic amendments in the current research improved soil pH and EC relative to inorganic fertiliser application. These finds supported previous studies which also found biochar, compost and their co-application to improve pH and EC (Meng et al., 2025). This improvement is associated with higher pH 8.5 and 7.3 (Table 3. 1) in biochar and compost materials (Meng et al., 2025). Improvement in pH supports the notion that biochar and compost can act as limiting material (Ding and Yu, 2024). Hence, the results of this research demonstrated that biochar-compost blend was an effective material to increase soil pH.

Biochar-compost blend is likely to be more beneficial in marginal soils with acidic pH. However, its use in alkaline soil may be of concern, as further increases in pH could move soil conditions beyond the optimal range for nutrient availability (Goldan et al., 2023). Improvement in electrical conductivity after organic nutrient amendments were used is because of the contribution of soluble salts contained in both amendments (Ding and Yu, 2024). The increase in total nitrogen and its fractions due to biochar and compost was previously reported (Meng et al., 2025) and is supported by the current findings. In addition, the current study supports findings in which biochar-compost application enhanced the total N and its fraction more than their sole applications (Frimpong et al., 2021).

The improvement in total N and its fractions after the application of biochar-compost in comparison to inorganic fertiliser, compost and biochar might be because of the high nitrogen level in compost (Goldan et al., 2023) as well as biochar's capacity to enhance N cycling and retention of available N (Ding and Yu, 2024; Yuan et al., 2025). Higher total nitrogen in this case indicates that biochar-compost blend is sustainable in the production of bioenergy crops compared to inorganic fertiliser and individual application of biochar and compost under marginal soils. Nitrogen with its importance to the production of plant biomass is key for the cultivation of biofuel (Frimpong et al., 2021). Thus, this study demonstrated biochar-compost blend as a cheap nitrogen source in marginal soils.

Improving the value and productivity of marginal soils is a key consideration in bioenergy crop production, particularly in reducing the high input costs associated with inorganic fertilizer use. Passed research reported that biochar, compost, and their 1:1 blend enhances available phosphorus (AvP) and soil organic carbon (SOC) (Chafik et al., 2025). This supports the current short-term study. Moreover, the collaborative relationship of biochar and compost increased AvP and SOC compared with their individual applications (Frimpong et al., 2021), which supports this research. Enhancement of AvP is because of the synergistic interaction between compost and biochar (Chafik et al., 2025). Compost provided soluble phosphate ions and organic acids that mobilized phosphorus, while biochar adsorbs and retains these ions to minimize leaching and maintain their gradual release (Gross et al., 2025).

Although the three organic amendments were applied at equivalent carbon levels per hectare, the higher SOC observed in the biochar-compost blend treatment suggests that the combined application enhances SOC sequestration more effectively than their individual applications. This might be because compost's labile organic matter stimulated microbial activities and aggregate formation, while biochar contributed stable carbon fractions that gets to be protected by stable aggregates (Cheng et al., 2025).

Additionally, biochar-compost blend has proved to decrease soil carbon loss by reducing basal respiration (Frimpong et al., 2021). This suggests that biochar-compost blend application can form an integral part of sustainable production of bioenergy crops like sweet sorghum on marginal soils by increasing SOC which is critical for soil quality and conservation.

The use of a 1:1 biochar-compost blend was previously reported to increase CEC and exchangeable base (Sebahire et al., 2024), which agrees with this study. This increase of CEC with exchangeable bases is associated with the synergistic physicochemical relationship between biochar and compost compared to their sole application (Garbowski et al., 2023). Compost provides labile organic matter and base cations, while biochar contributed to a highly porous surface area with stable functional groups which facilitated cation retention through adsorption and complexation (Ansar et al., 2025). Availability of sodium (Na^+) was lower under biochar and biochar-compost mixture treatments, thus supporting previous studies (Kebede et al., 2023). The reduction in Na^+ by biochar and biochar-compost blend might be because of the capacity of biochar to adsorb and immobilize excess sodium ions through its highly porous surface area (Kebede et al., 2023).

This study demonstrated that a 1:1 biochar-compost blend can serve as an effective source of nutrients for sweet sorghum grown on marginal soils, thereby enhancing soil nutrient availability and supporting nutrient cycling within bioenergy production systems. Furthermore, the lower soil Na^+ concentrations observed following the application of the biochar-compost blend suggest its potential to reduce soil sodicity and improve soil quality under sweet sorghum cultivation. While these findings highlight the potential of biochar, compost and biochar-compost blend as sustainable soil management strategies, the study evaluated their effects over a relatively short period.

Given that the beneficial effects of biochar are often more pronounced over the medium to long term, the present study may not have fully captured the cumulative impacts of biochar and biochar-compost blend applications on soil properties and crop productivity. Therefore, further research is recommended to assess the long-term effects of these amendments (biochar and biochar-compost blend) over multiple growing seasons and under different crops.

4.4 Conclusion

Biochar, compost, and their 1:1 blend were proven by this study to be more effective than inorganic fertiliser in improving pH and nutrient cycling on marginal soils under bioenergy sweet sorghum. In the short-term, a 1:1 biochar-compost blend is valuable in increasing the fertility status of marginal soils. Furthermore, biochar-compost blend also was found to have the potential to reduce Na+ which can be used as an indicator of the reduction in soil sodicity. However, these findings were based only on short-term, thus, future studies should include long-term experiments under different bioenergy crops. Moreover, inclusion of other sustainable productions like crop diversity and minimum soil disturbance should be considered.

CHAPTER 5: GENERAL CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Chapter 3 and 4 of the study evaluated the impacts of organic nutrient amendments on sweet sorghum biomass, brix content, estimated ethanol yield, availability of soil nutrients and pH under rainfed conditions on marginal soils.

The findings of chapter 3 demonstrate that biochar, compost and biochar-compost blend enhanced sweet sorghum biomass production and brix content compared to inorganic fertilisers. The improvement in biomass production and brix content is central to the improved estimated ethanol yield. A 1:1 biochar-compost blend is the main factor amongst organic amendments to influence biofuel production under rainfed conditions on marginal soils. The results of chapter 3 in this study showed that biochar-compost blend is a sustainable fertiliser management practice for enhancing the bioenergy productivity of sweet sorghum cultivated under rainfed conditions on marginal soils.

The results of chapter 4 in this short-term study indicate that organic amendments can influence pH and availability of nutrients in marginal soils to produce bioenergy sweet sorghum, compared to inorganic fertiliser application. In addition, organic nutrient amendments increased electrical conductivity (EC) in marginal soils. Improvement in soil pH indicates that biochar-compost blend can be more beneficial on marginal soils with high acidity. Furthermore, organic fertilisers improved total nitrogen and its constituent fractions, indicating that the biochar-compost blend is a cost-effective nitrogen source for marginal soils. Moreover, organic amendments enhanced cation exchange capacity (CEC) and the levels of extractable bases compared to inorganic fertiliser application.

Biochar and compost blend reduced the soil sodium concentration, demonstrating potential improvement in the sodicity status of marginal soil under sweet sorghum biofuel production. A 1:1 ratio was identified as an efficient practice to enhance fertility in marginal soils and supporting sustainable sweet sorghum biofuel production in the short term. As a result, the long-term impacts of these amendments on soil quality, nutrient dynamics, and crop productivity remain uncertain. Furthermore, the optimum biochar to compost ratio for maximising soil improvement and sweet sorghum performance under marginal soil conditions has not yet been established.

Future research should therefore focus on long-term and the evaluation of different biochar-compost ratios to identify the most effective amendment combination for sustainable biofuel feedstock production.

5.2 Recommendations

To build on the current findings, subsequent studies should address the following:

- The optimum ratio of the combined effect of organic nutrient amendments and conservation practices on sustainable production of bioenergy crops under rainfed and marginal soils conditions.
- Long-term impact of a 1:1 biochar-compost amendments, crop diversification and minimum soil disturbance for sustainable production of bioenergy crops.

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Nutrient availability and pH level as influenced by inorganic fertiliser, biochar, compost, and biochar-compost blend in bioenergy sweet sorghum under marginal soils in Cullinan, Gauteng, South Africa

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Marginal soils play an important role in the production of bioenergy crops. Sustainable production systems are consequently of paramount importance as a means to avoid further deterioration in the condition of marginal soils. The objective of the study was to determine the ameliorating effects of biochar, compost, and a biochar–compost blend on nutrient availability and pH in comparison with the use of inorganic fertiliser in the production of bioenergy sweet sorghum on marginal soils. The effect of biochar, compost, a 1:1 biochar–compost blend, and inorganic fertiliser on soil pH, electric conductivity (EC), total nitrogen (TN), total organic nitrogen (TON), ammonium (NH_4^+-N) and nitrate (NO_3^--N) nitrogen, available phosphorus (AvP), soil organic carbon (SOC), exchangeable bases, and cation exchange capacity (CEC) was studied in the context of bioenergy sweet sorghum production on marginal soils. The application of organic amendments increased soil pH, EC, AvP, SOC, potassium (K), calcium (Ca), magnesium (Mg), and CEC above the levels achieved with inorganic fertiliser treatment. The application of a biochar–compost blend enhanced the measured variables to a significantly greater degree than that of biochar, compost, and inorganic fertiliser treatments individually. In the short term, pH, EC, TN, TON, NH_4^+-N, NO_3^--N, AvP, SOC, K, Ca, Mg, and CEC were 4.76% to 67.35% higher following the biochar–compost blend treatment than following the inorganic fertiliser treatment. In addition, the biochar–compost blend resulted in a lower sodium (Na^+) concentration than the other treatments. A biochar–compost blend treatment has the potential to enhance the marginal soil fertility status for sustainable bioenergy sorghum production whilst reducing soil sodicity by reducing Na^+ availability in the soil. Future studies should include long-term experiments alongside other sustainable practices applied in the production of other bioenergy crops.

KEYWORDS
bioenergy, organic amendments, soil fertility, soil organic carbon, soil quality, sustainable production systems