



(RESEARCH ARTICLE)



Use of biochar in enhancing crop yields and its nutrient depletion over time

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International Journal of Science and Research Archive, 2025, 16(02), 1310-1338

Publication history: Received on 10 July 2025; revised on 17 August 2025; accepted on 19 August 2025

Article DOI: <https://doi.org/10.30574/ijrsra.2025.16.2.2414>

Abstract

Faecal sludge biochar, produced through pyrolysis, offers a dual solution to food insecurity in Africa and climate change by enhancing crop yields as a soil amendment while enabling carbon sequestration. This study investigated the effects of Rocket Astra (*Eruca vesicaria* subsp. *sativa*) on crop productivity and nutrient depletion over time, grown in sandy, acidic soil. Four treatments were compared: biochar alone, fertilizer alone, biochar plus fertilizer, and an untreated control. The biochar–fertilizer combination produced the highest yields for most parameters, except root length, where biochar alone excelled. Biochar alone outperformed fertilizer in overall yield, while the control group had the lowest productivity. The combination treatment also significantly reduced water runoff. However, results across growing cycles revealed marked nutrient depletion in cycle two, with declines in shoot and root biomass and increased water runoff. These findings underscore biochar's potential for sustainable agriculture in sub-Saharan Africa, while highlighting the importance of addressing nutrient loss over time and implementing policies to support farmer adoption and knowledge dissemination.

Keywords: Faecal sludge biochar; Crop yield improvement; Carbon sequestration; Nutrient depletion; Soil amendment

1. Introduction

Food is a human basic need, essential for survival (Watkins 2019). Globally, approximately 828 million people experienced hunger in 2021 and 150 million people in 2019, representing an increase of 8% in 2019 and 9.3% in 2022 (WHO 2022). Furthermore, it is estimated that over 600 million people will be severely affected by hunger in 2030, posing a great threat to achieving Sustainable Development Goal (SDG) number 2 of zero hunger in all its forms by 2030 (UN SDG report 2023). Sub-Saharan Africa ranks highest among hunger-stricken regions (Hannah et al., 2023). Severe hunger and malnutrition are large, complex obstacles to sustainable development and create a snare from which people cannot easily escape (UN SDG report 2023). Major drivers of rising hunger and starvation in sub-Saharan Africa include soil degradation (Nicholas et al., 2023), high cost of inorganic fertilizer (Gro-Intelligence, 2016), and climate change, multi-year droughts and floods (Nieva, 2022). These factors limit food production, stimulate a rise in food costs, and threaten food security (UN SDG report, 2023). In addition, nearly 6 billion people globally are projected to have limited access to safe and clean water by 2050 due to climate change-induced droughts, increased water pollution, and an escalating population (Nicholas et al., 2023).

In Sub-Saharan Africa, there are over 60% of small-scale farmers who make a significant contribution to the agricultural industry. For instance, small-scale farmers own more than 50% of the total arable land in Zambia and 39% in Tanzania (Jayne et al., 2016) because farming is not only critical to having access to food but as the only reliable source of income. However, with the increasing effects of climate change (yearly droughts), there is a high likelihood that food production will significantly reduce, subjecting the small-scale farmers to worse consequences on top of living in extreme poverty (World Resources Institute, 2021). Naturally, the soils in most of the African countries have low fertility due to low organic matter and low activities in clay minerals, making it difficult to retain nutrients, water, increase microbial activity (Nath et al., 2023; Farmerline 2023) and enhance optimum crop yield unless with the help of farming inputs (Forum for Agricultural Research

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in Africa 2022). Low soil fertility is exacerbated by the rampant scourge of deforestation, which contributes to soil degradation, soil erosion, and the removal of carbon from the soil, resulting in the depletion of nutrients (Slayi et al., 2024). Monoculture farming is common among small-scale farmers on the African continent; this, coupled with heavy application of pesticides (Pollmann & Podrzenski, 2019), leads to crop nutrient mining, where vital nutrients are rapidly lost without being replaced (Stewart et al., 2020).

Soil degradation and depletion of nutrients have resulted in high demand for inorganic fertilizers to improve crop productivity (Bai et al., 2022). However, the high cost of fertilizer and its scarcity on the African continent limit its wide application compared to the United States of America and Europe (Gro Intelligence 2016). For example, since 2022, fertilizer application in Africa has reduced from 42.5 kg per hectare to 34.5 kg per hectare (International Fertilizer Development Centre 2024). Additionally, when fertilizer is applied to crops, about 7 629 900 metric tons of major nutrients (nitrogen, potassium, and phosphorus) equivalent to US\$ 1.5 billion are lost annually (Banaante 2020). Inorganic fertilizer can also cause acidity in the soil and decrease the cation exchange capacity (CEC) (Kang et al., 2022). This happens by forming insoluble compounds, which limit the availability and absorption (Farmerline 2023) of vital elements, including phosphorus, needed for plant growth and development (Barrow, 2017). Inferences from this best explain why the use of inorganic fertilizer is not a sustainable measure to improve soil fertility and mitigate the increasing food insecurity on the African continent despite its overwhelming demands (Bai et al., 2022).

Fertilizer can significantly reduce living matter in the soil, essential for promoting a healthy soil structure, water holding capacity, and microbial activities (Nath et al., 2023; Farmerline, 2023). This leads to increased soil acidification, which interferes with plant development and the accessibility of important plant nutrients, and the leaching of nitrogen, resulting in pollution of underground water and the release of nitrous oxide (N₂O), which fuels global warming and climate change (M. Sainju et al., 2020). In addition to the increasing demand for fertilizer on the African continent (Bai et al., 2022), major fertilizer components, including phosphorus, are presently in a depleted form (O’Gorman Lalor, 2024). The remaining phosphate reserves, which are even very difficult to extract (Traffon, 2023), are only present in selected regions, including the Middle East, China, the United States of America, and Northern Africa (O’Gorman Lalor, 2024). Further, projections reveal that the remaining phosphorus deposits will be completely depleted 100– 400 years from now (Faradji & De Boer, 2016; Illakwahhi et al., 2024). Important to note is that soil erosion in Sub-Saharan Africa causes serious environmental effects on water, air, and soil, thus contributing to global climate change through the addition of greenhouse gases in the atmosphere (GHG) (Bai et al., 2022). Therefore, enhanced soil health and nutrient conservation through the integration of organic fertilizer (Banaante 2020) is humanity’s urgent measure needed to avert food insecurity and climate change (World Economic Forum 2023), particularly on the African continent (Bai et al., 2022). Governments in sub-Saharan countries, non-governmental organisations, and civil societies should enhance their efforts in assisting small-scale farmers to develop and build resilience to climate change (World Resources Institute, 2021) and food insecurity (Gomiero, 2016).

Climate-Smart Agriculture is one such approach that promotes the use of organic fertilizer, improves soil health, water holding capacity (Gomiero, 2016), recycling of nutrients, carbon sequestration, limiting the emissions of greenhouse gases, and promoting natural pest management while increasing biodiversity (Rehman et al., 2022). Integrating climate-smart agriculture has overwhelming potential to address the crisis of food insecurity, poverty (Gomiero, 2016), and the cascading effects of climate change, particularly in Sub-Saharan Africa (Pollmann & Podrzenski, 2019).

Adding to global food insecurity, about 2.3 billion people worldwide lack access to fundamental hygiene facilities, and about 2.1-2.6 billion individuals in developing countries rely on onsite waste management systems, hence producing huge volumes of raw faecal sludge (FS) per day (Nicholas et al., 2023). Lack of proper disposal of human waste pollutes water bodies and poses a threat to public health as a result of high microbial content, which ends up in the food chain (Ullah Bhat & Qayoom, 2022). There is a need for eco- and long-lasting mechanisms of managing faecal sludge to mitigate the high cases of hygiene and sanitation-related mortality (36.2 deaths per 100,000 individuals) in Sub-Saharan Africa (WHO 2024).

Biochar made by pyrolysis is a faecal sludge that can be processed through pyrolysis to destroy harmful pathogens, making it safe for human use while averting the crisis of raw faecal sludge disposal on public health and the environment at large (AFWASA 2020). Biochar is also a climate-smart agricultural organic fertilizer capable of restoring degraded, poor, and acidic soils due to its robust properties as a soil amendment (Banaante 2020). Biochar is a carbon-rich material generated by biomass pyrolysis at a temperature range of 350–1000 °C in the absence of or in a limited supply of oxygen (Hans-Peter Schmidt, 2015). The application of biochar as a permanent solution to soil degradation and improving crop yield has its origin back to the Ancient Amazonian civilization about 7000 years ago (PRI 2022), following the findings of black earth (Terra Preta) as a carbon-rich and fertile soil than the neighboring soil (Nicholas et al., 2023). Biochar can stably retain carbon for several hundreds of years, thereby averting the crisis of climate change by limiting the emission of greenhouse gases (Bo et al., 2023). Biochar, with its high cation exchange capacity, can retain a substantial amount of essential nutrients, limit nutrient leaching, and boost the uptake of minerals including magnesium (Mg²⁺), ammonium (NH⁴⁺), calcium (Ca²⁺),

and potassium (K⁺) by giving out the hydrogen (H⁺), thus stabilising the charge in the soil particles (Alkharabsheh et al., 2021). Previous studies have shown that biochar can improve microbial activities, thus contributing to improved soil health, crucial for crop yield (Pokharel et al., 2020). The soil amendment properties of biochar have been reported to have the potential to address the overdependence on expensive inorganic fertilizer (Banaante 2020). Biochar improves crop yield by increasing water-holding capacity (WHC) (Zhang et al., 2024), enhances soil's chemical and physical properties, improves cation-exchange capacity (CEC), and pH values in acidic soil (Nicholas et al., 2023). Biochar can revamp soil microbial life and offer a lasting solution to climate change through carbon sequestration (Lehmann et al., 2011).

Soil degradation, poor water holding capacity, and infertile and acidic soil are rampant in Sub-Saharan Africa (Gwenzi et al., 2015). Given that, biochar can be used as a soil amendment to revamp degraded acidic soils across Sub-Saharan Africa and address the crisis of food insecurity (Gwenzi et al., 2015). With the projected increase in food demand in Sub-Saharan Africa (SSA) due to population growth, climate change is projected to heavily affect food production (World Bank 2015). Extreme weather patterns, escalating temperatures, variations in rainfall patterns, and increased frequency are expected to compromise crop yields and general food production by 15-20% (World Bank 2015). The application of biochar across the African continent can help to address the threat of climate change, droughts, and food insecurity (Nicholas et al., 2023).

The intrapore found in the biochar creates space for water storage, making it effective for water retention critical for improved crop yields and the mitigation of water crises due to droughts (Liu et al., 2017). Faecal sludge biochar (FS) has a high concentration of phosphorus (3.2–3.9% and 5.4–8.1 wt.%). Therefore, biochar has the potential to provide the scarce phosphorus element good for plant growth (Nicholas et al., 2023). The use of biochar has been reported to improve water availability (Koide et al., 2015) and reduce wilting in tomato saplings grown under water-restricted conditions (Nicholas et al., 2023). The water holding capacity trait of biochar along with cation exchange capacity (CEC) are critical in retaining water and preserving nutrients needed for better crop yields, particularly in Sub-Saharan Africa (Nicholas et al., 2023). A biochar meta-analysis carried out by Bai (2022) revealed a crop yield of 48% when biochar was used in combination with inorganic fertilizer and an increase of 1060% in tomato yield when biochar was used on its own (Nicholas et al., 2023). However, more previous studies analysed the effects of biochar on soil fertility and crop yield (Edussuriya et al., 2023) with less focus on how biochar nutrients get depleted overtime (Long et al., 2024; Hossain et al., 2020). Considering the increasing food insecurity, limited phosphorus deposits (O'Gorman Lalor, 2024), and the increasing pressure on the soils to produce enough food to meet the increasing population (Maja & Ayano, 2021a), it is imperative that government agencies, civil societies, private stakeholders, and small-scale farmers get grounded with knowledge about the depletion of nutrients in biochar across time. This will maximise biochar's effectiveness in alleviating the impact of climate change and the increasing food insecurity mainly in Sub-Saharan Africa (Njenga et al., 2021).

The present study used rocket (*Eruca vesicaria*) as a model crop because it has similar requirements and conditions to common vegetables and other crops grown in Sub-Saharan Africa. Additionally, Rocket (*Eruca vesicaria*) has a short life cycle of 3–6 weeks (North Carolina State University, n.d.), making it easier for the researcher to repeat the investigations within a short period. Therefore, this study aimed to examine the application of faecal sludge biochar on the yield of rocket Astra (*Eruca vesicaria subsp. sativa*) and the depletion of nutrients overtime. Biochar's effects on the shoot and root length, plant heights, water runoff, and above and underground biomass across four treatments, including control (only soil), biochar (soil and biochar), fertilizer (soil with fertilizer), and biochar+ fertilizer (a combination of soil, fertilizer, and biochar) treatments, were investigated.

2. Materials and Methods

Faecal sludge biochar sourced from India was used in this experiment. The faecal sludge feed stalk was transported to the manufacturing point and stored in tanks to break down the sludge and make a uniform mixture, and later dried using the sun to remove the moisture content (Krueger et al., 2020). The drying process was escalated by broadcasting the sludge in 10 mm-deep layers, and later pyrolysis was used to produce biochar in the absence or limited supply of oxygen at a temperature range of 350–880 °C (Krueger et al., 2020). When biochar was ready, it was extinguished using the water bath method before being packed into 5 kg of sealable polythene papers (Nicholas et al., 2023). Additionally, sandy loamy acidic soil from Cathelyd Isaf Farm coordinates (51 ° 42' 38.0" N; 3 ° 54' 40.9" W) in the suburb of Swansea in Wale was used in this study (Nicholas et al., 2023). This type of soil was used in this study due to its limited amount of key nutrients, including nitrogen (University of Missouri Extension, n.d.), phosphorus (Bekchanova et al., 2024), and potassium (Nogueira et al., 2024), reduced cation exchange capacity, and organic matter similar to the soils found in sub-Saharan Africa (Hengl et al., 2017).

2.1. Plant growth experiment

Rocket Astra (*Eruca vesicaria subsp. sativa*) was used as a model crop to assess the application of faecal sludge biochar on both wet and dry above and underground biomass, plant heights, shoot height, root length, soil, water runoffs, and the depletion of nutrients overtime. The experiment consisting of two cycles was carried out in the West Garden glasshouse behind the Wallace building from 11th July to 3rd September 2024. The experiment was conducted in the glasshouse to uphold environmental conditions similar to field conditions while controlling other variables at the same time (Steam Powered Family, n.d.). The temperature range during the experimental period was from 21 °C to 40 °C with a mean temperature of 32 °C. Using 20 brown cylindrical plastic pots, a random block experimental design was used across four (4) treatments along with five duplicates (Figure 1). The four treatments included (i) control (soil only), (ii) biochar (soil with biochar), (iii) fertilizer (soil, biochar + fertilizer), and (iv) biochar + fertilizer (soil, fertilizer plus biochar).

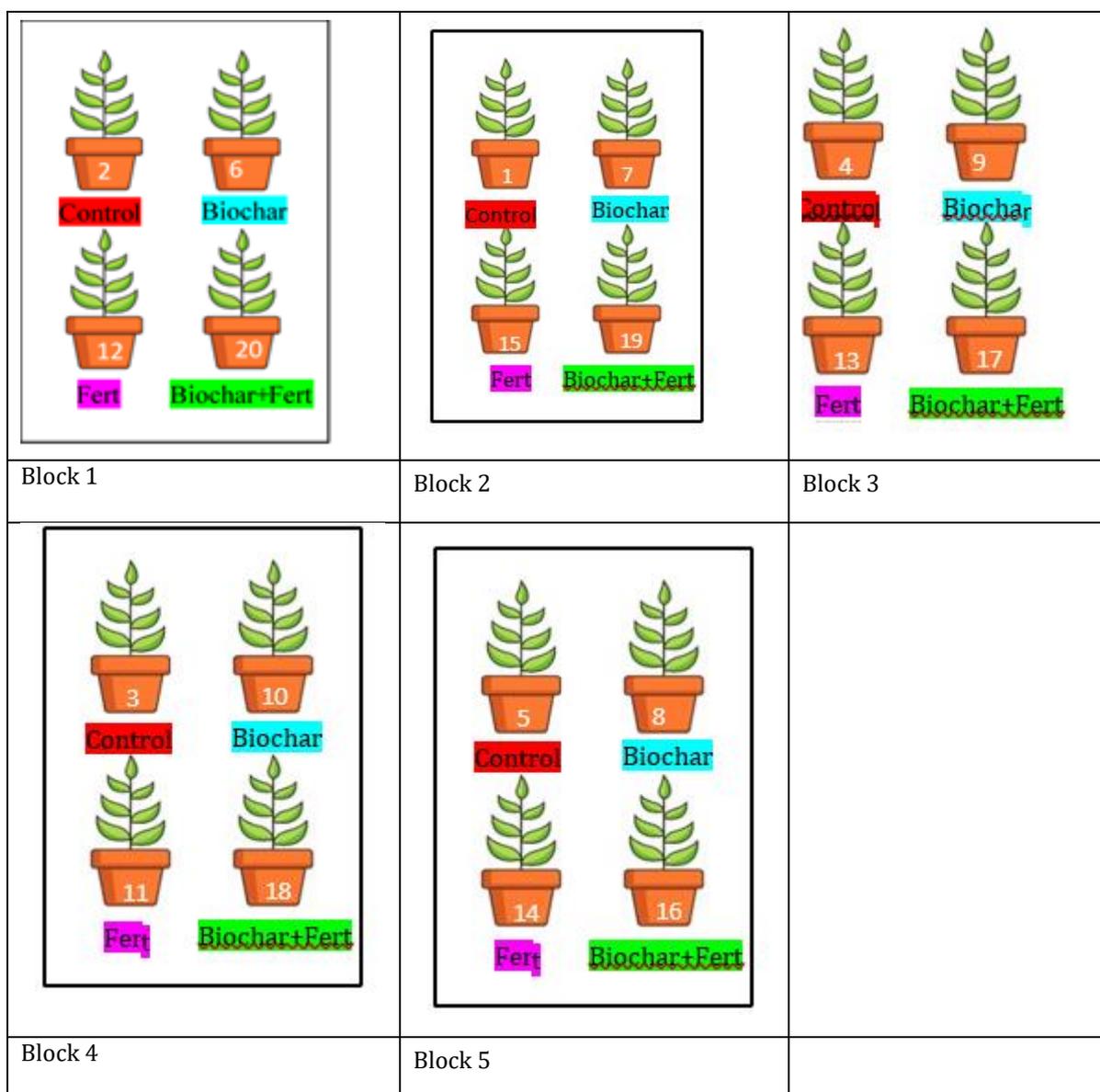


Figure 1 Diagrammatical representation of the random block experimental design

Tomorite commercial concentrated liquid fertilizer was used to supply nutrients to the model crop. The daily temperature for the entire trial period was measured using an environmental logger (Elitech multiuse temperature data logger model RC-51H).

Before planting, all 20 cylindrical pots were washed with clean water, left for one hour to remove the moisture content, and later weighed using an electronic scale. 100 g of dry soil was thoroughly mixed with 4.2 g of biochar, translating into 3000 kg of dry soil mixed with 126 g of biochar at a concentration of 4.2% w/w for a total of 10 pots for the biochar and biochar

+Fertilizer treatments. The multi-purpose blue paper weighing 10 g was covered at the bottom of each perforated pot to hold the soil particles. To the 10 pots for the biochar and biochar + fertilizer treatments, 312.6 g of dry soil plus biochar (300 g soil + 12.6 g biochar) was loaded, followed by the addition of 300 g of dry soil in the remaining 10 pots for the control and fertilizer treatments. The 20 pots with four different treatments were later watered with 200 ml of water before sowing the seeds to allow the soil to settle and improve its structure. An equal number of Rocket Astra (*Eruca vesicaria subsp. sativa*) seeds were sown in the treatment pots and covered with a cling film for two days to enhance the germination process. Germination started on the second day with over 70% germination success and was completed on day three with all the germinated seedlings established by day five. From day one up to the establishment day, 5-10 ml of water was watered in each pot to avoid too much water disturbing the tender establishing seedlings.

From day five, 100ml and 150ml of tap water, depending on the prevailing weather condition, were watered using a 100ml measuring cylinder and a 2L jar. Prior to watering, each treatment pot was carefully placed inside a sealable polythene bag to collect the water runoff for measurement. 2.3 ml of commercial liquid fertilizer was added to 1000 ml of tap water, and application of fertilizer started on day 7 after the establishment of the seedlings, and this was repeated once each week for the entire trial period. Taking measurements of the water runoff and measuring the plant height started on day five after the germinated seedlings established. After each watering session, the runoff was left to collect in the polythene bags for 2 hours and later decanted into a 100-ml measuring cylinder. Plant height was recorded 3-4 times per week from day 5 using a 30 cm ruler from the soil surface to the apex of the longest leaf onwards after plants reached reasonable height to warrant accurate measurements.

At the end of the experiment, the plants were carefully removed from each pot using hands and washed in clean water to remove excess soil particles from the roots. The wet plants were later spread on the blue paper to drain the suspended water, and measurements of the entire plant (root plus shoot) were taken and recoded in the spreadsheet document. Using a pair of scissors, the roots and the shoot were dissected, and both root and shoot length were taken using a 30 cm ruler and entered in the spreadsheet document. Both below ground and above ground wet biomass of every dissected plant was measured using the electronic scale before putting them in the foil tray labelled with the block number, pot number, treatment name, and the date for drying in the oven. At the end of the harvest, all the plants were dried in the ovens in Margam laboratory room 105 and the teaching laboratory room number 115, respectively, at a temperature of 70 ° C for a maximum of 72 hours to remove the moisture content. At the end of 72 hours, the below-ground and above-ground biomass were taken using the electronic scale.

2.2. Statistical analysis

Plant growth behavior including total plant height, shoot and root length, and below and above ground biomass and water run offs were investigated across four different treatments (control, biochar, fertilizer and a combination of biochar plus fertilizer (Li et al., 2024) using the analysis of variance (ANOVA) in R version 4.3.2 (R core Team,2023) followed by a post-hoc pairwise test (R Core Team 2020). ANOVA was used to investigate significant differences in crop yield across four different treatment groups. To carry out the ANOVA test, the (aov) function was incorporated since it provides optimum contrasts of means among treatments, thus rendering an organic procedure essential for a comprehensive effect of different treatment groups on crop yield (R Core Team 2020). Post-ANOVA, the Tukey's Honest Significance (HSD) post hoc test using the (TukeySHD) function was applied to figure out whether there were specific significant differences among treatments with regard to crop yield. This technique was used due to its ability to manage family-wise error incidences, thereby giving a genuine approach to knowing the pairwise variations between treatment groups (R Core Team 2020). To examine how biochar nutrients get depleted over time, a paired t-test was conducted with the help of the package tidyverse in order to maximize efficiency and simplicity of complex data (RStudio, n.d.). However, before conducting any statistical analysis, data were transformed using the Cox box technique based on the majority of the plant parameters, which were not normally distributed except for the plant total length, shoot length, and root length (cycle 2). The Cox box technique was supplemented by the Shapiro test to account for the statistical normality of the data. Further, the zeros in the dry root weight and water runoff data were removed to avoid errors resulting from plants that had zero biomass. The Akaike Information Criterion (AIC) (Thomas, 2021) paired with the biochar presence only, was used to investigate where biochar presence had a significant impact on crop yield than the combination of biochar+ fertilizer treatment. This analysis was also extended to the fertilizer treatment to ascertain whether fertilizer was the primary factor accounting for variations in plant growth (yield). To account for which model was most parsimonious, the AIC scores for each specific model were compared (Thomas, 2021). The above analyses were equally applied to the soil property, the water runoffs in particular.

3. Results

3.1. Crop yield (Plant growth responses)

Across cycles, the best crop yield (growth responses) came from the combination of biochar plus fertilizer treatment and biochar only (root length in cycle 1). However, biochar alone and the combination of biochar and fertilizer revealed similar performance of 0.02 g on the dry root weight. The comparison of biochar and fertilizer alone also showed similar effects of 0.06 g on the wet root weight and 0.02 g dry root weight, respectively (Table 1). Apart from the above similar effects, the biochar treatment group generally performed better compared to the fertilizer treatment across both time and parameters. Nevertheless, the lowest crop yield came from the control treatment group, despite similar effects on the dry shoot weight between fertilizer and the control treatment in cycle 2 (Table 1).

Table 1 Mean values for measured plant parameters across treatments (Biochar, fertilizer, control and biochar combined with fertilizer) for cycle 1 and 2.

Plant Growth Response	Treatments			
	Control	Fertilizer	Biochar	Biochar+ Fertilizer
Total plant height cycle 1	10.17	17.14	18.54	24.19
Total plant height cycle 2	12.57	17.66	21.48	22.39
Root Length cycle 1	5.11	8.27	9.74	11.24
Root Length cycle 2	26.91	8.73	11.29	10.89
Shoot Length cycle 1	5.06	8.66	9.31	12.95
Shoot Length cycle 2	5.65	9.11	10.18	11.50
Wet Root Weight cycle 1	0.03	0.06	0.06	0.20
Wet shoot weight cycle 2	0.03	0.05	0.10	0.11
Wet shoot weight cycle 1	0.07	0.42	0.46	1.32
Wet Shoot Weight cycle 2	0.19	0.37	0.38	0.61
Dry shoot weight cycle 1	0.03	0.20	0.23	0.66
Dry shoot weight cycle 2	0.02	0.02	0.03	0.05
Dry root weight cycle 1	0.01	0.02	0.02	0.04
Dry root weight cycle 2	0.00	0.01	0.02	0.02
Water runoffs cycle 1	33.6	27.8	18.76	12.17
Water runoffs cycle 2	28.26	21.65	19.01	11.83

3.1.1. Total plant height and accumulative plant height over time

Results for total plant height showed a significant difference of 2.038879 (P-value = 0.0223958, Table 2) between plants that were fed with biochar fertilizer and plants that were fed with biochar alone (Figures 2a and 2b). The plants that were grown in the soil treated with a combination of biochar plus fertilizer showed greater heights than those grown in the biochar treatment (Figure 2). However, a comparison between biochar and fertilizer separately revealed that biochar performed better than fertilizer alone, as the application of fertilizer had a significantly lower plant height than biochar alone (Table 2). Further, the rest of the treatments were significantly different from the control (Table 2). The best model accounting for the marked differences was the one that consisted of all the treatments because the model had the lowest AIC scores of 803.2755 and 817.6237 (Table 3), cycle 2. In comparing the two cycles to see how biochar nutrients were depleted over time, the results showed a consistent performance across cycles (Table 4).

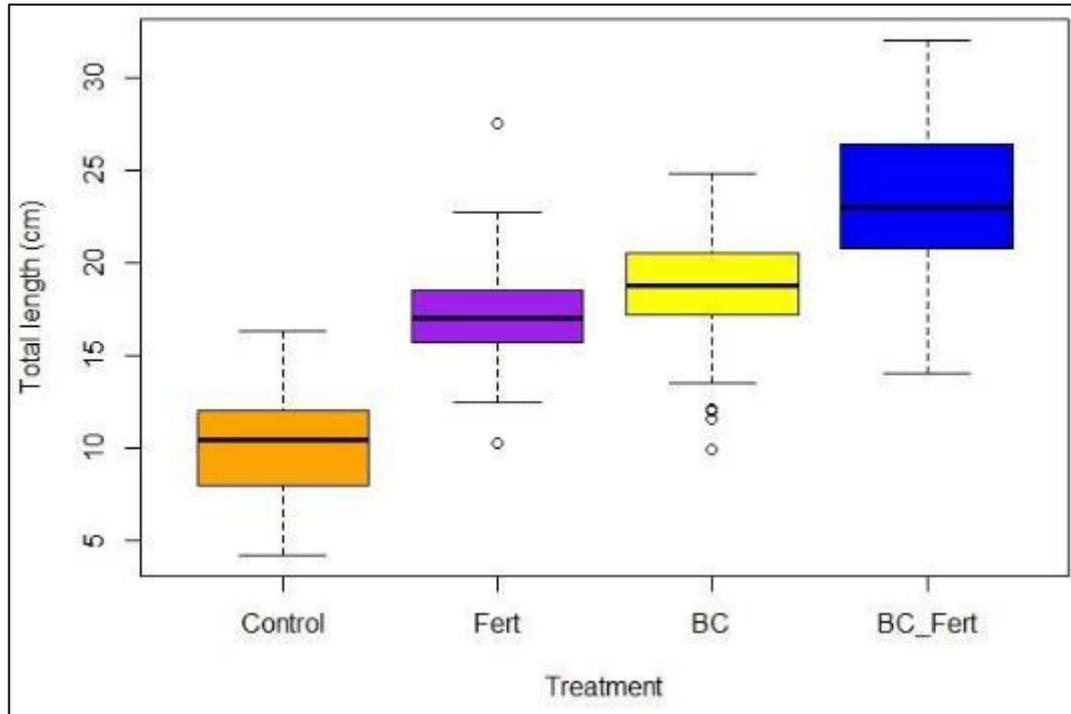


Figure 2a Mean plant height across different soil treatments (Biochar, fertilizer, control and biochar combined with fertilizer) for cycle 1 recorded at the end of the experiment

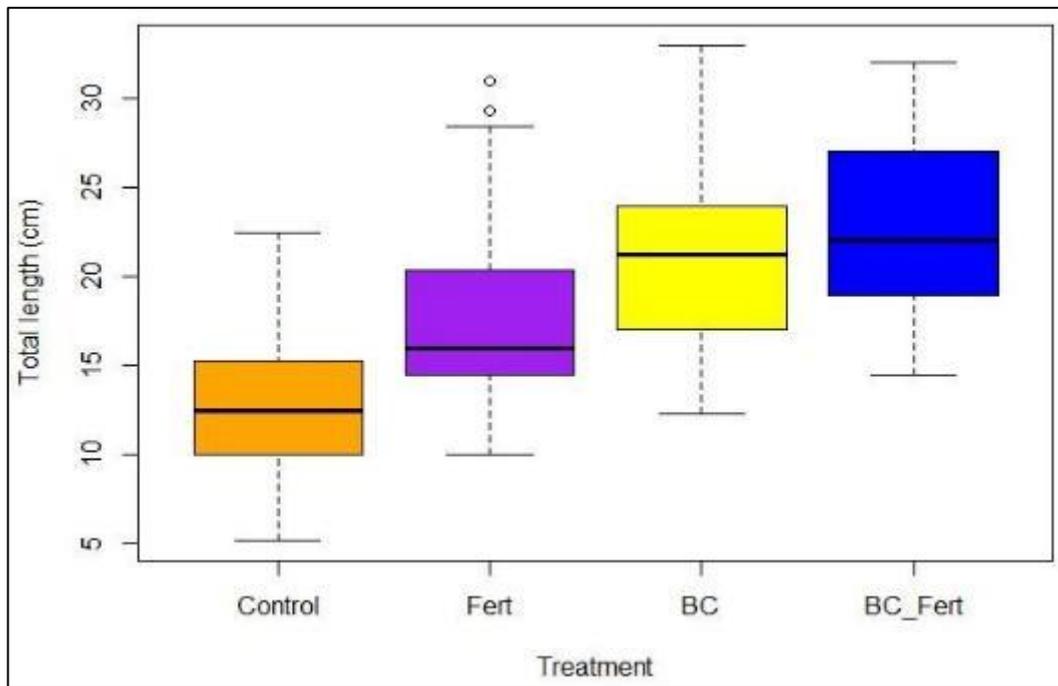


Figure 2b Mean plant height across different soil treatments (Biochar, fertilizer, control and biochar combined with fertilizer) cycle 2 which were recorded at the end of the experiment

Table 2 The application of four different treatments known as control (soil only), fertilizer (soil plus fertilizer), biochar (soil mixed with biochar) and biochar+fertilizer treatment (soil plus biochar and fertilizer) on crop yield (plant growth) and ANOVA test followed by a post hoc pairwise comparison for the total plant length, root length, shoot length, wet shoot weight, wet root weight, dry shoot weight, dry root weight and water runoffs for cycle 1 and 2.

Treatment Comparison	Total Plant	Root Length	Shoot Length	Wet Weight	Shoot	Wet Weight	Root	Dry Weight	Shoot	Dry Weight	Root	Water Runoffs
Biochar Plus (Cycle 1)	0.0223958	0.0001393	0.0000000	0.0000090		0.0000154		0.3467962		0.0000		0.0847359
Biochar Plus (Cycle 2)	0.0223958	0.0001393	0.0000000	0.0000090		0.0000154		0.3467962		0.0000		0.0000278
Control vs Biochar (Cycle 1)	0.0000000	0.0000000	0.0000000	0.0000000		0.5870654		0.0000000		0.0000		0.0120132
Control vs Biochar (Cycle 2)	0.0000000	0.0000000	0.0000000	0.0000000		0.5870654		0.0000000		0.0000		0.0002819
Fertilizer vs Biochar (Cycle 1)	0.0034004	0.0111060	0.3987399	0.9994789		0.9999947		0.8753221		0.0000000		0.1222223
Fertilizer vs Biochar (Cycle 2)	0.0034004	0.0111060	0.3987399	0.9994789		0.9999947		0.8753221		0.0000000		0.7241279
Control Plus Biochar (Cycle 1)	0.0000000	0.1218804	0.0000000	0.0000000		0.0000000		0.0000004		0.0000		0.0000007
Control Plus Biochar (Cycle 2)	0.0000000	0.1218804	0.0000000	0.0000000		0.0000000		0.0000004		0.0000		0.0000000
Fertilizer Plus Biochar (Cycle 1)	0.0000001	0.2817402	0.0000000	0.0000087		0.0000107		0.7109460		0.0000		0.0000390
Fertilizer Plus Biochar (Cycle 2)	0.0000001	0.2817402	0.0000000	0.0000087		0.0000107		0.7109460		0.0000		0.0000002
Fertilizer vs Control (Cycle 1)	0.0000000	0.0000064	0.0000000	0.0000000		0.5446702		0.0000000		0.0000		0.8140467
Fertilizer vs Control (Cycle 2)	0.0000000	0.0000064	0.0000000	0.0000000		0.5446702		0.0000000		0.0000		0.0115449

P Values for Individual Parameters Assessed Across Cycles

Table 3 Akaike's information criterion summary outputs for three separate models across plant yield including total plant height, shoot length, root length, wet shoot weight, wet root weight, dry shoot weight, dry root weight and soil characteristics which included the water runoffs. Model one composed of treatment as a factor with various levels (control, biochar+fertilizer, fertilizer and biochar).

Table 3 Alkaline 's information criterion summary outputs for three separate models

AIC Model outputs across cycles			
Plant Growth Response	All Treatments	Fertilizer Presence	Biochar Presence
Total plant height cycle 1	803.2755*	955.2212	932.3016
Total plant height cycle 2	817.6237*	873.7140	866.4910
Root Length cycle 1	696.9850*	797.7121	757.7575
Root Length cycle 2	526.3034 *	537.2421	534.6941
Shoot Length cycle 1	615.0930*	735.6196	741.4946
Shoot Length cycle 2	557.3634*	678.3499	670.1181
Wet Root Weight cycle 1	-580.9733*	-496.3122	-510.7050
Wet Root Weight cycle 2	-499.7426 *	-477.3510	-477.2296
Wet shoot weight cycle 1	240.3156*	365.1223	370.6246
Wet shoot weight cycle 2	-83.82447*	-22.86981	-22.72757
Dry shoot weight cycle 1	-576.4116*	-495.6958	-499.0069
Dry shoot weight cycle 2	-819.3399*	-743.0528	-742.5539
Dry root weight cycle 1	-1190.261*	-1052.368	-1080.368
Dry root weight cycle 2	-956.7015*	-854.4004	-855.5713
Water runoffs cycle 1	1439.148*	1463.889	1468.081
Water runoffs cycle 2	834.9686*	897.0645	898.7541

Model one composed of treatment as a factor with various levels (control, biochar+fertilizer, fertilizer and biochar. Model two was attached as a binary absence/presence factor with biochar presence and absence. Model three had fertilizer presence and absence only. Model scores denoted with * is the most parsimonious as evidenced by the lowest AIC value for cycle 1&2.

Table 4 t and p =values for t-test analysis conducted to compare the performance of biochar on crop yield including total plant height, shoot length, root length, wet shoot weight, wet root weight, dry shoot weight and dry root weight across cycles. The p -value denoted with * the depletion of nutrients overtime.

t and p -values for the paired t-test measured across cycles		
Plant Growth Response	t-value	P= value
Total plant height cycle 1-2	-2.8305	0.005233
Root Length cycle 1-2	-2.8938	0.004328
Shoot Length cycle 1-2	-1.9962	0.04757
Wet Root Weight cycle 1-2	-0.2352	0.8143
Wet shoot weight cycle 1-2	2.7422	0.006786*
Dry root weight cycle 1-2	1.9804	0.04934*
Dry shoot weight cycle 1-2	10.739	< 2.2e-16*
Water runoffs cycle 1-2	-11.375	< 2.2e-16*

Further, when comparing effects of biochar and fertilizer, the model with biochar presence only as a factor had a lower AIC score (932.3016) and (866.4910) (Table 3) than the model that incorporated fertilizer alone as a factor (955.2212) cycle 1 and (873.7140) cycle 2 (Table 3) and both models were significantly different from the model with all the treatment terms.

Nevertheless, when investigating the accumulative plant height across blocks and treatments for the entire trial period (Figure 3a & b plus figure 3aw & 3bx) the plants fed with either biochar, fertilizer and a combination of biochar plus fertilizer portrayed a similar growth trend except for the plants grown in the control medium.

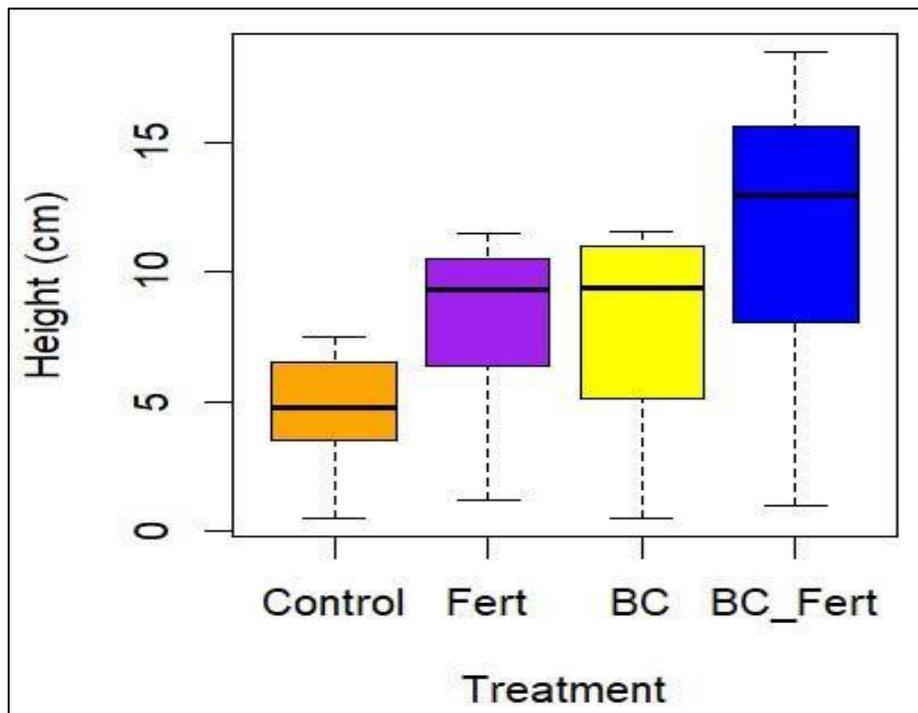


Figure 3a Box plot for the accumulative plant height (cycle 1) across biochar, fertilizer, control and biochar+fertilizer treatments recording during the experimental period at the interval of three to four times a week

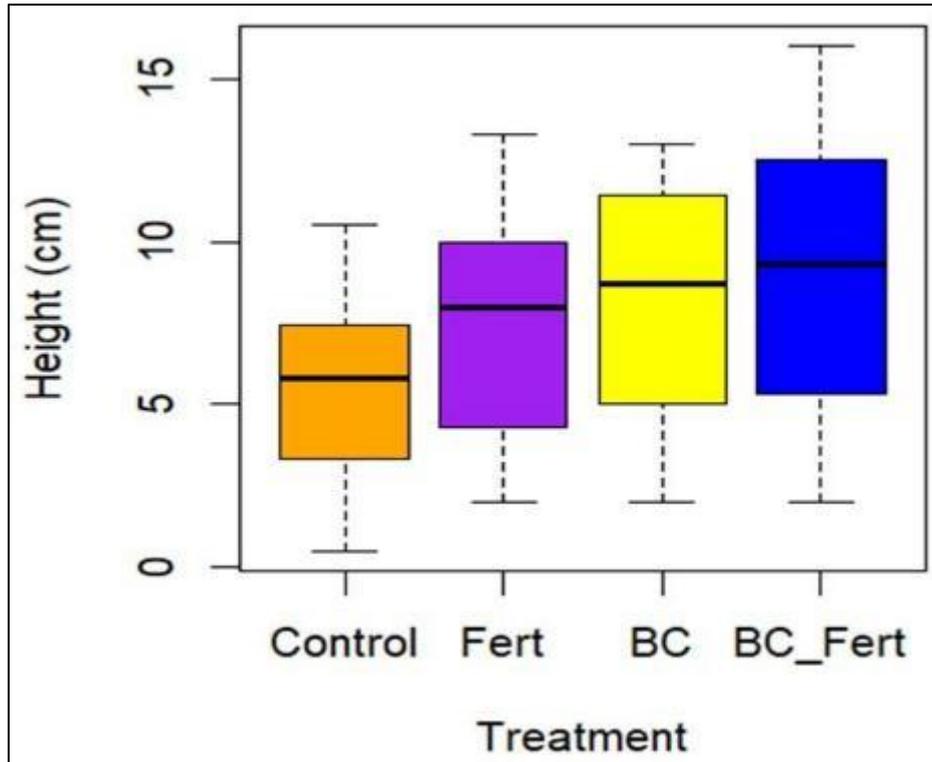


Figure 3b Box plot for the accumulative plant height (cycle 2) across biochar, fertilizer, control and biochar+fertilizer treatments recording during the experimental period three to four times a week

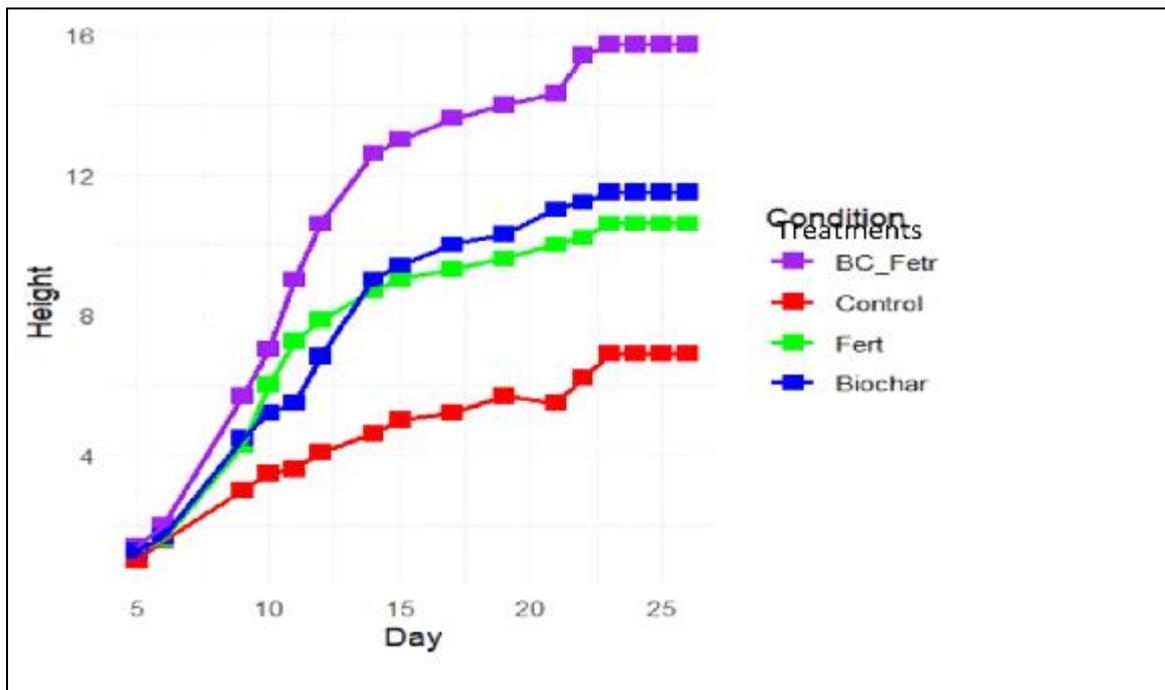


Figure 3aw Accumulative plant height cycle 1 across biochar, fertilizer, control and biochar+fertilizer treatments recorded during the experimental period three to four times a week.

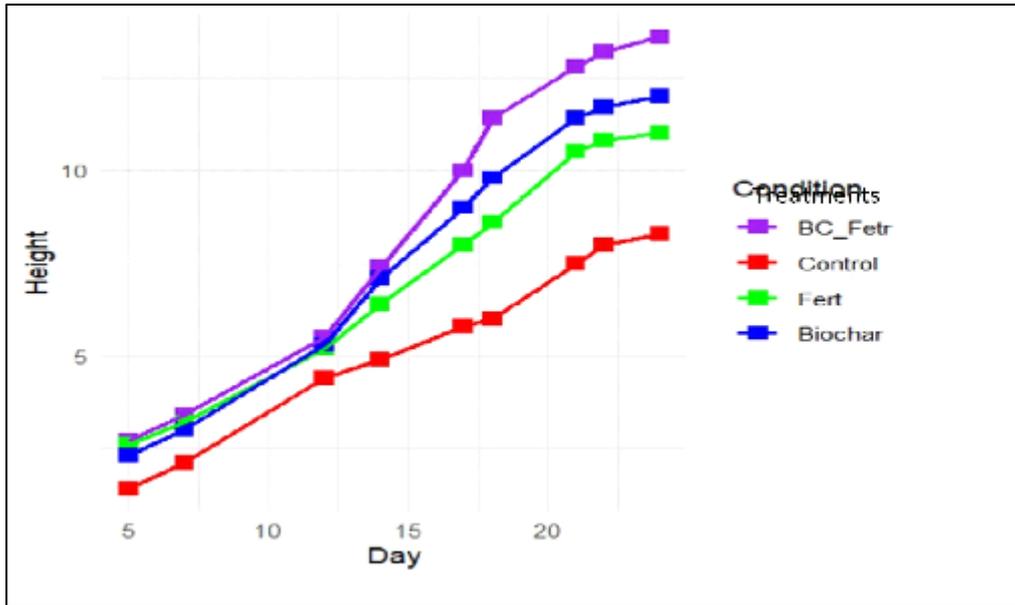


Figure 3bx Accumulative plant height cycle 2 across biochar, fertilizer, control and biochar+fertilizer treatments recorded during the experimental period, three to four times a week

3.1.2. Shoot length

Similar to the total plant height, plants treated with biochar+fertilizer (Figures 4a&b) displayed taller shoot length than those treated with biochar alone across cycles, p-value 0.0000000 (Table 2), but there were no significant differences between biochar alone and fertilizer treatment across cycles, pvalue 0.3987399 (Table 2). The model with all experimental terms was the most parsimonious model, with the lowest AIC values of 615.0930 and 557.3634 (Table 3). In comparing the models with biochar presence only with the model that had fertilizer presence only across time, models with biochar presence only were the most parsimonious models with the smallest AIC scores (Table 3). The comparison of the two planting cycles deduced a steady performance of biochar, resulting in improved shoot length (Table 4).

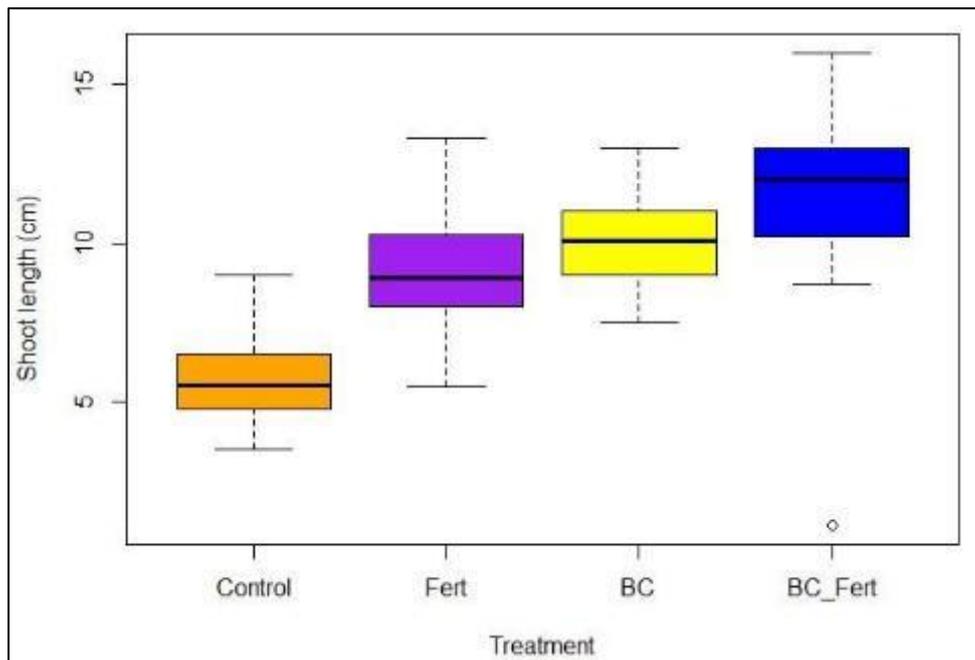


Figure 4a Plant shoot length for cycle 1 measured at the end of the experiment across four different treatments (Control, fertilizer, biochar and biochar+fertilizer).

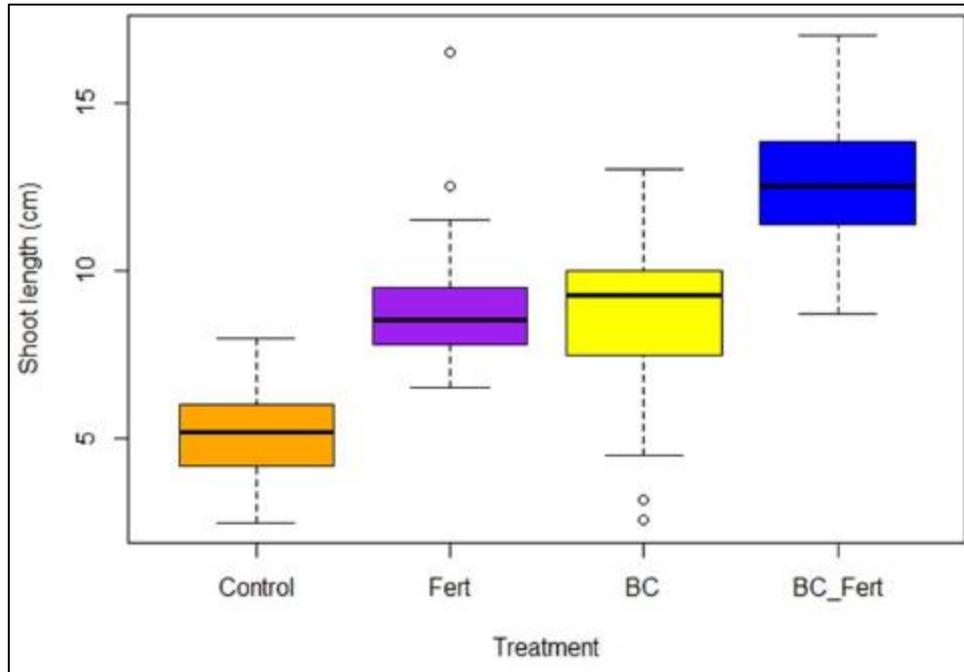


Figure 4b Plant shoot length for cycle 2 measured at the end of the experiment across four different treatments (Control, fertilizer, biochar and biochar+fertilizers).

3.1.3. Root length

The longest root length was observed in plants that were treated biochar+fertilizer (Table 1) compared with other treatments. However, there was no significant difference in root length between control and biochar + fertilizer (Table 2). In contrast, the box plots (Figures 5a&b) provide contradictory findings with the ANOVA test. Major observable reasons behind this could be the presence of outliers in the control, biochar and fertilizer treatment. Generally, the consistent ANOVA results suggest reliable treatment effects. The best model accounting for the root length was the model which included all the treatment terms as it had the lowest AIC value of 696.9850 and 526.3034 (Table 3). Overall, biochar alone showed consistent effects demonstrating the potential to improve crop yield than fertilizer, however, the combination of biochar plus fertilizer appears to be more effective in improving crop yield than biochar on its own. In examining the differences across cycles, cycle 2 performed better than cycle 1 (Table 4).

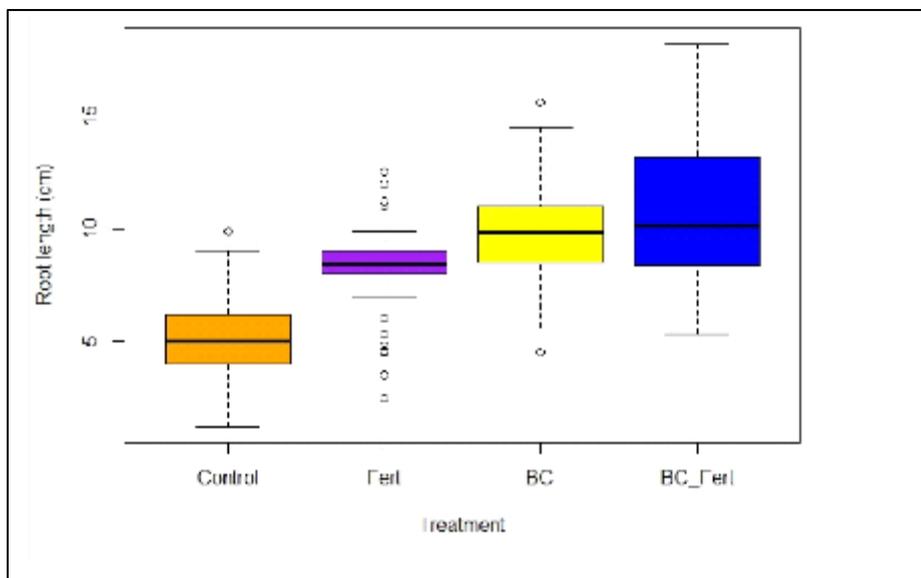


Figure 5a Root length cycle 1 measured at the end of the experiment across four different treatments (Control, fertilizer, biochar and biochar+fertilizer)

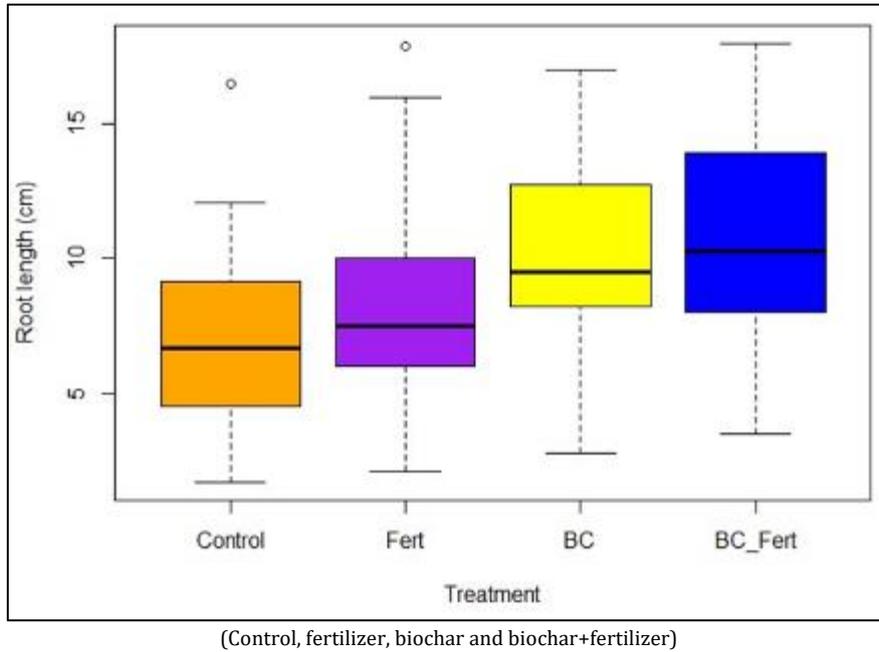


Figure 5b Root length cycle 2 measured at the end of the experiment across four different treatments

3.1.4. *Wet shoot weight*

As for the above-ground biomass, there was a significant difference between plants treated with biochar+fertilizer and the other three treatments (Figures 6a&b). Biochar+ fertilizer performed much better in improving wet shoot weight compared to biochar alone (Table 2), while the control treatment had the least effects, resulting in a significant decrease in wet shoot weight compared with other treatments. However, there was no significant difference in wet shoot weight between plants grown in biochar and fertilizer medium. Further, despite the ANOVA results showing a consistent trend in the effect of treatments across cycles, the notable discrepancies between the statistical analysis and the box plots could be due to the outliers across treatments. The model that had all the treatments was the most parsimonious model, with the lowest AIC values of 240.3156 and -83.82447 (Table 3), and both the models that included biochar presence and fertilizer presence displayed non-significant differences from the model that had all the treatment factors. As of which cycle performed better, cycle 1 significantly performed better (t value = 2.7422) and the (p value = 0.006786) than cycle 2 (Table 4).

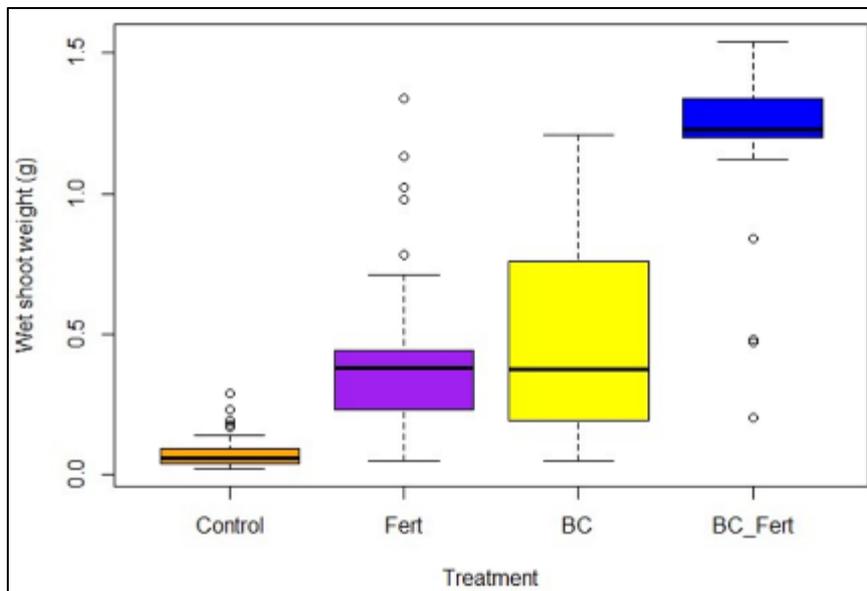


Figure 6a Wet shoot weight(biomass) cycle 1 measured at the end of the experiment across four different treatments (Control, fertilizer, biochar and biochar+fertilizer)

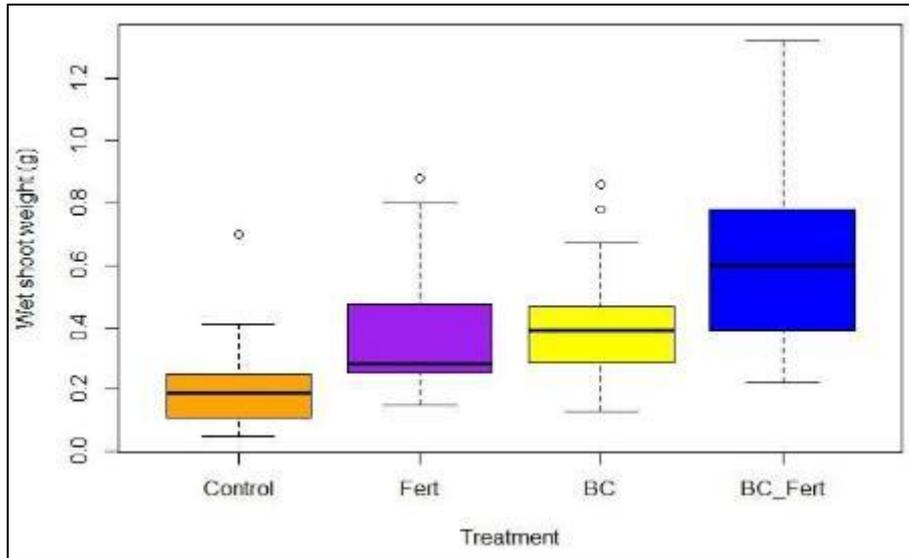


Figure 6b Wet shoot weight(biomass) for cycle 2 measured at the end of the experiment across four different treatments (Control, fertilizer, biochar and biochar+fertilizer)

3.1.5. *Wet root weight (Below ground biomass)*

Similar to the wet shoot weight, the combination of biochar+fertilizer had a significant difference in promoting wet root weight compared to biochar alone (Figures 7a&b). Yet, there was no significant difference between the control and biochar or fertilizer alone (Table 2). It is also important to mention that while the biochar alone did not result in increased wet root weight, its combination with fertilizer has positive effects on plant growth. The model with all the treatment factors was the most parsimonious, as it had the lowest AIC score of -580.9733 and -499.7426 (Table 3). The model with biochar presence only had notable variation to the model with fertilizer presence; additionally, the biochar presence only model was more effective than the model with fertilizer presence only (Table 3). However, when we compared the biochar presence only and fertilizer presence only in cycle 2, the two models accounted for the limited variations compared to the model with all the treatment terms (Table 3). Additionally, when investigating the depletion of nutrients in biochar over time, the two planting cycles had similar effects without any significant difference between cycles (Table 4).

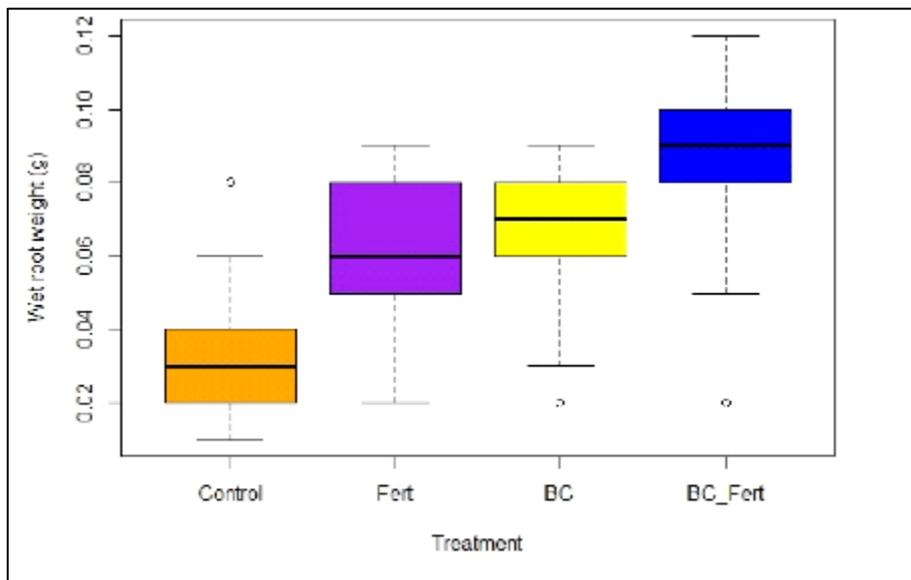


Figure 7a Wet root weight (wet below-ground biomass) cycle 1 measured at the end of the experiment across four different treatments (Control, fertilizer, biochar and biochar+fertilizer)

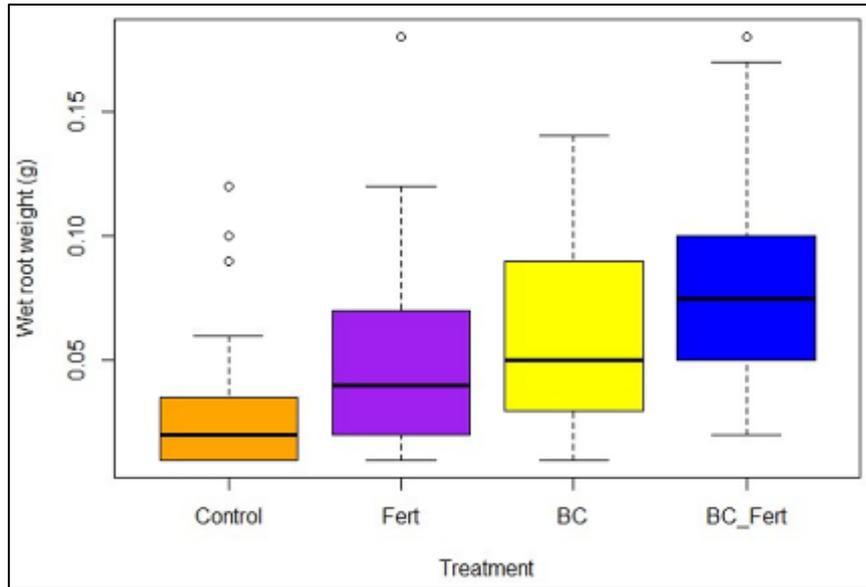


Figure 7b Wet root weight (wet below ground biomass) for cycle 2 measured at the end of the experiment across four different treatments (Control, fertilizer, biochar and biochar+fertilizer)

3.1.6. *Dry shoot weight (above ground) biomass*

The dry shoot weight (above ground) biomass across time was notably greater in the biochar alone, fertilizer and a combination of biochar+fertilizer treatments (figures 8a&b) compared to the control treatment (Table 2). This means that subjecting plants to the control treatment significantly decreases the (dry shoot weight) above-ground biomass, while feeding plants with a combination of biochar +fertilizer or biochar alone significantly leads to an increased above-ground biomass. The most parsimonious model was that that included all the treatment factors since it had the smallest AIC values of -576.4116 and -819.3399 (Table 3). In cycle 1, the three different models differed significantly (Table 3), while in cycle 2, there was no significant difference between the model with biochar presence only and the one with fertilizer presence compared to the model with all the treatment teams (Table 3). An examination of the performance of biochar cross cycles showed significant better performance in cycle 1 compared to cycle 2 (t value =10.739 and p value = < 2.2e-16) (Table 4).

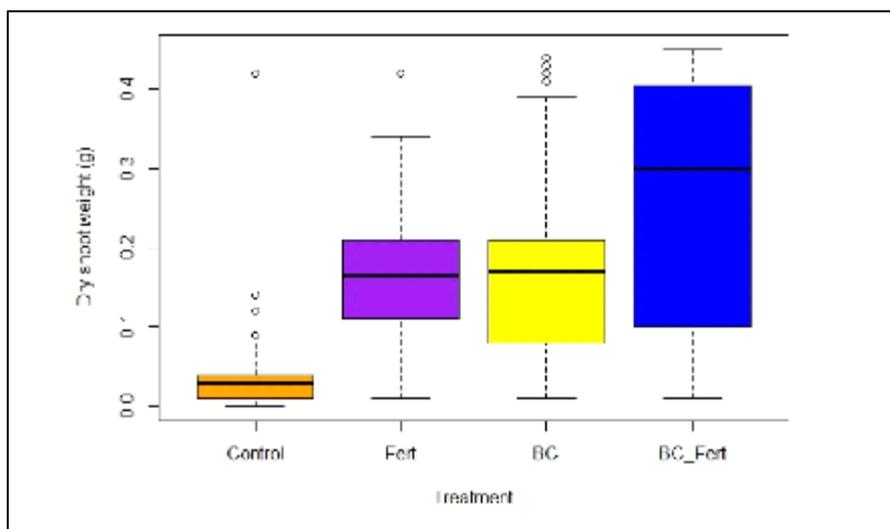


Figure 8a Dry shoot weight (above ground) biomass cycle 1 measured at the end of the experiment across four different treatments (Control, fertilizer, biochar and biochar+fertilizer)

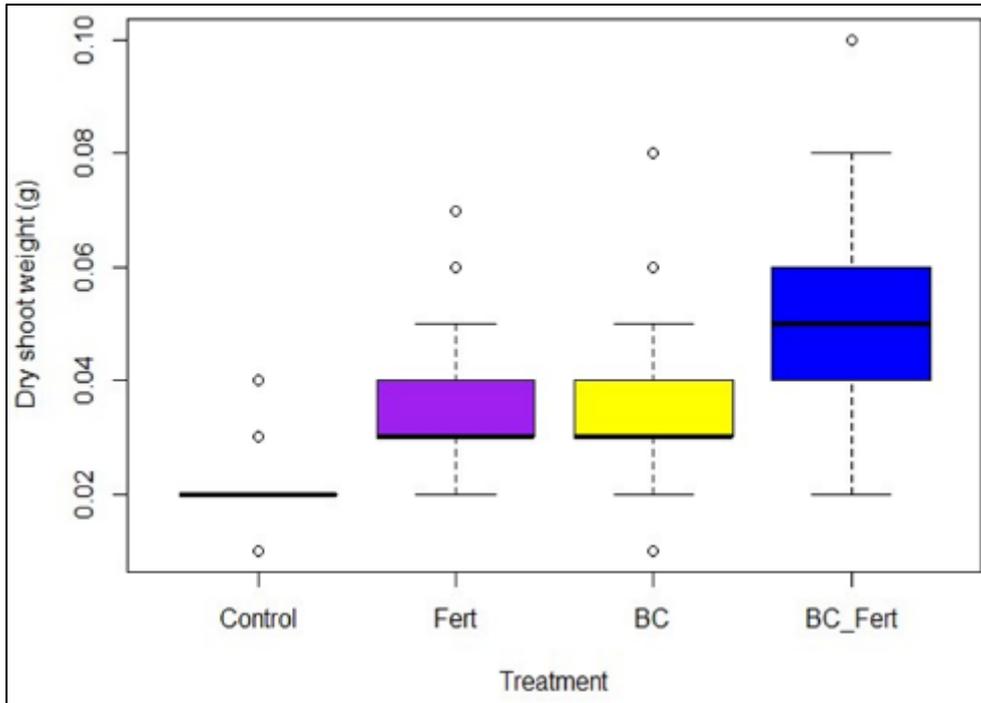


Figure 8b Dry shoot weight (above ground) biomass for cycle 2 measured at the end of the experiment across four different treatments (Control, fertilizer, biochar and biochar+fertilizer)

3.1.7. *Dry root weight (below ground) biomass*

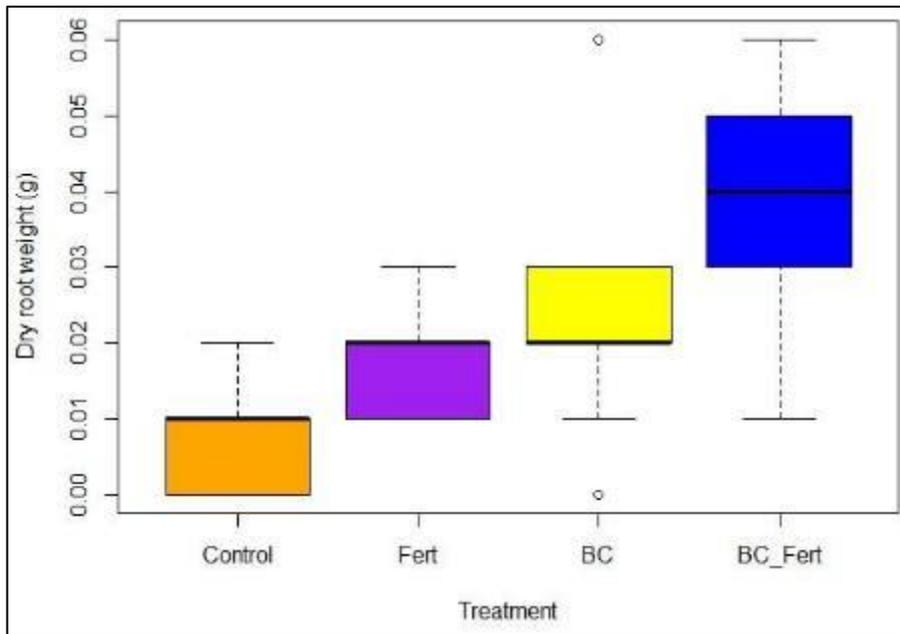


Figure 9a Dry root weight (below ground) biomass cycle 1 measured at the end of the experiment across four different treatments (Control, fertilizer, biochar and biochar+fertilizer)

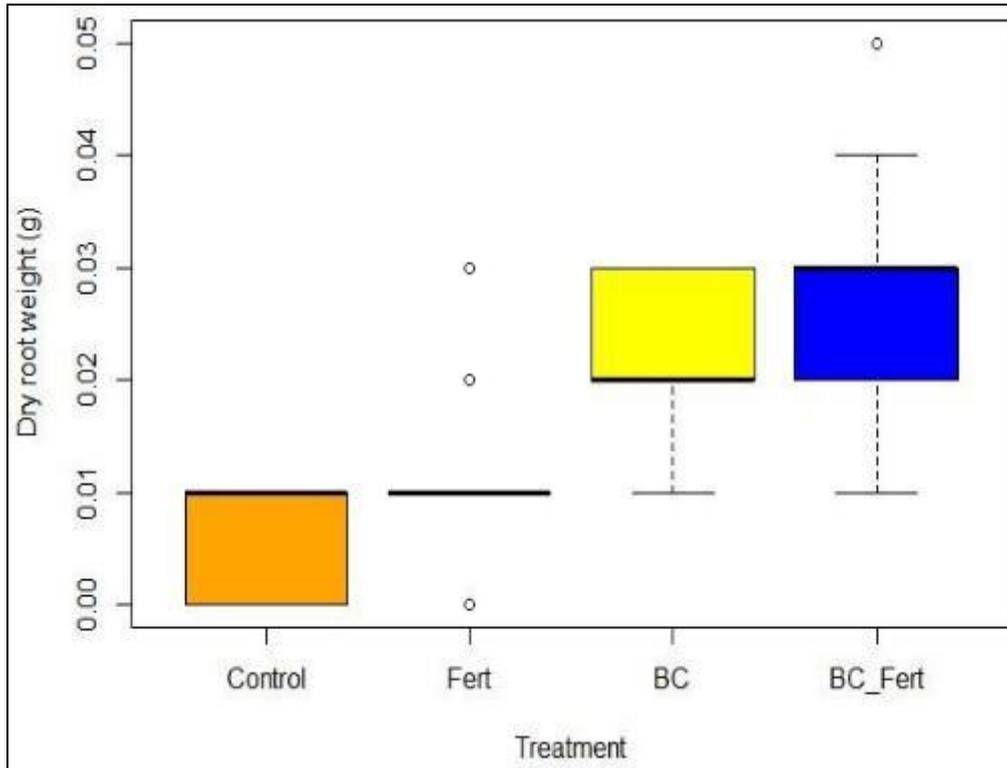


Figure 9b Dry root weight (below ground) biomass for cycle 2 measured at the end of the experiment across four different treatments (Control, fertilizer, biochar and biochar+fertilizer)

In examining the application of various treatments on the dry root weight (below ground) biomass, all treatments displayed significant differences among themselves. However, a combination of biochar plus fertilizer had a significant difference compared to biochar alone (Figures 9a&b). Furthermore, biochar treatment on its own had a significant result on the dry root weight compared to the fertilizer treatment alone (Table 2). On the other hand, the control treatment had consistently reduced effects on the dry root weight, suggesting the significance of treating the control with biochar as a soil amendment critical for enhancing root growth. The most parsimonious model was the one that consisted of all the all-experimental variables, which had the lowest AIC score of -1190.261 and 956.7015 (Table 3). The comparison of the models with biochar presence only and the model with fertilizer presence alone showed significant differences, with the biochar presence model alone being better than the fertilizer presence alone model. Results from the comparison of the two cycles revealed greater performance in cycle 1 (Table 4), implying that nutrients contained in biochar get depleted overtime.

3.1.8. Water runoffs

The control and fertilizer treatments had the highest water runoffs compared to other treatments across cycles (Figures 11a&b), yet there was no significant difference between them. Similarly, there was no significant difference between water runoffs in the soil treated with biochar alone and fertilizer on its own (Table 2). This trend was further observed when comparing the difference between biochar and biochar plus fertilizer. Despite the combination of biochar plus fertilizer having a slight decrease in water runoffs compared to biochar alone, the difference was not statistically significant (-0.8637987) and P-value = 0.0847359 (Table 2). Nevertheless, in cycle 2, there was a significant difference (2.5077659) between biochar and a combination of biochar and fertilizer (P-value= 0.0000278) (Table 2). Overall, this study had the highest water runoffs across cycles from the control treatment and the lowest from a combination of biochar plus fertilizer. The most parsimonious models were those that included all the treatment variables, as evidenced by the lowest AIC values of 1439.148 and 834.9686 (Table 3). Yet, the model with fertilizer presence only performed better than the one with biochar presence only, with a significant difference in cycle 1, unlike cycle 2 (Table 3). Additionally, the comparison of the water runoffs across cycles showed significant water runoff from cycle 2 with a difference of (-11.375) than in cycle 1 (Table 4).

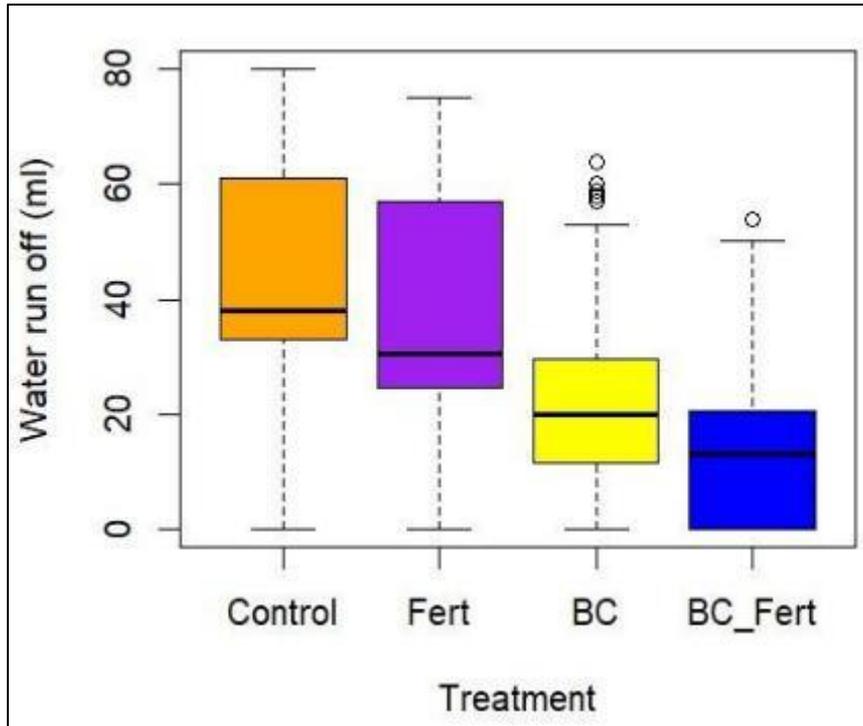


Figure 10a Water runoffs measured across treatments (control, biochar, biochar+fertilizer and fertilizer) during the experimental period three to four times a week (cycle 1)

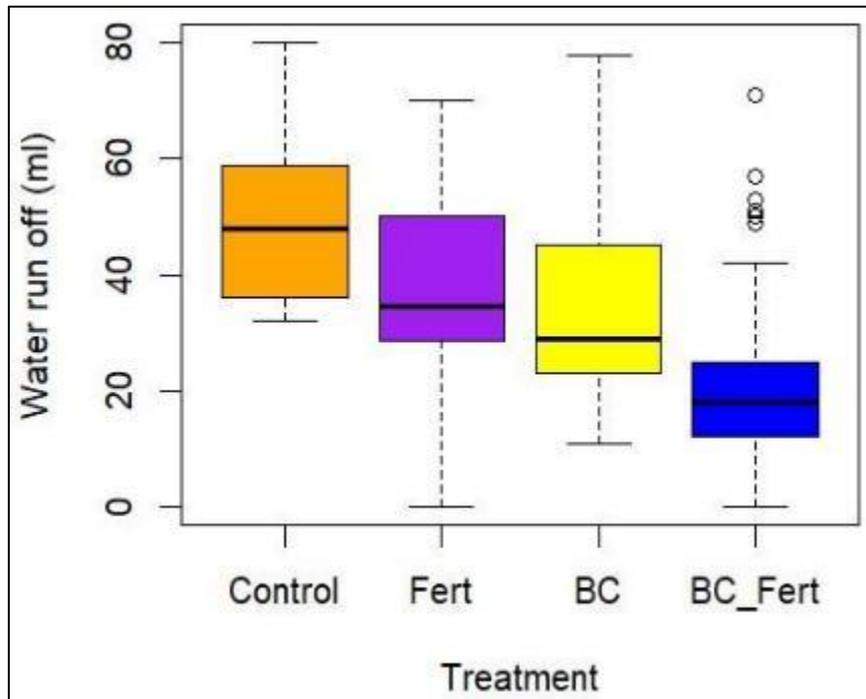


Figure 10b Water runoffs that were measured across treatment (control, biochar, biochar+fertilizer and fertilizer) during the experimental period three to four times a week (cycle 2)

4. Discussion

The study set out to examine the application of biochar on crop yield and the depletion of nutrients over time. Generally, biochar enhanced crop yield in terms of plant growth. Biochar alone performed better in improving root length.

Nevertheless, this was different on the dry root weight, wet shoot weight, shoot length, and total plant height, where a combination of biochar and fertilizer surpassed the biochar treatment. Despite that, there were no significant differences between the biochar and fertilizer on the above-outlined variables. This implies that biochar is a potential replacement for expensive chemical fertilizer (Benson & Moguees, 2018), particularly on the African continent, which has poor acidic soil in addition to soil degradation due to unsustainable agricultural practices to feed the growing population (Agegnehu et al., 2021). The results pointed at the biochar combined with fertilizer as the best treatment group for higher crop yield. The major reason behind this is that biochar is capable of holding soil nutrients, including enhancing the uptake of nutrients in crops by invigorating microbial and enzyme activities (Peng et al., 2021).

Investigations about the application of biochar in soil chemical behaviour revealed reduced water runoffs in the soils that were treated with biochar compared to the soils not fed with biochar (control and fertilizer groups). This revelation was acceptable considering biochar's effectiveness in boosting the soil's water-holding capacity (Ndede et al., 2022) and suppressing water loss by evaporation (Zhang et al., 2024). The improved water-holding capacity is primarily due to the porous nature of biochar. These pores provide a large specific surface area for water accumulation galvanised with its recalcitrant nature, making biochar stable in soil, offering long-lasting effects, and revamping water availability in the soil (Nicholas et al., 2023; Li & Tasnady, 2023). The combination of biochar+fertilizer group had the least amount of water runoff owing to higher water affinity by the plants raised in the combination treatment since they had an overall significantly higher yield, not necessarily the variations in soil chemistry between biochar+fertilizer and biochar alone.

Regarding the depletion of nutrients across cycles, the present study showed a consistent positive effect of biochar on crop yield (Table 3). It is likely that nutrients in biochar do not deplete within a single planting generation; rather, it gradually releases nutrients across time, thus improving the soil fertility (Joseph et al., 2021). Therefore, studies with more planting cycles are crucial to investigate the depletion of nutrients over time (Ding et al., 2016). Biochar enhances cation exchange capacity and water holding capacity (Zhang et al., 2024) and escalates both plant biotic and abiotic processes, especially in the rhizosphere, which improves the availability and uptake of nutrients, facilitates plant growth (Joseph et al., 2021), and improves endurance to environmental shock (Chi et al., 2024). This explains the observed consistent performance of biochar in the two planting cycles used in this study. The consistent property of biochar revealed in this study is backed by a meta-analysis that showed that biochar boosts the availability of phosphorus by a factor of 4.6 (Joseph et al., 2021) and oxygen content and surface oxygen-containing functional groups, which are essential for soil health and plant growth (Long et al., 2024). However, comparisons across cycles suggest depletion of nutrients leading to decreased wet shoot weight, dry shoot weight, dry root weight, and increased water runoffs in the second planting cycle (Table 4). These findings align with a study by Alkharabsheh et al. (2021), which reported that the ageing effects of biochar had a negative effect on earthworms and reduced the shoot and root weight (biomass) in tomato and rice plants. Therefore, one of the reasons explaining the observed signs of nutrient depletion is the ageing of biochar, which lowers the soil pH, ash, hydrogen, carbon, and nitrogen content in the soil, which are critical for plant growth (Long et al., 2024). Optimal soil pH is critical for plant growth. It promotes the availability of nutrients, rejuvenates microbial processes, and improves entire plant health (Duddigan et al., 2021). However, when the soil is acidic, cation exchange capacity reduces; vital nutrients, including phosphorus, bind with iron, forming insoluble chemical compounds that plants cannot absorb, thus limiting the availability of such crucial elements needed for enhanced crop yield (Duddigan et al., 2021). Soil acidity promotes aluminum (Al^{3+}) and hydrogen (H^{2+}) ions to occupy the cation exchange sites and significantly limit the presence of these areas for key mineral cations including magnesium (Mg^{2+}), potassium (K^{2+}), and calcium (Ca^{2+}) (University of Delaware, n.d.). Biochar has high water holding capacity (Hossain et al., 2020). The increased moisture content in biochar improves the disintegration of organic matter and increases the presence of nutrients in the soil particles, which are later lost through leaching (Hossain et al., 2020). This implies the minimal depletion of nutrients observed in this study is due to reduced microbial activities, pH, cation exchange capacity, and reduced water holding capacity as shown in the second planting cycle (Table 3). However, these findings are not conclusive, as this study did not examine the soil properties and overall, the use of biochar is a potential innovation given that it does not require frequent application owing to its ability to persist in the soil particles for many years (Li & Tasnady, 2023).

4.1. Implications for crop yield (plant growth)

Hitherto, studies reported that treating the soil with biochar boosts crop yields in durum wheat (*Triticum durum L.*) and sorghum (*Sorghum bicor. L.*) (Hussain et al., 2017; Bo et al., 2023) and plant growth in rocket (*Eruca sativa Mill.*, respectively; Barouchas & Tsakalidi, 2021). Further, similar research revealed significant tomato and lettuce yield when treated with faecal sludge biochar (Nicholas et al., 2023). The present study supports the above findings precisely, indicating that the use of biochar alone improved root length. This study demonstrated that there was no significant difference in total plant height, dry root weight, wet shoot weight, or shoot length between biochar alone and fertilizer. The great performance observed in biochar alone and the combination of biochar plus fertilizer is crucial in improving

food production, leading to improved food security, particularly in the African continent, which has the highest risk of food insecurity and climate change (Trentinaglia et al., 2023). Considering many challenges faced in accessing chemical fertilizer, including the high fertilizer costs, late deliveries, lack of subsidy programmes and limited understanding of fertilizer application (Mashamaite et al., 2024), biochar is the only promising solution to the increasing food insecurity in the developing countries (Maja & Ayano, 2021b). This is contrary to the application of chemical fertilizer aligned with the far-reaching negative impacts of speeding up the soil degradation leading to environmental pollution (Tyagi et al., 2022).

Contrary to the findings of the present study, previous studies showed that the use of biochar alone had no significant effect on crop yield compared to the control (Vijay et al., 2021). This was not surprising as the experimental trial was conducted in alkaline soils in comparison with this study, which was conducted in a dark, acidic soil poor in nutrients and water retention capacity. This means that biochar is best effective when applied in acidic soil, as it has the potential to increase water holding capacity, nutrient retention, and cation exchange capacity. Given this background, faecal sludge biochar, which has a higher pH value and higher water holding capacity, can be used to neutralize the acidic soil, improve the availability of moisture content, and improve crop yield, critical for the mitigation of the rising challenge of food insecurity in Sub-Saharan Africa.

Biochar on its own performed better compared to the fertilizer treatment despite having no great differences in certain parameters, including total plant length, root length, and wet root weight. Given this, it becomes clear that biochar has sufficient nutrients key for improved crop yield. In tandem with previous studies (Nicholas et al., 2023), biochar enhanced water holding capacity in sand soil and improved the cation exchange capacity in sandy loamy soil. This resulted in revamped nutrient retention and reduced leaching in the soil, similar to the soil used in the current study, and this clarifies the variations in crop yield between biochar and the fertilizer group.

The substantial crop yield reported by many researchers is primarily due to the liming effect contained in alkaline biochar (Mosharrof et al., 2021). The liming effect in biochar neutralizes the proton produced, thus decreasing soil acidity (Murtaza et al., 2024) when applied in poor acidic soils. This corresponds to Nicholas et al.'s (2023) study, which deduced that biochar is most impactful when applied in poor acidic soils by making the soil more suitable for improved crop yield. Furthermore, this study revealed that the combination of the biochar+fertilizer group produced outstanding results in crop yield compared to both the control and fertilizer groups. This best aligns with previous studies (Ye et al., 2020; Rivelli & Libutti, 2022), which revealed similar effects mainly due to liming effects in biochar, which enhance nutrient availability and uptake of nutrients. Mineral elements, including phosphorus, calcium, and potassium, are largely affected by soil alkalinity despite being critical for proper growth and development (Najafi & Jalali, 2016). Potassium and calcium easily get leached in acidic soils, while phosphorus performs well in neutral soils. Once exposed to either acidic or alkaline soils, phosphorus binds with iron and aluminum, thus limiting its availability for crop yield (Najafi & Jalali, 2016).

A recent study (Nicholas et al., 2023) reported that the liming effects in biochar can potentially lower soil exchangeable acidity and escalate soil exchangeable base cations, which in turn improves soil cation exchange capacity and enhances crop yield (Nicholas et al., 2023). Biochar contains surface functional groups with the potential to revamp cation exchange capacity, thus inhibiting leaching and increasing nutrient retention critical for proper growth and maximum crop yield (Nicholas et al., 2023). Generally, this study revealed that the use of faecal sludge biochar enhanced yield in rockets, particularly when biochar was mixed with fertilizer, suggesting biochar is a sustainable and effective form of organic fertilizer in addressing the crisis of food insecurity in regions with rampant soil degradation (Bekchanova et al., 2024). This is because the increased cation exchange capacity of biochar boosted the uptake of fertilizer and improved the water holding capacity due to the increased specific surface area created by the porous nature of biochar (Batista et al., 2018). In this study, biochar outperformed fertilizer treatment, giving us an alternative to chemical fertilizer, which is not only expensive but also pollutes the environment.

In contrast, nutrients contained in biochar tend to get depleted due to ageing (Long et al., 2024). As time goes on, biochar experiences chemical and physical alterations that reduce its nutrient retention property, increasing microbial colonization and leading to the absorption of nutrients, thus limiting the availability of nutrients for plant growth (Hossain et al., 2020). This makes crops struggle to acquire vital minerals, including phosphorus, potassium, and nitrogen (Hossain et al., 2020), resulting in reduced plant growth and poor crop yield. Increased understanding of biochar is critical for sustained soil nutrients and improved crop yield (Alkharabsheh et al., 2021). Government and agricultural practitioners should ensure that farmers have sufficient knowledge about the life span of biochar and its correct application (Sharma, 2024), as this has a positive implication on crop yield and food security (Pandian et al., 2024).

4.2. Effects on soil property (water runoffs)

The water runoffs from the soils treated with biochar alone and fertilizer were statistically similar and better than the control treatment. (Table 2). This was contrary to previous studies, which reported significantly reduced water runoff to the soils treated with biochar alone (Nicholas et al., 2023). The soil that was treated with a combination of biochar mixed with fertilizer had the lowest water runoffs in comparison with the biochar group (Figures 11a&b). This was primarily due to the largest plants fed with a combination of biochar plus fertilizer with a larger moisture need. Predominantly, treating the soil with biochar improved water holding capacity and enhanced crop yield, particularly in the soil fed with a combination of biochar + fertilizer, thus offering a long-lasting solution to barren land and regions prone to droughts as a result of climate change (Nicholas et al., 2023). However, considering that biochar nutrients get depleted over time (Long et al., 2024; Hossain et al., 2020), and as evidenced in this study, it is imperative that policymakers consider coming up with policies that advocate for the use of biochar, including giving grants to farmers and biochar-producing companies and subsidising schemes, as these will ensure affordable, high production of biochar (Bhattacharyya et al., 2024). This will sustain the water-holding property of biochar, which is necessary in the mitigation of climate change, droughts, and food insecurity (Trentinaglia et al., 2023) along with the projected water crisis in Sub-Saharan Africa (Isaacman & Musemwa, 2021). In addition, improved water holding capacity has a critical bearing in improving the health structure of the soil and minimising environmental pollution by filtering pollutants, including heavy metals and pesticides, and sequestering carbon (U.S. Department of Agriculture, Natural Resources Conservation Service, n.d.).

4.3. Impact on food security

The use of biochar+fertilizer treatment greatly increases crop yield. This is particularly critical to small and medium-scale farmers in developing countries where the application of inorganic fertilizer is significantly limited due to several factors, including lack of subsidy programmes, late deliveries, and unbearable product costs. For instance, the cost of fertilizer in Sub-Saharan Africa is four times more expensive compared to Europe (Gro Intelligence 2016). In Zambia, the price of fertilizer inputs was reported to be 30%–40% higher than in Thailand and twice in Uganda compared to other regions, including Europe and the United States of America (Gro Intelligence 2016). This explains the limited use of inorganic fertilizer in developing countries compared to developed countries. The findings of this study confirm that using biochar instead of fertilizer can produce similar or greater yields. However, there is a need for field trials as opposed to findings from the glasshouse since conditions in the field may differ and the glasshouse pot-based results may lack application for conclusive results.

Another crucial benefit of using biochar in enhancing crop yield is its ability to recycle key minerals, including potassium, phosphorus, and nitrogen (Jindo et al., 2020). This implies that using faecal sludge biochar in crop growth would reduce the challenges associated with accessing phosphorus, a critical ingredient in fertilizer due to limited phosphate reserves and being only available in a few countries (Jindo et al., 2020). Phosphorus is critical in the transfer of energy in plants as an essential part of ATP (adenosine triphosphate), converting sunlight energy needed for photosynthesis and promoting root development central for the uptake of water and mineral salts (Harman, 2017). However, phosphorus is a non-renewable element currently in an exhausted state, with the remaining deposits only found in limited regions including China, the Middle East, Northern Africa, and the United States (O’Gorman Lalor, 2024) and not easy to extract (Trafton, 2023). Future projections reveal that the remaining phosphorus reserves will be finished in the coming 100-400 years (Faradji & De Boer, 2016; Illakwahhi et al., 2024). Important to note is that faecal sludge biochar has the potential to enhance the availability of phosphorus through recycling and minimise the overdependency on inorganic fertilizer (Strawn et al., 2023). Fertilizer applied on farmland enters the food chain and is later excreted (O’Gorman Lalor, 2024). Therefore, the use of biochar as a form of organic fertilizer lessens the threat of the projected phosphorus depletion (Faradji & De Boer, 2016; Illakwahhi et al., 2024). Additionally, Nicholas et al. (2023) reported that the concentration of phosphorus in faecal sludge biochar is around 3.2-3.9% and 5.4-8.1 wt.%. The preparation of faecal sludge biochar through pyrolysis recycles the phosphorus from food wastes, thus addressing the concern of phosphorus in many countries (Nicholas et al., 2023) and limiting the overdependency on unavailable and unevenly distributed inorganic fertilizer at a global scale (O’Gorman alor, 2024). Globally, about 50% of land has the potential for crop production. However, only a limited percentage is used due to the challenge of soil acidity (Nicholas et al., 2023). Soil acidification is common in sub-Saharan Africa (15%) of all the arable land (GABI, n.d.). Additionally, Sub-Saharan Africa is prone to climate change-induced annual droughts (Masih et al., 2014) and the crisis of sandy, acidic soils with low water retention capacity (Food and Agriculture Organization of the United Nations, n.d.). Nevertheless, the liming effect of alkaline biochar can restore the soils affected by acidity to the optimum ranges favourable for improved water holding capacity (Warner et al., 2023) and improved crop growth (Murtaza et al., 2024). This is particularly important in addressing the current low food production and food insecurity in developing countries (Trentinaglia et al., 2023).

The application of faecal sludge biochar has been reported to enhance degraded and poor soil and increase crop yield (Zhang et al., 2023). Arable land is generally becoming scarce in many parts of the world, including Southern Asia and Sub-Saharan Africa, due to the high food demand to meet the rising population (Maja & Ayano, 2021b). The majority of the soils in these regions are sandy with significantly low nutrients and reduced organic matter (Nicholas et al., 2023). The scientific community has projected that these regions will become more arid and lack water security due to changing climates (IPCC, 2022); this is the major attribute hindering improved plant growth and sound crop yield in water-stressed regions (IPCC, 2022). The power of faecal sludge biochar to restore the moisture content and nutrients resulted in enhanced soil health in poor, dry, and sandy soil and increased fruit yield of tomatoes grown in sandy loamy soil with insufficient moisture content (Nicholas et al., 2023).

Leveraging on the above foregoing and the findings of this study, it is acceptable to conclude that biochar is capable of improving crop yield and can play a key role in achieving United Nations Sustainable Goal number 2, which aims at ending hunger in all its forms by 2030 with special reference to the developing countries, including Sub-Saharan Africa (Maja & Ayano, 2021b). The present study also reported decreased water runoff in the soil treated with biochar. These results have serious implications for onwards water security. With the water crisis already affecting over 3.6 billion globally (United Nations World Water Assessment Programme, 2018), in the coming decades the water demand is likely to intensify, thereby triggering water wars and water conflicts and, consequently, causing regional instability (World Economic Forum, 2018; Xia et al., 2021). This will negatively affect arable farming, a sector that needs enough moisture content. The future water crisis is aligned with climate change-facilitated droughts. Climate change-induced droughts are anticipated to be severe and damaging owing to the lack of ample rainfall and increased evapotranspiration (U.S. Geological Survey, n.d.; World Bank, 2023). Yet, the application of faecal sludge biochar has shown enhanced resistance to drought in tomato saplings and absorption of nutrients in cabbage saplings in arid conditions (Nicholas et al., 2023).

Findings of this study suggests that biochar nutrients get depleted as time goes (Table 4). This increases the demand for inorganic fertilizer. Nevertheless, considering the significance of phosphorus in plant growth and its scarcity (O`Gorman Lalor, 2024), and its uneven availability and distribution (O`Gorman Lalor, 2024) policymakers and other stakeholders should invest more in research and development programmes to deepen the understanding of the soil and nutrient systems (Gurwick et al., 2013). This will ensure that biochar nutrients are sustained, as biochar is very effective in limiting leaching, sustaining soil nutrients, and increasing the availability and uptake of essential elements like magnesium (Mg²⁺), phosphorus (P), potassium (K⁺), ammonium (NH₄⁺), and calcium (Ca²⁺) (Alkharabsheh et al., 2021). Therefore, proper soil management is an important aspect of food security, particularly in sub-Saharan Africa, where soil degradation, acidity, and low food production are common among small-scale farmers. With statistics showing that small-scale farmers on the African continent are the major producers of food (Giller et al., 2021) over 60% and 39% in Tanzania (Jayne et al., 2016), good soil management, improved funding, research and development, and correct application (Gurwick et al., 2013), biochar can offer a lasting solution to global food security (The Nature Conservancy, n.d.) and the mitigation of climate change (World Economic Forum, 2023) as this can ensure that the possible depletion of nutrients is regularly evaluated and appropriate remedial actions are taken timely and precisely.

5. Conclusion

The combination of biochar plus fertilizer significantly improved crop yield. This was not only reported by this study but several other previous studies (Zhao et al., 2024; Hu et al., 2024; Liu et al., 2022). The comparison between biochar and fertilizer revealed a better yield when biochar was used alone, aligning to Nicholas `s study 2023. Considering the increasing population and the demand to grow more food, amending degraded soil with biochar alone or with a combination of biochar plus fertilizer has serious positive implications in averting food insecurity, climate change, and the disposal of faecal sludge in developing countries, particularly on the African continent (Bhattacharyya et al., 2024). The present study revealed that biochar nutrients get depleted over time. However, long studies are needed to have a conclusive finding pointing to when nutrients in biochar get depleted, unlike the present study, which only considered two planting cycles without water and soil properties results. .

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