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Original Article

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Charcoal Amendment Enhances Sorghum Yield and Biomass Production: A Sustainable Approach to Improved Crop Performance.

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ABSTRACT

Field experiment was conducted during the 2024 rainy season at the Teaching and Research Farm, Faculty of Agriculture, Bayero University Kano (BUK), and the National Horticultural Research Institute (NIHORT), Bagauda, to assess the effect of charcoal on the growth and yield of sorghum. Four charcoal application rates (0, 5, 10, and 15 t/ha) were arranged in a randomized complete block design with three replications. Results of the study indicated that charcoal application significantly ($p < 0.05$) influenced plant height, panicle weight, 1000 grain weight, grain yield, and biomass weight. The 10 t/ha treatment consistently produced the highest values for panicle weight (2656 kg/ha and 2958.96 kg/ha), biomass (5391 kg/ha and 5807.41 kg/ha), and grain yield (2244.44 kg/ha and 2686 kg/ha) at both locations. Grain yield showed a strong positive correlation with plant height, panicle weight, panicle length, and biomass. The findings suggest that charcoal enhances soil productivity and sorghum performance, with 10 t/ha identified as the optimal rate under the study conditions.

Keywords: *Charcoal, Crop productivity, Soil fertility, Savannah soils.*

INTRODUCTION

Sorghum (*Sorghum bicolor* (L.)) ranks as the fifth most important cereal crop globally, cultivated across more than 100 countries (Hao *et al*., 2021). It serves as a staple for over 500 million people in over 30 countries, particularly in sub-Saharan Africa (Prasad *et al*., 2021). In this region, several wild sorghum relatives also thrive (Ananda *et al*., 2020). Archaeological findings suggest that sorghum domestication began as early as the fourth millennium BC in eastern Sudan (Winchell *et al*., 2017).

Globally, the United States is the leading producer of sorghum, contributing 9.4 million metric tonnes (MMT), followed by Nigeria (6.3 MMT), Ethiopia (5.1 MMT), Mexico (4.7 MMT), and Sudan (2.6 MMT) (FAOSTAT, 2020). Nigeria remains the top producer in West Africa, with production reaching approximately 7 million tonnes in 2021 and an average yield of 1160 kg/ha (FAOSTAT, 2021). Sorghum accounts for nearly half of Nigeria's cereal output and covers about 45% of cereal cultivation area (FAOSTAT, 2020).

Despite this importance, sorghum yields in several key producing nations, including India and Sudan, have declined due to shifts toward other cash crops like rice and wheat (FAO, 2022; Nagaraj *et al*., 2013). Sorghum typically yields less compared to other cereals like maize, rice, and wheat (Ndlovu et al., 2021).

Sorghum is cultivated extensively across sub-Saharan Africa, yet yields in Nigeria remain persistently low. This is largely attributed to poor soil fertility, particularly in the Sudan Savanna zone where continuous cultivation and limited organic amendments have led to severe nutrient depletion. Previous studies have explored various soil improvement strategies, but there is limited evidence on how best to enhance sorghum productivity using locally available amendments.

In Nigeria's Sudan Savanna Zone, where sorghum thrives, extensive arable land supports grain crops like maize, millet, rice, and wheat (FFD, 2012). Yet, average yields remain at 1.7 t/ha, well below the global average of 4.0 t/ha (FAOSTAT, 2012), largely due to poor soil fertility. Nitrogen is particularly limiting in this region, with most of the available nitrogen released at the onset of rains, but underutilised by crops during early growth stages (Gosh *et al*., 2007; Kamara *et al*., 2005).

To address these challenges, charcoal, often referred to as biochar when used in soils, has emerged as a promising soil amendment. Historical scientific literature on the use of "charcoal" as a fertiliser date back to the nineteenth century (Thomas and Gale, 2015). When applied to soil, charcoal can enhance nutrient retention by boosting the cation exchange capacity (CEC), thereby reducing nutrient leaching (Ippolito *et al.,* 2015). Biochar improves soil cation exchange capacity (CEC), water retention, and microbial activity (Lehmann and Joseph, 2015; Masiello *et al*., 2015). Recent studies report its ability to reduce nutrient leaching and nitrogen volatilisation, particularly when used alongside chemical fertilisers (Mustafa *et al*., 2022; Adekiya *et al*., 2020).

While several studies have documented the general benefits of charcoal on cereal crops, few have specifically examined optimal application rates for sorghum grown in the Sudan Savanna soils of Nigeria. This knowledge gap restricts the development of region-specific recommendations that could sustainably improve sorghum yield while reducing reliance on costly synthetic inputs.

This study investigates the effect of charcoal on the growth, yield components and grain yield of sorghum and to determine the optimal application rate of charcoal of sorghum, particularly in the Sudan Savanna agroecological zone of Nigeria.

MATERIALS AND METHODS

Experimental Sites

The experiment was conducted during the 2024 rainy season at two locations: the Teaching and Research Farm, Faculty of Agriculture, Bayero University Kano (1°58′47.5″ N, 8°25′13.3″ E; 475 m above sea level), and the National Horticultural Research Institute, Bagauda Kano (11°23′ N, 8°23′ E). The study area experiences temperatures ranging from 18.4°C in winter to 45°C in summer

Soil Sampling

Before land preparation, soil samples were randomly collected from a 0–30 cm depth using an auger at each experimental site and analyzed for their physical and chemical properties. Charcoal samples were also analyzed using standard chemical methods, similar to those used for the soils.

Treatments and Experimental Design

The experimental treatments comprised of four charcoal application rates (0, 5, 10, and 15 t/ha) using a randomized complete block design with three replications.

Cultural Practices

Each gross plot measured 13 m² (3m × 4.5m) with six ridges and ten stands per ridge, while the net plot (3m × 1.5m) included two central rows. Plots and replications were spaced 1m apart. Charcoal powder was procured from local vendors where it is regarded as a waste by-product while the exact pyrolysis conditions were not documented, the material was consistent with typical low-temperature charcoal commonly used in the region, and later it was incorporated into the soil one day before sowing, and all agronomic practices were uniformly applied across plots.

Data Collection

Data were collected from five randomly tagged plants within the net plot (two middle rows) to assess plant height, panicle height, grain yield, and biomass. Plant and panicle heights were measured at physiological maturity using standard measuring tools. Panicles were weighed and converted to kg/ha. A 1000-grain weight was determined from dried samples. Grain yield was measured per net plot using a weighing balance. Stalks were air-dried and weighed to estimate biomass, calculated per hectare using the below formula. The harvest index was derived by dividing grain yield by biomass weight and expressed as a percentage.

$$\text{Biomass weight} = \frac{Stalk\ weight\ of\ net\ plot\ (kg)}{Harvested\ area\ per\ net\ plot\ (sq.m)} \times 10000$$

Data Analysis

Data were subjected to Analysis of Variance (ANOVA) and significant treatment means were separated using Tukey's HSD test at $p < 0.05$ using appropriate statistical software. Correlation analysis was conducted to assess relationships between growth and yield parameters. Graphical representations, including correlation matrix heatmaps and point plots, were generated using Matplotlib and Seaborn libraries (Hunter 2007, Waskom *et al*. 2020). Regression analysis was also performed to predict the optimal charcoal application rate.

RESULTS AND DISCUSSION

Physical and Chemical Properties of Soils at the Experimental Sites

Table 1 presents the soil analysis results from the experimental sites. Soils at BUK were classified as loamy sand with high sand content (81%), while NIHORT soils were sandy loam with more silt and clay. BUK soil had a near-neutral pH (6.77), while NIHORT was more acidic (6.17). Organic carbon was significantly higher at BUK (0.733%) than NIHORT (0.258%), indicating better organic matter content, although total nitrogen was slightly higher at NIHORT (0.252%). Available phosphorus was moderately higher at NIHORT (10.33 mg/kg). BUK had higher potassium (0.24 cmol/kg) and calcium (3.671 cmol/kg), while NIHORT had slightly higher magnesium and sodium. Cation exchange capacity (CEC), reflecting nutrient-holding capacity, was greater at NIHORT (7.072 cmol/kg), but so was exchangeable acidity, indicating stronger acidity.

Table 1: Physical and Chemical Properties of Soils at BUK and NIHORT during the 2024 Rainy Season.

Properties	BUK	NIHORT
pH (H_2O)	6.77	6.17
pH($CaCl_2$)	6.12	5.62
EC (ds/m)	0.084	0.322
OC (%)	0.733	0.258
N (%)	0.224	0.252
P(mg/kg)	9.52	10.332
K(cmol/kg)	0.24	0.18
Ca(cmol/kg)	3.671	2.236
Mg(cmol/kg)	1.719	2.077
Na(cmol/kg)	0.119	0.144
CEC(cmol/kg)	5.314	7.072
EA(cmol/kg)	0.167	0.334
Sand (%)	81	55
Silt (%)	15	33
Clay (%)	5	13
Textural Class	Loamy sand	Sandy loam

Analyzed at the Laboratory of Soil Science BUK

Chemical Properties of Charcoal

Table 2 presents the chemical analysis results of the charcoal sample. The charcoal sample showed a strongly alkaline pH (8.58), indicating its potential to neutralize soil acidity when applied. The electrical conductivity (EC) of 1.154 dS/m suggests a moderate salt level, which should be considered when applied in large amounts. The charcoal had a very high organic carbon content (27.24%), reflecting its richness in organic matter, although its nitrogen content was low (0.08%). However, it contained exceptionally high levels of phosphorus (1419.66 mg/kg), potassium (2421.01 mg/kg), calcium (8084.35 mg/kg), and magnesium (73,276 mg/kg), indicating its potential as a nutrient-rich soil amendment. Moderate levels of ammonium (63.05 mg/kg) and nitrate (56.04 mg/kg) suggest it can contribute some plant-available nitrogen. Sodium content (2.48 cmol/kg) is notable but not excessive.

Table 2: Chemical Properties of Charcoal.

Properties	Charcoal
pH (H_2O)	8.58
EC (ds/m)	1.154
OC (%)	27.24
N (%)	0.08
P($mgkg^{-1}$)	1419.66
K($mgkg^{-1}$)	2421.01
Ca($mgkg^{-1}$)	8084.35
Mg($mgkg^{-1}$)	73276
Na(cmol/kg)	2.48
NH_4(mg/kg)	63.045
NO_3(mg/kg)	56.04

Analyzed at the Laboratory of Soil Science BUK

Effect of Charcoal on Plant Height of Sorghum.

Figure 1 showed that the Charcoal application significantly influenced Plant height of sorghum at BUK and NIHORT ($p < 0.05$). The tallest plants at BUK were observed at 15 t/ha (207.3 cm), while the shortest were at 0 t/ha (188.1 cm). At NIHORT, the tallest height was recorded at 10 t/ha (209.8 cm), statistically similar to 15 t/ha (206.9 cm), with the shortest at 0 t/ha (187.7 cm).

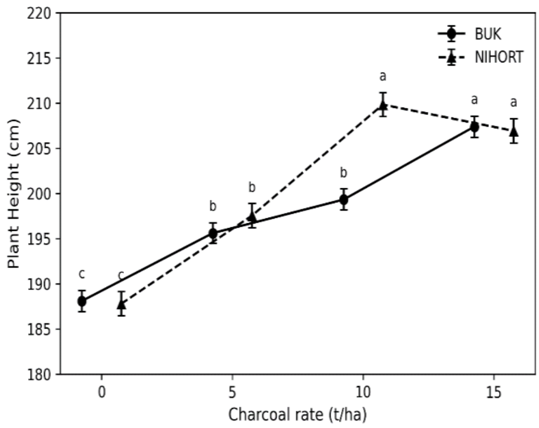

Figure 1. Effect of Charcoal on Plant Height of Sorghum at Buk and Nihort. Means followed by the same letter(s) within treatment columns are not significantly different at a 5% probability level using Tukey's test. Point plots represent the mean values and SE±.

Effect of Charcoal on Panicle Weight of Sorghum.

Figure 2 showed that the Charcoal application significantly affected Panicle weight of sorghum at both BUK and NIHORT ($p < 0.05$). Panicle weight, significant differences were observed with charcoal treatments. At BUK, panicle weight increased from 1810.81 kg/ha at 0 t/ha to 2796.37 kg/ha at 10 t/ha. At NIHORT, the highest weight (2958.96 kg/ha) was recorded at 10 t/ha, also significantly higher than 0t/ha (2235.63 kg/ha).

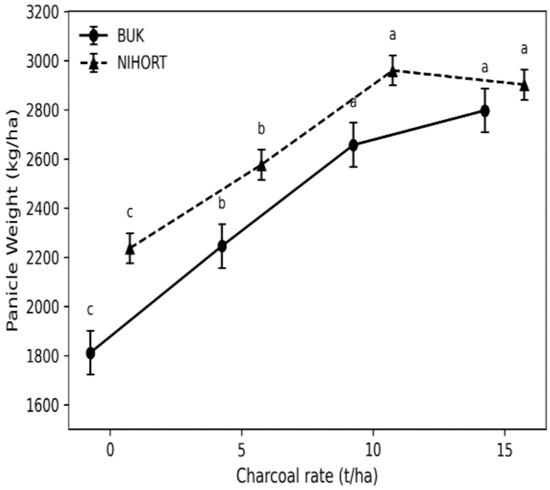

Figure 2. Effect of Charcoal on Panicle Weight of Sorghum at Buk and Nihort. Means followed by the same letter(s) within treatment columns are not significantly different at a 5% probability level using Tukey's test. Point plots represent the mean values and SE±.

Effect of Charcoal on 1000 Grain Weight and Grain Yield of Sorghum.

Figures 3&4 showed that the Charcoal application had a significant effect ($p < 0.05$) on both 1000 grain weight and grain yield of sorghum at BUK and NIHORT. At BUK, the highest 1000 grain weight (45.18 g) was recorded at 10 t/ha, statistically similar to 15 t/ha, while the lowest (37.56 g) was at 0 t/ha. At NIHORT, the heaviest grains (47.27 g) were at 15 t/ha, and the lightest (38.83 g) at 0 t/ha. Grain yield also increased significantly with charcoal. At BUK, the highest yield (2244.44 kg/ha) was at 10 t/ha, statistically similar to 15 t/ha, while the lowest (1435.19 kg/ha) was at 0 t/ha. At NIHORT, 10 t/ha produced the highest yield (2686 kg/ha), also statistically similar to 15 t/ha, and the lowest (1859.26 kg/ha) occurred at 0 t/ha.

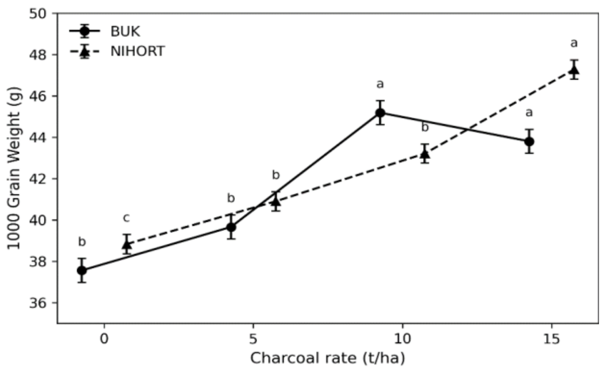

Figure 3. Effect of Charcoal on 1000 Seed Grain Weight of Sorghum at Buk and Nihort. Means followed by the same letter(s) within treatment columns are not significantly different at a 5% probability level using Tukey's test. Point plots represent the mean values and SE±.

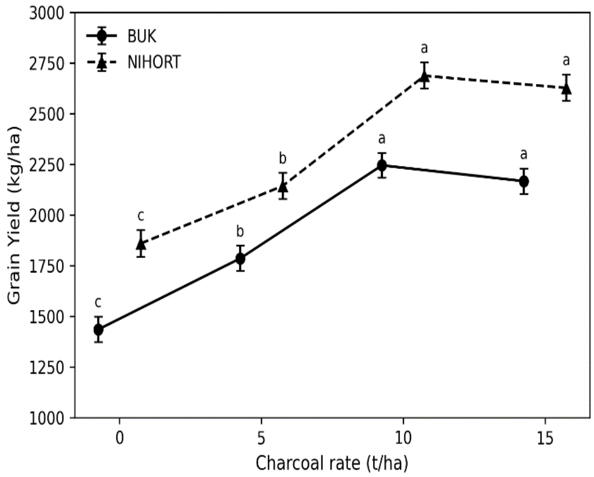

Figure 4. Effect of Charcoal on Grain Yield of Sorghum at Buk and Nihort. Means followed by the same letter(s) within treatment columns are not significantly different at a 5% probability level using Tukey's test. Point plots represent the mean values and SE±.

Effect of Charcoal on Biomass Weight and Harvest Index of Sorghum.

Figures 5&6 showed that the Charcoal application significantly affected biomass weight and harvest index of sorghum at both BUK and NIHORT ($p < 0.05$). At BUK, the highest biomass weight (5391 kg/ha) was recorded at 10 t/ha, statistically similar to 15 t/ha, while the lowest (2355.56 kg/ha) occurred at 0 t/ha. At NIHORT, biomass peaked at 5807.41 kg/ha with 10 t/ha, also statistically similar to 15 t/ha, and was lowest (2846.30 kg/ha) at 0 t/ha. For harvest index, the highest values were observed at 0 t/ha: 63.46% at BUK and 68.33% at NIHORT, while the lowest indices were at 15 t/ha (41.86%) at BUK and 10 t/ha (45.75%) at NIHORT—both statistically similar to other higher charcoal treatments.

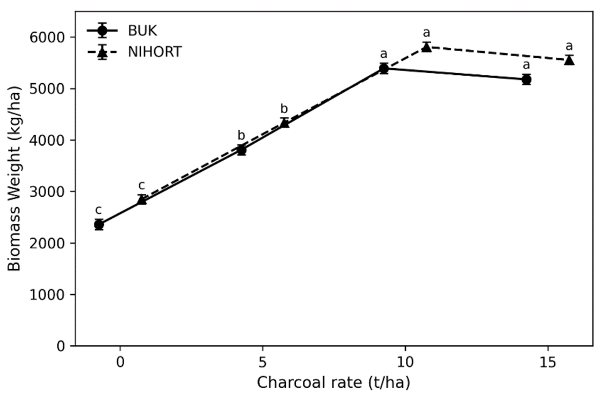

Figure 5. Effect of Charcoal on Biomass Weight of Sorghum at Buk and Nihort. Means followed by the same letter(s) within treatment columns are not significantly different at a 5% probability level using Tukey's test. Point plots represent the mean values and SE±.

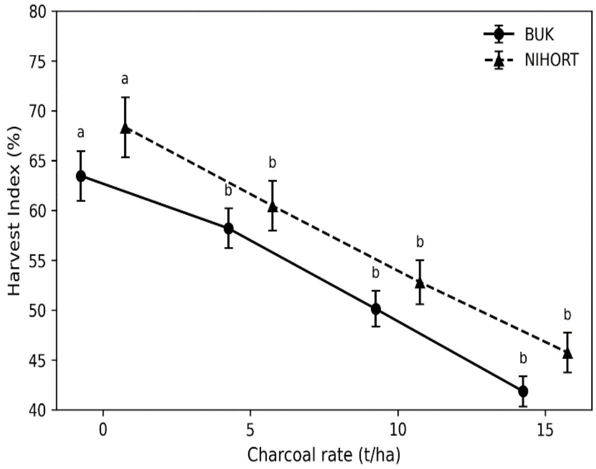

Figure 6. Effect of Charcoal on Harvest Index of Sorghum at Buk and Nihort. Means followed by the same letter(s) within treatment columns are not significantly different at a 5% probability level using Tukey's test. Point plots represent the mean values and SE±.

Simple Correlation Matrix of Growth and Yield Parameters of Sorghum.

Figures 7&8 showed the correlation analysis at BUK and NIHORT which revealed that grain yield of sorghum was significantly and positively correlated with several growth and yield components, including plant height, panicle weight, panicle length, and biomass weight**.**

At both sites, grain yield showed a negative correlation with days to 50% maturity and harvest index, indicating that earlier-maturing plants and those allocating less biomass to grain had lower yields. The results suggest that improved vegetative growth and panicle development were key drivers of higher grain yield, while delayed maturity and higher harvest index were associated with reduced yield under charcoal treatment.

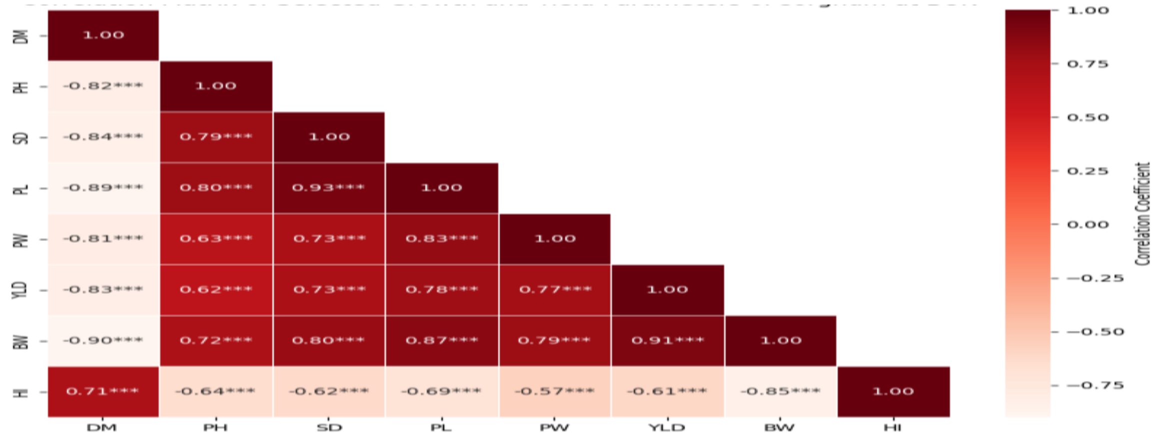

Figure 7. Pearson Correlation Matrix at BUK. DM = Days to 50% Maturity, PH=Plant Height, PL = Panicle Length, SD = 1000 Seed Grain Weight, PW = Panicle Weight, GY = Grain Yield, BMW = Biomass Weight, HI = Harvest Index. *= r-value significant at (p≤0.05), **= r-value significant at (p≤0.01), ***= r-value significant at (p≤0.001), n = 12, Df=(n-2) =10.

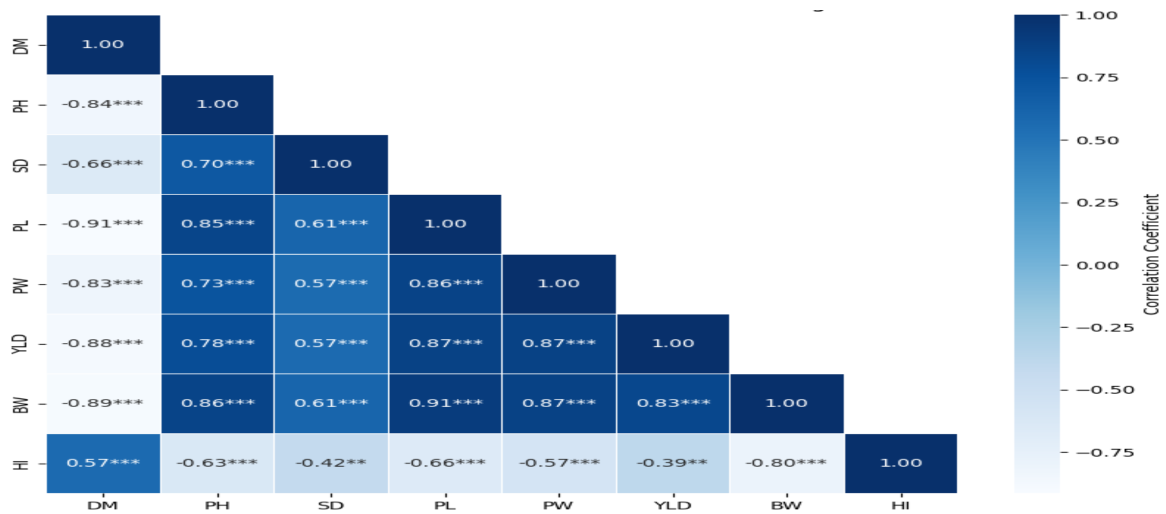

Figure 8. Pearson Correlation Matrix at NIHORT. DM = Days to 50% Maturity, PH=Plant Height, PL = Panicle Length, SD = 1000 Seed Grain Weight, PW = Panicle Weight, GY = Grain Yield, BMW = Biomass Weight, HI = Harvest Index. *= r-value significant at (p≤0.05), **= r-value significant at (p≤0.01), ***= r-value significant at (p≤0.001), n = 12, Df=(n-2) =10.

Regression of Charcoal against Grain Yield of Sorghum.

At figure 9 linear regression analysis showed a significant positive relationship between charcoal application rate and grain yield of sorghum at both BUK and NIHORT ($p < 0.0001$).

At BUK, the regression equation was GY = 53.07x + 1509.81 with $R^2 = 0.56$, indicating that each 1 t/ha increase in charcoal resulted in a 53.07 kg/ha increase in grain yield.

At NIHORT, the equation was GY = 56.82x + 1901.67 with $R^2 = 0.57$, showing a 56.82 kg/ha increase in grain yield per unit of charcoal applied. These results confirm that charcoal application had a strong and consistent positive effect on sorghum yield across both sites.

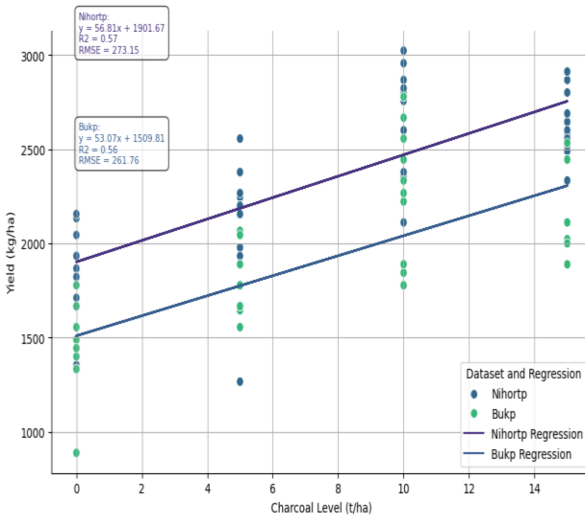

Figure 9. Regression of Charcoal against Grain Yield of Sorghum at BUK and NIHORT during the 2024 Rainy Season.

DISCUSSION

Effect of Charcoal on Growth Parameters of Sorghum

The significant differences in plant height across charcoal application levels may be attributed to charcoal's adsorption capacity, which enhances nitrogen retention and availability. This finding aligns with Steiner *et al*. (2007), who reported increased plant height with charcoal use, and Khan *et al*. (2022), who observed similar effects with biochar and farmyard manure.

Effect of Charcoal on Yield Parameters of Sorghum.

The significant improvement in panicle weight, grain yield, and biomass weight of sorghum following charcoal application may be due to charcoal's ability to enhance soil nutrient retention, reduce leaching, and improve overall plant nutrition. This supports findings by Salih *et al*. (2019), who reported that charcoal combined with nitrogen significantly improved soil properties and crop performance. Similarly, Thapa *et al*. (2024) found that coal char combined with manure (CC650M) significantly increased grass biomass over three years, highlighting charcoal's sustained positive impact on yield. The drastic drop in harvest index is also supported by the works of Jin *et al*. (2024) demonstrated that continuous biochar application effectively reduced reactive nitrogen losses in paddy fields, but did not enhance rice yield or harvest index its influence on crop partitioning may favor vegetative growth over grain production, thereby reducing harvest index.

The 10 t/ha charcoal rate offers an optimal balance improving soil structure, water retention, and nutrient availability without causing nutrient dilution or pH disruption seen at higher rates. But excessive application can reduce efficiency, consistent with Liang *et al.* (2010) on biochar's nuanced effects on nutrient cycling.

Conclusion and Recommendations

The study demonstrated that charcoal application significantly improved sorghum performance. The 10 t/ha charcoal treatment resulted in heavier panicles, greater biomass, and higher grain yield compared to the control (0 t/ha) confirming its positive effect on crop productivity. Applying charcoal at a rate of approximately 10 t/ha is recommended for sorghum production on Sudan Savanna soils. Farmers should incorporate charcoal evenly into the root zone and combine it with balanced fertilizer application to maximize efficiency.

Further studies should Investigate whether repeated or sustained charcoal application maintains its benefits or alters soil chemistry over multiple growing seasons, evaluate whether the yield gains from 10 t/ha justify the costs of producing, transporting, and applying charcoal under smallholder farming conditions and to assess potential issues such as carbon footprint, biomass sourcing for charcoal production and effects on soil biodiversity to ensure recommendations are both economically and ecologically sustainable.

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Authors' Contributions

A.S.A conceptualized the study. S.U.Y supervised the experiment and provided technical guidance. A.S.A and A.M.G collected data, performed data analysis, and wrote the first draft of the manuscript. A.M provided inputs, performed literature searches and reviewed the first draft of the manuscript. All authors read and approved the final draft of the manuscript.

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