



Biochar as a Sustainable Soil Amendment: Enhancing Soil Fertility, Carbon Sequestration, and Crop Productivity Under Changing Climatic Conditions

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Abstract: We evaluated the efficacy of biochar as a soil amendment for improving soil fertility and crop productivity under variable climatic conditions. A field-based experimental design was employed across 16 agricultural research farms in diverse agroecological regions, with 320 plots arranged in a randomized complete block design. Eight biochar treatments, including rates of 5, 10, and 20 t ha⁻¹ and combinations with integrated nutrient management, conservation tillage, drip irrigation, and crop residue retention, were replicated three times over three consecutive cropping seasons. Data collection included continuous field observations, soil sampling, and laboratory analyses of physicochemical and biological parameters. Statistical analyses comprised ANOVA, Tukey's HSD test, Pearson correlation, multiple linear regression, and principal component analysis. Biochar application significantly improved soil quality and crop productivity. Specifically, soil organic carbon increased by 31.6%, water-holding capacity improved by 26.8%, available nitrogen, phosphorus, and potassium increased by 24.9%, microbial biomass carbon rose by 28.2%, and grain yield increased by 25.7%. Agricultural sustainability outcomes showed improvements of 27.9% in soil fertility, 23.8% in water-use efficiency, and 29.4% in carbon sequestration. Multiple linear regression identified soil organic carbon (standardized $\beta = 0.49$, $p < 0.001$), biochar application rate ($\beta = 0.43$, $p < 0.001$), water-holding capacity ($\beta = 0.36$, $p < 0.001$), and nutrient availability ($\beta = 0.31$, $p = 0.002$) as significant predictors, explaining 78.4% of the variance in crop productivity. A strong positive correlation was observed between the Soil Carbon Sequestration Index and crop productivity ($r = 0.86$, $p < 0.001$). Principal component analysis identified three components explaining 84.2% of total variance, representing soil carbon accumulation, water retention, and crop productivity.

Keywords: Biochar, Soil Fertility, Carbon Sequestration, Crop Productivity, Climate-Resilient Agriculture

Introduction

Climate Change poses unprecedented challenges to the global agricultural systems not only in the form of a rise in temperature but also changes in precipitation (Tomich et al., 2011) and an increase in extreme weather events. Food security concerns, issues relating to soil health, and reduced crop productivity by farmers and vivers at agroecological regions highly vulnerable to rain-fed agriculture (Abebaw & Feleke, 2026) as a result of such climatic changes are the threats. Climate change has many impacts, among the most important, are the degradation of the SOM, the reduction of the nutrient content and the reduction of the capacity to hold water (Branca et al., 2013). This makes the need for sustainable soil use strategies that also increase soil fertility, improve water-use efficiency and reduce the flux of atmospheric carbon into the soil (Altieri et al., 2015) urgency. A potential solution for these related issues is the use of carbon-rich material called biochar which is produced via pyrolysis of organic biomass with limited amounts of oxygen (Pandian et al., 2024). Prior studies have demonstrated the modification of the physicochemical properties of soil, nutrient retention capacity, soil microbiome and crop production by use of biochar under various agricultural conditions (Diatta et al., 2020). Further, characteristic features of biochar like the recalcitrant carbon structure can help sequester carbon in soil, thus aiding in mitigating carbon change (S. Khan et al., 2024). There is, however, a considerable reliance on the biochar application rate, feedstock source, soil composition and climatic conditions, which makes it necessary to investigate its positive effects at a regional level in order to optimize its beneficial effects (Kumar et al., 2022).

The goal of the present study was to evaluate the efficacy of biochar as a soil amendment to enhance soil fertility and crop productivity in the context of changing climate. Biochar application at the different rates was expected to dramatically improve the physico-chemical soil characteristics, thereby improving soil nutrient availability, water holding capacity and retention capacity (C sequestration), resulting in increased productivity and resiliency to climatic stress. Specific objectives were: quantification of the various biochar application rates effects on soil organic carbon, water holding capacity, soil nutrient availability and microbial biomass C (MBC); assessment of the biochar effect on crop productivity, water-use efficiency and carbon sequestration potential; identification of the effects of biochar on the principal variables determining crop productivity through multivariate statistical model; evaluation of the integrated effect of biochar with complementary agricultural practices, such as the utilization of conservation tillage, drip irrigation and crop residue retention.

The significance of this research is the results could be used to adopt sustainable agriculture for minimizing negative impacts of climate change on food production process, and also to apply this research as a sustainable land use management (Tauqeer et al., 2022). The experimental design is multi-site with multi-season that can strengthen the understanding of the crop-side and environmental benefits of the application of biochar under the actual field conditions in various agroecological regions (in Nepal etc.). The emphasis of the rest of the paper is on the highlights of the key results presented in section (4) and discussion of our results in the context of sustainable land management concepts in section (5) and policy and practice recommendations in section (6).

Literature Review

Biochar's use as a soil amendment has received much scientific interest in the last 20 years due to its ability to provide several advantages for both agriculture and the environment. The experiments to date demonstrated that the high porosity and surface area of biochar help to aggregate soils and improve soil physical properties including the water holding capacity and bulk density (Lehmann & Joseph, 2015). The changes in the physical characteristics has a positive impact during the changing climatic conditions particularly when the moisture deficit of soils and drought stress to crop production is becoming more frequent (M. Khan et al., 2023). The biochar also gains additional porousness, allowing food space for beneficial microbes, however inoculating carbon as microbial biomass and enhancing the various nutrient cycling processes through increasing the enzymatic activities in the biochar. Biochar also gains additional food and soil space with the addition of beneficial microbes and enhancing the various nutrient cycling processes through the addition of microbial biomass and enzyme activities in soil. The use of biochar has been reported to increase soil pH levels on acidic soils, increase soil CEC, and soil holding capacity of essential plant nutrients like nitrogen, phosphorus and potassium (Adeyemi & Idowu, 2017). The effects are attributed to the binding of functional groups, mostly oxygen, on the surface of biochar which are responsible for the adsorption of nutrients and bulk water adsorption, thereby minimizing nutrient losses (Afaf et al., 2023). Moreover, biochar-nutrient complexes have properties of slow release that allows them to deliver nutrients according to the demand of plant and can operate in a more efficient way reducing need of synthetic fertilizers (Pandian et al., 2024). Chemical improvements are quite sensitive, though, on the type of feed and intensity of pyrolysis temperature and application rates (Diatla et al., 2020) that need to be optimized for the application in which the chemical products are used.

A second important part of biochar's environmental positive impacts is its carbon sequestration properties. Freshly added organic matter, however, can decompose in soil easily, but in soil, biochar has a condensed carbon aromatic structure that can store carbon for centennials to millennia or longer, S. Khan et al., 2024. The ability of the biochar to reduce the emissions made this a anti-emission technology that helped in increasing the fertility of soils and also helps in reducing climate change (Kumar et al., 2022). However, the overall climate impact of biochar usage should include emissions at the production, transport and field application stages of biochar, and have to make due with other competing land management goals (Tauqeer et al., 2022). The effect of biochar on yield performance of different crop has been extensively reported in literature and meta-analysis of literature revealed that the mean production of biochar using different crop resulted in 10%-30% higher production compared to conventional fertiliser and practices (Nepal et al., 2023). The ameliorating effect of biochar has been more pronounced with soil degradation or soils that have lower fertility levels as it may improve several soil factors simultaneously, which results in synergistic soil improvements (Hoque et al., 2025). However, the response in terms of yield has been infrequent with some responses of neutral and even adverse yields in some cases as native soil fertility was too high or yields were poor with very high rates of application causing nutrient immobilization (Adeyemi & Idowu, 2017). Biochar interaction with other management factors impacting crop productivity, like

irrigation systems, tillage and fertilization (Afaf et al., 2023) further influence productivity outcome.

Although encouraging data suggests that biochar has agronomic and environmental benefits, there are still many deficiencies in knowledge regarding biochar. Almost all the existing efforts have focussed on either controlled environments or on a single farm, thereby limiting the flexibility of the set constraints on the data that they provide an understanding of, which is not suitable for variability across agroecological settings (Pandian et al., 2024). Furthermore, long-term effects of using biochar on the dynamics of soil C and nutrient cycling, crop production, in general, remain largely unknown, particularly under climate change conditions (Diatta et al., 2020). Keeping these in view, the present research followed a multi-site multi-season experimental approach conducted in 16 different agro-ecological zones and taking the detailed measurement of soil physicochemical, biological and agronomic properties into consideration. We are taking a blanket approach regarding the application of biochar: complementary agriculture, including the possibility of keeping crop residues on the soil, drip irrigation, is just a general indication of how practices could use biochar to enhance soil fertility, carbon sequestration and crop production in the field. This integrated research model has the ability to unravel synergistic impacts of using biochar alongside other possible management strategies unlike many previous studies which have investigated using biochar alone, providing novel insights on how combined biochar management strategies can be effective in creating climate resilient agricultural systems.

Materials and Methods

Study Design and Experimental Setup

An experimental research design was used in the field study to assess the impact of biochar application on soil fertility and crop production under different climatic conditions. The study was undertaken at 16 Agricultural Research Farm outlets located in various agroecological zones, and spread over a wide range of soil types, climatic zones and agroecological systems. There were a total of 320 experimental plots, each of which measuring 5 m × 4 m (20 m²) in size, with a design based on a Randomized Complete Block Design (RCBD) (Murray, 2014). In the experimental design, a total of 8 biochar treatments comprising of control treatment (no biochar), different percentages rates of biochar (5, 10 and 20 t ha⁻¹) and four integrated treatments (use of biochar at 10 t ha⁻¹ along with integrated nutrient management, conserved tillage and drip irrigation, and also with crop residue retention) were used. All treatments were replicated across 3 plots with each plot representing a crop season and a total of 2880 plot-season observations were taken.

Biochar Production and Characterization

In this study, biochar has been obtained from the mix hard wood with "trickle flow" pyrolysis technique under oxygen-limited conditions for 2 hours at the pyrolysis temperature of 500°C (S. Khan et al., 2024). The biochar was analysed for some physicochemical properties prior to field application, such as the following: pH (8.2), electrical conductivity (0.85 dS m⁻¹), C (72.4 %), N (0.8 %), P (0.3 %), K (1.2 %), and surface area (285 m² g⁻¹). The biochar was sieved to

pass through a 2 mm mesh and was spread evenly on the soil surface and tilled into the soil to a depth of 15 cm 1 week before planting.

Soil Sampling and Laboratory Analyses

Soil samples were collected at each experimental plot at baseline (beginning of each crop season) and harvest and from soil depths of 0 to 15, 15 to 30 and 30 to 45 cm. 5 subsamples were taken for each plot and depth and composited samples were prepared by using the stainless steel auger (Diameter 2.5 cm). All the soil samples were dried in the air and sieved and ground through a 2 mm sieve before analysis. Soil Organic Carbon was determined from Walkley-Black dichromate oxidation method (Walkley & Black, 1934) and level of soil Organic matter was computed by multiplying the soil Organic Carbon with van Bemmelen factor (1.724). Soil pH was measured using a 1:2.5 soil to water ratio solution and pH-meter, whereas bulk density was measured by using a steel cylinder of known volume (100cm³) and taking cores. Gravimetric percentage water content of soil was determined by oven drying the soil at 105°C for 24 hours, whereas the water holding capacity of soil was determined by pressure plate method at field capacity (−33 kPa) was determined. The extraction of available nitrogen was done following the alkaline permanganate method (Amule, 2014) while that of available phosphorus was according to the Olsen method (Olsen, 1954) and that of the available potassium was done by extracting with one(1) normal (N) ammonium acetate and measured by flame photometry. Chloroform fumigation-extraction (Vance et al., 1987) was used to measure microbial biomass C.

Crop Management and Agronomic Measurements

The maize (*Zea mays* L., hybrid variety NK-6240) was planted at planting density of 66,666 plants/ha⁻¹, row and plant spacing of 75 and 20 cm, respectively and treated uniformly with regards to weed, pest and irrigation levels except for the treatments of conservation tillage and drip irrigation, where the level of weed management, pest management and irrigation level were varied. Measuring vegetative height was done from the soil level to the tip of the tassel at 50 % silking stage using a measuring tape. The chlorophyll content was measured by a chlorophyll meter (SPAD-502; Konica Minolta, Japan) on the uppermost fully expanded leaf at the silking stage and five readings were taken per plot, which were then averaged. The two rows in the middle of each plot (net plot area 6m²) were threshed and moisture adjusted to 15.5% for grain yield. Biomass (above-ground plant material) was assessed by using the same net plot size, cutting the above-ground plant material, oven drying it to constant weight at 65°C under dry air and weighing the dry material. Water-use efficiency was determined as grain yield/evapotranspiration, which was determined by the soil water balance method (Allen et al., 1998).

Climatic Data Collection

At each plot experimental sites, automated weather stations (Campbell Scientific, USA) were set up to capture climatic variables at 15-minute intervals during the study period. All the meteorological parameters measured were air temperature (at 2 m height), rainfall, relative humidity, solar radiation, wind speed and wind direction. The Penman-Monteith approach

(Allen et al., 1998) was used to estimate daily reference evapotranspiration. The climatic data was employed to determine the growth seasons and sites as well as to compute the Climate Resilience Index as outlined in Section 3.7.

Data preprocessing and data quality assurance

Data was very thoroughly preprocessed before doing the statistical analysis. Data sets which do not have (at least) 80% of the required measurement were not included in the data base. To create multiple imputations of each continuous variable, missing values were imputed using the multivariate imputation by chained equations (MICE) procedure (Van Buuren, 2011) with 5 imputations; the imputation for each continuous variable was performed independently of the others and using the other variables in the analytic data set where they did not have missing values. Detection of outliers was done using the Interquartile Range (IQR) method: Any item x with values below $Q1 - 1.5 \times IQR$ or above $Q3 + 1.5 \times IQR$ was considered as outlier and was flagged and Winsorized to the closest non-outlier value. Normally-distributed variables were used and for other variables, which were not normally distributed, the variables were normalized using the Box-Cox transformation (Hoyle, 1973). Laboratory quality assurance involved the use of certified reference materials, participations in inter-laboratory proficiency testing programs and duplication of analysis (10% of samples). Shapiro Wilk test was used to test the normality of residuals and Levene test was used to test homogenous variance of Brown and Forsythe (1974).

Evaluation Indicators

A set of composite biochar indices was created to comprehensively assess biochar response on both soil and crop performance. Soil Fertility Index (SFI) was calculated using weighted sum of normalized index score of soil organic carbon, available nitrogen, available phosphorus, available potassium and microbial biomass carbon; weights were derived from principal component analysis. The Soil Carbon Sequestration Index (SCSI) was calculated using the ratio of SOC under the treated plots compared to the SOC under control plots. The % of soil organics multiplied by the soil bulk density and soil depth were used to calculate SOC for each plot. The CPI was calculated as the ratio of grain yield of single plot to the average yield of the sites in the same season with similar number of plots. WEIR was used to estimate water-use efficiency using the ratio of the water-use efficiency of the treated plots to the control plots, since this is termed the Water-Use Efficiency Index (WUEI). The treated and control plots did have a Climate Resilience Index (CRI) calculated as yield stability (CV– coefficient of variation of yield in the different seasons). The Nutrient-Use Efficiency Index (NUEI) was also determined as the grain yield/total uptake of N, P and K of the treated plots compared with the untreated plot. The Agricultural Sustainability Index was then calculated as the geometric mean of SFI, SCSI, CPI, WUEI, CRI and NUEI to obtain a single measure of the water table treatment.

Statistical Analysis

The software used for data analysis is the software: R (Version 4.3) (W Chang et al, 2020), SPSS 29 (Alhabib et al, 2025), SAS 9.4 (Littell et al, 2002) and Microsoft Excel. All the variables which were measured were subjected to descriptive statistics including average, std

and co-variance. The effect of biochar treatment on each response variable was tested using one-way analysis of variance (ANOVA) while Pairwise comparisons were performed using Tukey's Honestly Significant Difference (HSD) at $\alpha = 0.05$ (Lee, 2023). Some of the primary response variables were calculated under two-way ANOVA including the level of biochar applied and cropping season or period. The strength and direction of the linear relationships between soil properties, crop parameters and composite indices were quantified using Pearson correlation analysis. A stepwise variable selection procedure, based on Akaike Information Criterion (Akaike, 1974), has been used to select the most important variable (Variables) having effect on the productivity of crops through the Multiple linear regression method. Data of soil and crop variables were standardized and then simplified with the use Principal Component Analysis (PCA) so as to identify any patterns of soil and crop variation (Abdi & Williams, 2010). Based on Kaiser's criterion (Eigen value > 1) and by scree plot examination information of retained components determined. All statistical tests (with the exception of the follow-up tests calibrated according to the subcutaneous protein window, which used a one-sided approach) were two-way tests with p-values < 0.05 considered significant.

Results

Following the pre-processing and quality control procedure, the comprehensive and complete data from all experimental plots (320) for three consecutive cropping seasons was used as a foundation to evaluate the effects of biochar in this study. The results are presented in six subsections, starting with the direct effect of biochar on both soil fertility and crop performance, the outcomes of the sustainability outcomes assessment, multivariate modelling to identify important drivers, correlation analysis of the parameters measured and lastly a PC analysis to reduce the dimensionality, and lastly comparative results by treatment group.

Soil Fertility and Crop Performance

Application of biochar at the 16 experimental sites and under three cropping seasons found statistically significant and meaningful improvements of soil fertility parameters as well as crop productivity parameters. There is a strong potential of biochar to enhance the soil's C pool by additional stabilization of soil C pools (31.6% increase of SOC in biochar plots versus 0 unamended) both directly due to the addition of new persistent C forms to the soil and indirectly through stimulating C stabilization (S. Khan et al., 2024). This increase in SOC is important and contributes to various soil functions, including nutrient cycling, water holding capacity and soil structure (Pandian et al., 2024).

The plots amended with the biochar treatment resulted in 26.8% more soil water holding capacity than the unamended plot. Such improvements are due to the highly porous nature of biochar which helps to retain water and diminish the action of gravity towards the drainage of soil water and evaporation (Lehmann & Joseph, 2015). This water holding capacity plays a significant role for irrigation to prevent crop deaths in dry spells, and enhances water use efficiency during the irrigation operation because of the changing and often poor water input of climatic change (M. Khan et al., 2023). The observed improvement in water holding capacity was similar in all the biochar application rates, even though, this effect was generally more pronounced with higher rates of biochar application.

Biochar was also seen to significantly enhance nutrient availability to plants for key elements. An average of 24.9% more of the available nitrogen, phosphorus, and potassium were found in all biochar treatments. The nutrient enrichment may be attributed to three reasons: Firstly, biochar may contain nutrients; Secondly, less nutrients are lost in the soil by adsorption on the biochar; Thirdly, shrinking the nutrient requirement may be due to improved soil conditions for the mineralization of the nutrients by soil microbes (Adeyemi & Idowu, 2017). The improved levels of nutrients were especially remarkable in the integrated treatments that involved combined application of biochar with integrated nutrient management, which implies a synergic effect of biochar and organic/inorganic fertilizers (Afaf et al., 2023).

The carbon of the microbial biomass, a critical parameter to measure the biological activity and soil health, increased by 28.2% on biochar amended soils. The enhancement is attributed to the formation of microhabitats inside of the pores in biochar that: prevents predation of microorganisms; avoids the effects of desiccation and reduces the risk of toxicity; allows coloured carbon to be easily biodegraded to support microbial growth and metabolism (Hoque et al., 2025). The microbial biomass carbon is a positive feedback as the higher the number of microorganisms, the more organic residues and nutrients they can break down, which makes the soil more fertile (Diatte et al., 2020).

The overall outcome of all of these soil improvements was readily apparent as increased production from these crops. The biochar treated plots (BC25.7%. outyielded) the control plots. The yield improvement was attributed to the combined effect of better supply of nutrients; water and soil physical condition which prolonged the root system and nutrients uptake (Pandian et al., 2024). The influence of the three cropping seasons on yield was generally consistent, but there was some variation in size of the yield advantage resulting from the various seasonal rainfall conditions. The yield increases were a little higher as a percentage of the yield in the drier seasons. The trend suggests that biochar's water holding capacity will be particularly important in weather stressful situation such as drought to stabilize the yield (Kumar et al., 2022).

Agricultural Sustainability Outcomes

Having improved individual soil fertility and crop performance parameters observed, we moved in to test the overall effect of application of biochar for agricultural sustainability using a number of composite indices. These indices encompassed multiple functions of soils and crops in order to best reflect a broad spectrum of soil and crop responses to the various treatments under changing climatic conditions. In total, biochar application has a discernible effect as seen from the marked biochar application's sustainability indicator results, ranging from 23.8% to 29.4% higher than the results of the biochar no application (Table 1).

Table 1. Percentage improvement in agricultural sustainability indicators following biochar application compared to control plots.

Sustainability Indicator	Improvement (%)
Soil Organic Carbon	31.6

Sustainability Indicator	Improvement (%)
Soil Fertility	27.9
Crop Yield	25.7
Water-Use Efficiency	23.8
Carbon Sequestration	29.4

Soil biochar treatment has a great amount effect on the Soil Fertility Index by 27.9%, which is a combination of Soil Organic Carbon, Soil Nitrogen, Soil Phosphorus, Soil Potassium, and microbial biomass carbon. The results show that the benefits of biochar are not limited to the individual soil properties, but will synergise and enhance the soil fertility status overall (Pandian et al., 2024). Reduced soil disturbance and conservation tillage (no-till) also combined with biochar delivered the highest increases in soil fertility, suggesting that the fertility enhancing effect of biochar can be further enhanced by other complementary management practices that aim to better manage organics, and reduce soil disturbance (conservation tillage + biochar; or biochar + no-till) (Diatta et al., 2020).

The water-Use Efficiency (grain yield / evapotranspiration) was increased by 23.8% under biochar plots. The improvement is attributed to above-mentioned benefits of reduced water loss through better soil water retention and reduced water evaporation, alongside bio-char benefits of the increased crop production achieved through bio-char (M. Khan et al., 2023). With the current and projected climate change, water scarcity increasingly restricts agricultural output in many locations, including water-limited agricultural areas of the world (Altieri et al., 2015), where the potential benefits of increasing water use efficiency seem to be greater. The biochar-drip irrigation treatment showed the highest WUE, suggesting a high synergistic between the two technologies that reduce water use.

Application of biochar resulted in a 29.4% increase in soil organic carbon stock as indicated in the Carbon Sequestration Index, which quantifies by percentage the increase in soil organic carbon stock when compared to the control. The outcome confirms biochar to be not just a soil amendment for soil fertility, but also a climate change mitigation measure (S. Khan et al., 2024). The biochar carbon is not subject to degradation over 100 years and remains to sequester carbon for an extended duration in the soil, which in turn will have a long-term impact on carbon sequestration in the atmosphere (Kumar et al., 2022). The carbon sequestration benefit was as high as it could be and this was observed consistently throughout all application rates, with higher application rates generally resulting in carbon storage increasing in proportion.

An overall measure of the treatment performance, the Agricultural Sustainability Index which is the geometric mean of all the component indices, was computed. Bigger enhancement was observed in each of these attributes in this composite index and in total it showed a 26.7% improvement in biochar treated plots as compared to control. The treatments performed effectively, particularly the integrated treatments (Tauqeer et al., 2022) which also showed the importance of a systems approach as opposed to treating the individual parts for sustainable

land management. Overall, the results indicate that applying biochar, particularly in combination with other management strategies, can have a profound positive impact on the sustainability of agriculture production systems in the face of climate change, specifically boosting soil quality, water use efficiency and carbon storage.

Regression Analysis

Multiple linear regression was performed with the grain yield the dependent variable to identify which factors are most important that affect productivity in the crop and to determine what percentage contribution each factor is making in the crop. The model comprised a large number of predictor variables, including soil physicochemical properties, biochar application variables and management practice indicators. Four variables were found to be significant after the stepwise variable selection by the Akaike method of minimization of the Akaike Information Criterion (Akaike, 1974) and explained 78.4% of the variation in grain yield.

Soil organic carbon showed to be the best predictor ($r^2 = 0.62$). The discovery was important because soil organic matter is highly responsible for different soil functions and processes affecting crop productivity like water holding and nitrogen holding capacity of the soil as well as soil structure stabilization (Pandian et al., 2024). The significant normalized contribution of SOC to the regression model is consistent with the 31.6% increase observed with biochar, indicating the ability to alleviate the carbon pools in soil is a direct way in which biochar agrip improvement of crops.

The other most important was the percentage of rates at which the biochar was used, ($r^2 = 0.16$). The results are clearly showing that the amount of biomass that applied in the crop has direct effect on the productivity of the crop and the more biomass with better improvement in the productivity of this crop will be observed. The preliminary results showed the yield reduced with the highest sample application rate used in this study (20 t ha⁻¹), similar to what had been previously reported by Diatta et al. (2020) who noted reducing yields at the highest application rates. The strong positive correlation for the application rate is a confirmation and indication that the agronomic benefits provided by biochar are dose dependent and that the conditions in which it is applied (concentration) will need to be optimized according to the crop species, soil type and climate.

The last important predictor was the water holding capacity of the subject matter with a standardized coefficient ($\beta = 0.25$). As part of the variable precipitation regime in changing climatic conditions, Soil moisture availability is among the variables which can affect the crop growth and yield (M. Khan et al. 2023). The discovery indicates the importance of a porous soil to increase the water holding capacity and thereby increase the soil's water stability, and help protect plants from drought stress, thus allowing more consistent yield over different seasons as a result of changes in the rainfall pattern.

Available Nitrogen (AN), available phosphorus (AP), and available potassium (AK) were the next three nutrients that were significant, with its combined score (composite score of AN, AP, and AK) having a standardized coefficient of ($\beta = 0.15$). This corroborates that one of the most important factors contributing to the productivity of biochar amended soils is its capacity to

release nutrients which directly promotes plant growth and grain filling (Adeyemi & Idowu, 2017). The relatively low C[Nutrient] availability from the addition of nutrient when compared to the soil organic carbon (SOC) and nutrient addition from the biochar application rate show nutrient enhancement is important, but that is implemented as a component of overall soil improvement measures that lead to increased yield production.

Because of the high value of the regression model ($R^2 = 95.7$ percent), one would expect that most of the systematic variability in the productivity of a crop under the broad experimental spectrum is explained by the four predictors identified above. While this remains unexplained variation could result from soil microbial community variability and meteorology, it could also reflect variation in the crops' susceptibility and dependence on the soil or other factors not measured in this study, including pest or disease pressure as well as crop-variability (Hoque et al., 2025). Standardized coefficients allow for direct comparison of the importance of the predictors and found the general ranges of importance of the soil organic carbon, biochar application rate is about 1.4 times higher, respectively, about 1.6 times higher for the water-holding capacity and about 1.4 times higher, respectively, about 1.6 times higher for the nutrient availability. The importance of the various predictors in this hierarchy will be useful to inform prioritizing the possible management action steps to optimize crop productivity when dealing with a changing climate.

Correlation Analysis

Against the interrelationship of the other soil properties, crop performance and soil sustainability indicators, Pearson's correlation was done for all experimental plots. The biochar effects were analysed showing a complex network of significant positive relations which suggests a synergistic effect of the biochar effects on the soil-plant system. The Soil Carbon Sequestration Index (SCSI) showed a particularly good correlation with crop productivity (correlation coefficient $r = 0.95$). When nutrient augmentation for soil carbon stock is tightly coupled with increased grain yield, the processes responsible for improvements in the carbon stock of the soil also lead to a more favorable soil environment for the development of plant biomass, such as improving the stability of soil organic material and soil aggregates (Pandian et al., 2024). According to this high correlation, biochar also deals with less contending carbon sequestration and crop productivity as it plays a pivotal role in enhancing carbon sequestration under sustainable land management practices that can ultimately reduce climate change effects while sustaining food security (Kumar et al., 2022).

Water-use efficiency and water-use efficiency were significant for soil organic carbon which is one of the components of the carbon sequestration index. A very strong positive correlation of $r = 0.95$ was detected between SOM and SWUE which indicates the importance of the relationship between SOM and SWUE, as soil moisture holding and loss due to evapotranspiration (ET) are well documented. This is particularly important in a changing climate as the better the water use efficiency, the lower the impacts of drought stress and of irrigation. The positive correlation indicates that the boost of soil organic carbon by biochar fosters the efficient use of available water resources; which will benefit the resilience of agriculture-based production systems to water shortages (Altieri et al., 2015).

Similarly, the relationship between soil organic C and nutrient use efficiency of applied nutrients by crops was inferred to be (), indicating that the higher the soil OC, the better will be the nutrient use efficiency for applied nutrients by crops. Adeyemi & Idowu, (2017) concluded the following mechanisms are responsible for this relationship – biochar is able to bind nutrients and prevent leaching, biochar affects how nutrients are released and absorbed by the plant, and biochar stimulates the activity of microbes that enable the cycling of nutrients. There is a strong positive correlation between soil organic carbon and nutrient-use efficiency, indicating that soil depth under biochar is statistically associated with soil nutrient-use efficiency meaning that lower nutrient input from fertilizers is required for biochar soils, further reducing the production costs and potentially reducing the amount of nutrients leaching into the environment (Hoque et al., 2025).

There was also some other measured parameters of which were seen to have significant positive correlations other than the above correlations. Microbial biomass carbon (,) for instance appeared to be positively related with soil water holding capacity with the effect that the soil microbial community is more dynamic and abundant in better soil water condition. This is based on the assumption that water in soil food webs is required by the organisms, and that the water-holding capacity of soils is associated with better microhabitats for soil microorganisms (Lehmann & Joseph, 2015). Further, nitrogen seemed positively positively related with grain production (; all ; available N and K did not correlate positively with grain yield) confirming the direct relationship of improved nutrient availability with crop productivity and extending the findings of others who investigated nitrogen and potassium available to plants as they relate to crop yields.

The positive correlations among soil properties and productivity were significantly high, indicating a so far synergistic chain of improvements in soils caused by the application of biochar. Such a synergy of relationships allows the almost simultaneous improvement of multiple parameters as described in the integrated sustainability indices in which higher values of one parameter will generally lead to higher values of other parameters. Therefore, the correlation analysis can help to support this result (regression analysis) showing the important soil factors affecting the crop productivity indicated in the multiple linear regression model are not independent but rather parts of the complex soil-plant system that gets influenced in a similar way by biochar amendment.

Principal Component Analysis

We used Principal Component Analysis (PCA) on the standardized matrix of soil and crop variables to further clarify underlying multivariate data structure and the major dimensions of variation related to biochar application. The PCA reduced the dimension of the data and the 3 largest factors retained most of the variance - 84.2% of the full variance of the data set were captured. From this high cumulative explained variance it is found that three extracted components are responsible for capturing the important patterns of covariation among the measured soil plant parameters that the biochar amendment induced in the soil, hence the extracted components have a parsimonious representation of the complicated interaction involved in soil plant system, (Abdi & Williams, 2010).

The first principal component (PC1) explained 40.6% of variance and had high positive scores for soil organic carbon, soil organic matter, microbial biomass carbon and Soil Carbon Sequestration Index. Available nitrogen, phosphorus and potassium were other components with significant loadings along with the Soil Fertility Index. These loading patterns led to the conclusion that PC1 was believed to represent fertility enhancement and soil carbon accumulation. The relevance of this contribution to the overall variance is related to the fact that only by adding biochar the improvement of the soil organic matter and nutrient status is the primary characteristic that leads to an improvement of the system's conditions, which is influencing its behaviour. The results revealed that all the changes in soil fertility explained by PC1 are not isolated but related to several fertility improvements as reflected by the high value of carbon sequestration index (CSI) for PC1 (Pandian et al, 2024). The results were found also to be in line with the outcome of the regression and correlation analysis where soil organic C as a sustainability indicator is the best near significant model for crops productivity and it was much highly correlated to the other sustainability indicators.

The second principal component (PC 2) accounted for 27.3% of the total variance and mainly comprised of high positive loadings from soil water-holding capacity, soil moisture content, water-use efficiency, and the Water-Use Efficiency Index. It received moderate available nutrients (heavy loads of potassium) and Nutrient-Use Efficiency Index component loading. Thus, PC2, which was determined to be a dimension of water retention and nutrient availability, was presumed. The appearance of this separate aspect has given an understanding of the physical effects that biochar can have on soil hydrology as a complementary and important part of biochar effects. The PCA are separated by water related variables from carbon related variables indicating two different mechanistic pathways being created, dependent on which variable water and carbon are correlated to (as follows in correlation analysis). Furthermore, the water storage component of PC2 comes with particular significance in the face of climate change where more water can be stored translates to buffering crops when they are stressed due to droughts and improving the resilience of farming systems (M. Khan et al., 2023). The third principal component (PC3) accounted for the maximum positive loadings for all the grain yield, biomass production, plant height and chlorophyll content and Crop Productivity Index data, with 16.3% of the total variation. Similarly, this indicator also showed moderate loadings with two other indexes: Climate Resilience Index and Agricultural Sustainability Index. So, for this condition PC3 was taken as the dimension for Crop productivity and climate resilience. The inclusion of a productivity portion indicates that soil productivity is strongly related to the soil C and water holding dimension represented by the PC1 and PC2 and that there are some other soil-level dimensions of soil productivity that are not captured. Some of these inconsistent results may be attributed to climate impacts in growing seasons, management practices in combination with biochar, plant nutrient efficiency, and direct growth impacts of biochar (Hoque et al., 2025). The loading of the climate resilience index on PC3 is the ability of biochar to maintain yield in the face of climate changes which is part of the yield aspect.

Both Kaiser criterion, eigen values bigger than 1, and a scree plot indicated the three component solution having a sharp cut off after the third component. The loadings exhibited on the

components were sound when using different rotation techniques (varimax and oblimin), implying that the structure has some stability and is not merely a function of the analytical method used. The benefits are there in a systematic picture and it seems the benefits relate to three dimensions; nutrient fertility created by carbon, nutrient availability created by water and productivity/resilience increased by the biochar directly. This dimensional structure is also important because the implementation of management practices on one dimension (carbon sequestration) would have an impact on the other dimensions, although specific practices may be needed to maximize the impact on each dimension. Additionally the value of total explained variance, 84.2%, suggests good representation of the most important processes of biochar's action on soil and crop performance by the variables included in this study and supports the overall findings in this work.

Comparative Findings

To achieve this, we directly compared all measured parameters between biochar amended and control (untreated) plots, as well as in our composite indices. The results of the above 'finding' section are dimensionally synthesized within a common format in this comparative evaluation and the extent of the benefits from biochar in the many agroecological settings included in this study are recorded. Table 2 shows that the use of biochar resulted in very significant and statistically different results in all dimensions with increases of between 23.8% and 31.6% compared to control.

Table 2. Comparative summary of key soil and crop parameters between biochar-treated and control plots.

Parameter / Index	Improvement (%)
Soil Organic Carbon	31.6
Carbon Sequestration	29.4
Soil Fertility	27.9
Grain Yield	25.7
Water-Use Efficiency	23.8

The highest improvement was seen in soil organic carbon which was 31.6% higher in biochar treated plots as compared to control plots. This result is in line with the well documented effects of biochar on enhancing the storage of recalcitrant carbon in soil and on enhancing the stability of native soil organic matter (S. Khan et al., 2024). In comparison to the short study period (three cropping seasons), this is impressive, suggesting that for the biochar, a more rapid time frame for the carbon sequestration effects could be obtained and could be robust over several years. An increase in the Carbon Sequestration Index of 29.4% further corroborates the positive effect on Soil Organic Carbon that can be directly traced to improvement in carbon storage in long-term holds, thus supporting the potentiality of biochar as a noteworthy NEGAT for climate change mitigation (Kumar et al., 2022).

The Result of the Soil Fertility Index (SOFI) as a composite of several parameters of nutrient availability and biological activities showed the treated plots with biochar as 27.9% higher.

This improvement is due to the synergism of biochar in improving other soil chemical and biological properties such as nutrient retention capability, Cation Exchange capacity (CEC) and microbial biomass carbon (Pandian et al., 2024). The soils and climate of the 16 experimental sites were highly diverse, but the outcomes of the experiments showed uniformity, suggesting possible application of biochar as a soil fertility amendment in a diversity of soil types and climate. Treatment that used both conservation tillage and crop residue retention with biochar had the greatest effect on increased fertility, indicating that applying biochar, in addition to these other growing methods, in similar soils further enhanced the nutrient supplying potential of soils amended with biochar (Diatta et al., 2020).

Immediate agronomic pay-off occurred following application of Biochar as the increased yield of grain has been noted by 25.7% in the biochar treated plots as compared to the control and has direct impact on food security in the day of climate change. It is on par with or higher than the increase in yield previously reported in the majority of other meta-analyses of the impacts of biochar on crop yields which generally found yield increases in the range of 10–30% (Adeyemi & Idowu, 2017). Rainfall and temperature provide the crop season-related variability, while crop yields were found to be consistent across all the three seasons indicating increased resilience of crop production in response to climate variability when grown on the biochar. This resilience is particularly crucial in Agriculture systems where drought stress is the greatest constraint for productivity, such as rain-fed Agriculture systems (M. Khan et al., 2023).

Overall benefit found with use of biochar amended plots with increased amount of grain production and reduced evapotranspiration loss led to increased efficiency of water use by 23.8%. The need for this improvement is largely due to biochar's porous structure which helps to increase water retention in the soil and decrease evaporative water loss from the soil surface (Lehmann & Joseph, 2015). Increased water shortage is projected to be one of the main barriers to agriculture in many parts of the world, under the present and future projected climate scenarios (Altieri et al., 2015), and efficient water-use is a key objective. The results showed that the water use efficiency achieved by biochar + drip irrigation was superior to the other water management techniques, indicating that the approach of using both techniques simultaneously is advantageous.

Results in Table 2 indicate that the biochar influence on soil carbon-related parameters (Soil Organic Carbon and carbon sequestration) is the most pronounced followed by the influence on soil fertility and crop production and Water use efficiency. This hierarchy actually suggests that the more basic mechanism of action exhibited by biochar is related to its ability to induce increases in soil OM, soil carbon storage, etc. and thereby a corresponding increase in water holding capacity and nutrient availability, and thus crop productivity. By improving soil functions on all five of these parameters with percentage gains that range above 23% in all cases, it was clear that biochar application has multiple parameters of improving soil functions, not just one. Here the results agree with possibility of biochar as sustainable land use long-term storage soil amendment contributing to enhance climate resilience and long-life land use.

Discussion

The results from this study can be used for theory and practice of sustainable agriculture in the age of climate change. From the theoretical standpoint, the fact that soil organic carbon is one of the few soil variables with a high predictive value in the regression model and a high loading for the first principal component further supports the conceptual model that pointed out soil organic matter as a master variable that affects several soil variables (Pandian et al., 2024). In addition, the experimental results presented here indicate that biochar also leads to an additive effect on water retention, nutrient cycling and biological activity as there is a strong correlation between the parameters. That's saying biochar creates a positive soil-plant eco-system loop, kindling a cascade of positive effects on the soil, which are further enhanced by biochar. In terms of impact, the 10.7% increase in grain yield and 10.8% improvement in water use efficiency (WUE) gained by various smallholder farms and large-scale farms show that biochar can be considered a feasible means to improve smallholder food security and reduce drought stress for both small and large farms. The potential for regionally different recommendations for biochar use amount and as an add-on to other good practices (conservation tillage and drip irrigation) was detected based on our findings. Furthermore, the 30% carbon sequestration improvement provides any farmer with a chance to obtain carbon credits and offers a sustainable approach for the country in sequestering carbon for agricultural use (Kumar et al., 2022).

The outcome is relatively solid and reliable, but some things need to be commented upon, methodologically. While three years provided coverage of inter-annual climate variability, this study might not fully capture long-term biochar-soil dynamics – the study was conducted over three successive cropping seasons. Biochar impacts on soil properties and crop productivity can change over long time periods, such as through surface oxidation and biochar ageing over years to decades because of changes in biochar pore structure, and interactions with mineral components of the soil (Lehmann & Joseph, 2015). Our design was fairly complicated on the one hand (16 sites for 320 plots), but on the other hand did not result in a combination of all the management practices, and thus cannot be broken down into individual complementary higher order effects. Furthermore, the study was restricted to certain soil and crop parameters and one could imagine that soil composition of the biological community, mycorrhizal colonization, and greenhouse gas emissions (in addition to carbon sequestration) would be other parameters of the environmental impact that could be captured. The use of the same biochar feedstock (wood) and the same production method at all sites, however, ensured consistency, but did not necessarily capture the advantages that can be derived from biochar material produced from different feedstocks, e.g. agricultural residues or manure, all of which could result in significant differences in their physicochemical properties (S. Khan et al., 2024). Finally, experiments are conducted in a controlled setting with management procedures that are standardized and followed in practice under a more variable and less controlled farming situation can lead to other results.

There are several specific areas that should be investigated in future research, in order to overcome these limitations. Making a assessment of the aging effect of biochar on soil function including carbon dynamics, nutrient cycling and crop productivity requires at least 10 years of field trials, during which time the stabilization and alteration of the effect of biochar on soil

carbon dynamics, nutrient cycling, and crop productivity needs to be measured. These should be physically and chemically characterized periodically and linked to function; "aging" the process should be studied to see how the physical and chemical properties of the biochar evolve over time. In order to evaluate the effect of the use of biochar created from different feed stock sources (including agricultural waste products, Municipal green waste and manure) on the agronomic and environmental parameters, further studies are needed. This is particularly true in the dissemination of circular economy principles; such that all materials treated as waste are valued as soil nutrients. New applications of biochar to the agricultural sector, such as, but not limited to, bioflocks, precision irrigation and variable rate fertilizer application and cover cropping are not reported here and should be explored as future avenues for enhancing the sustainability benefits of biochar. Furthermore, future research is needed to consider the socio-economic components influencing the adoption of biochar (such as costs-benefit analyses, farmer perceptions and constraints) for recommendations to facilitate the transfer of scientific findings into practice. Lastly, there are needs for mechanistic study by combining advanced analytical technique like stable isotope probing, metagenomics, and nano-scale imaging to elucidate the specific mechanism of biochar enhancing stabilization of soil organic matter, nutrient transformation, and plant-microbe interaction (Hoque et al., 2025).

Conclusion

There is great potential for using biochar under different climatic conditions as a soil amendment to enhance soil fertility and crop productivity and in this study we found enough empirical evidence to begin and a potential to continue using biochar sustainably in agriculture. The results clearly showed that testifying soil water holding capacity (WWC + 26.8%) and testifying soil nutrient availability (+ 24.9%) resulted in increment of grain yield (+ 25.7%) and soil WUE plant (+ 23.8%) respectively over agroecological regions. The findings align with our main hypothesis that application of biochar soil amendments (particularly in combination with other recommended practices—conservation tillage and conserving crop residues) results in cumulative benefits of biochar on the soil physicochemical properties and biological activity that extends beyond the individual benefits of organic and inorganic soil amendments and contributes to improved global soil use on farms to support agricultural sustainability. What we have brought into this field is an example of how biochar-induced carbon sequestration and crop productivity are compatible – the highest correlation between Soil Carbon Sequestration Index and the grain yield is $r = 0.86$; $p < 0.001$.

Long-term field trials (10 years or more in duration) should be the priority to investigate the impact of the aging processes of biochar on soil surface (such as by surface oxidation and by interaction with soil minerals) over longer term under study on soil carbon dynamics and crop performance. More research is needed to explore the biochar from different feedstocks to develop comprehensive guidelines with discussions of the feedstock-specific effects on agronomic and environmental outcomes. In addition, use of advanced analytical methods, such as stable isotope probing and metagenomics would allow a more mechanistic understanding of the mechanisms by which changes in nutrient transformations and plant-microbe interactions due to biochar can impact observed sustainability gains.

References

- Abdi, H., & Williams, L. (2010). Principal component analysis. *Statistics for Sensory and Consumer Science*.
- Abebaw, S., & Feleke, T. (2026). Systematic review on the impact of climate change on soil properties: Implications for sustainable land management. *Applied and Environmental Soil Science*.
- Adeyemi, T., & Idowu, O. (2017). Biochar: Promoting crop yield, improving soil fertility, mitigating climate change and restoring polluted soils. *World News of Natural Sciences*.
- Afaf, A., ALosaimi, J., Alharby, H., & Alayafi, A. (2023). The importance of initial application of biochar on soil fertility to improve growth and productivity of tomato plants (*solanum lycopersicum* l.) under drought stress. *Gesunde Pflanzen*.
- Akaike, H. (1974). A new look at the statistical model identification. *IEEE Transactions on Automatic Control*.
- Alhabib, H., Alhabib, A., Mohamed, N., Serhan, L., et al. (2025). Differences in quality of life between patients on peritoneal dialysis and hemodialysis in saudi arabia: A cross-sectional study. *Cureus*.
- Allen, R., Pereira, L., Raes, D., & Smith, M. (1998). Crop evapotranspiration-guidelines for computing crop water requirements-FAO irrigation and drainage paper 56. *Fao, Rome*.
- Altieri, M., Nicholls, C., Henao, A., & Lana, M. (2015). Agroecology and the design of climate change-resilient farming systems: MA altieri et al. *Agronomy for Sustainable Development*.
- Amule, F. (2014). *Determination of available nitrogen in soil by alkaline permanganate method*. Management of Soil Health: Challenges; ..., 2014.
- Branca, G., Lipper, L., McCarthy, N., et al. (2013). Food security, climate change, and sustainable land management. A review. *Agronomy for Sustainable Development*.
- Brown, M., & Forsythe, A. (1974). Robust tests for the equality of variances. *Journal of the American Statistical Association*.
- Diatta, A., Fike, J., Battaglia, M., Galbraith, J., et al. (2020). Effects of biochar on soil fertility and crop productivity in arid regions: A review. *Arabian Journal of Geosciences*.
- Hoque, M., Saha, B., Scopa, A., & Drosos, M. (2025). Biochar in agriculture: A review on sources, production, and composites related to soil fertility, crop productivity, and environmental sustainability. *C*.
- Hoyle, M. (1973). Transformations: An introduction and a bibliography. *International Statistical Review / Revue Internationale de Statistique*.
- Khan, M., Basir, A., Adnan, M., Fahad, S., Ali, J., et al. (2023). Biochar to improve crops yield and quality under a changing climate. *Biochar to Improve Crop Production*.
- Khan, S., Irshad, S., Mehmood, K., Hasnain, Z., Nawaz, M., et al. (2024). Biochar production and characteristics, its impacts on soil health, crop production, and yield enhancement: A review. *Plants*.
- Kumar, A., Bhattacharya, T., Mukherjee, S., & Sarkar, B. (2022). A perspective on biochar for repairing damages in the soil-plant system caused by climate change-driven extreme weather events. *Biochar*.

- Lee, H. (2023). Inference using analysis of variance (ANOVA) for comparing multiple means. *Foundations of Applied Statistical Methods*.
- Lehmann, J., & Joseph, S. (2015). Biochar for environmental management: An introduction. *Biochar for Environmental Management*.
- Littell, R., Stroup, W., & Freund, R. (2002). *SAS for linear models*. books.google.com.
- Mice, R. (2011). Multivariate imputation by chained equations. *J Stat Softw*, 2011.
- Murray, L. (2014). Randomized complete blocks designs. *Wiley StatsRef: Statistics Reference Online*.
- Nepal, J., Ahmad, W., Munsif, F., Khan, A., et al. (2023). Advances and prospects of biochar in improving soil fertility, biochemical quality, and environmental applications. *Frontiers in Environmental Science*.
- Olsen, S. (1954). *Estimation of available phosphorus in soils by extraction with sodium bicarbonate*. books.google.com.
- Pandian, K., Vijayakumar, S., Mustaffa, M., et al. (2024). Biochar-a sustainable soil conditioner for improving soil health, crop production and environment under changing climate: A review. *Frontiers in Soil Science*.
- Tauqeer, H., Turan, V., Farhad, M., & Iqbal, M. (2022). Sustainable agriculture and plant production by virtue of biochar in the era of climate change. *Managing Plant Production Under Changing Environment*.
- Tomich, T., Brodt, S., Ferris, H., Galt, R., et al. (2011). Agroecology: A review from a global-change perspective. *Annual Review of Environment and Resources*.
- Vance, E., Brookes, P., & Jenkinson, D. (1987). An extraction method for measuring soil microbial biomass c. *Soil Biology and Biochemistry*.
- W Chang, and, McGowan, L., François, R., et al. (2020). R: A language and environment for statistical computing. *Journal of Open Source Software*.
- Walkley, A., & Black, I. (1934). An examination of the degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Science*.