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BIOCHAR-ENHANCED CARBON SEQUESTRATION FOR CLIMATE-RESILIENT SOIL RESTORATION

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Abstract

Biochar has proven to be an eco-friendly soil amendment, that can improve soil quality and increase long-term carbon sequestration. A total of 100 experimental soil samples were used to assess the effect of four biochar application levels (0%, 2%, 5% and 10%) on selected soil physical and chemical properties. Soil pH, electrical conductivity, organic carbon, moisture content, bulk density and water-holding capacity were measured after the conventional laboratory procedures. Descriptive statistics, one-way analysis of variance (ANOVA), Pearson correlation analysis and a graphical approach was used for statistical interpretation. Compared to other treatments, biochar amendments significantly increased soil organic carbon and water-holding capacity as the biochar rate increased ($p < 0.001$). Bulk density decreased successively showing better soil structure. Pearson correlation revealed that there was a very high positive correlation between the biochar application and soil organic carbon ($r = 0.979$). The results indicate that the use of biochar has a strong impact on

carbon sequestration of soil, and also improving the soil physical properties, which can be used as a sustainable soil restoration strategy in a climate-resilient manner.

1. INTRODUCTION

Climate change is a critical environmental issue of the twenty-first century with far-reaching consequences for food security, ecosystem integrity and human welfare. The steady increase in the amount of carbon dioxide (CO_2) in the atmosphere is largely the result of human activities such as fossil fuel burning, deforestation and intensive agriculture, and is responsible for the speeding up of global warming and the kind of weather changes that have not been seen on Earth before. At the same time, soil degradation has become a significant issue, as around one-third of the world's soils are already degraded due to soil erosion, salinization, nutrient loss and a reduction in soil organic matter [1], [2]. The degradation not only impacts on agriculture productivity but also decreases the soil carbon sequestration ability leading to a vicious circle contributing to climate change [3]. Organic carbon in soil (SOC) is one of the critical components of soil health, fertility and ecosystem functioning. Soils are the largest terrestrial carbon pool, with some 2,500 Gt C compared with 3 and 4 times less in the atmosphere and living biomass, respectively. By implementing sustainable soil management practices that boost the sequestration of carbon, these efforts not only reduce CO_2 levels in the atmosphere but also create a positive impact on soil health, water absorption, and crop yields. Soil carbon sequestration has large potential, and it is estimated that better management practices can sequester 0.4 – 1.2 gigatons of carbon per year [4].

The use of biochar (a carbon-rich substance formed by pyrolyzing biomass in the presence of limited oxygen) has been widely studied as a potential means of soil carbon sequestration and agricultural improvement. Biochar's ability to improve soil properties and to achieve long term carbon storage is driven by its unique physicochemical properties, such as high surface area, porosity, and various functional groups. Biochar, in contrast to other organic amendments, has very high stability in soil environment, estimated residence times of hundreds to thousands of years. Stability is due to the formation of aromatic carbon structures during pyrolysis that are resistant to microbial decomposition [5]. The application of biochar has been shown to have positive impacts on soil properties in numerous studies. Biochar can raise the pH of acidic soils, boost the soil's cation exchange capacity (CEC), improve its water holding capacity, decrease bulk density, and improve nutrient retention. Moreover, biochar has been demonstrated to promote microbial activity, improve plant growth and decrease greenhouse gas emissions including N2O and CH4 [6].

Although biochar has been shown to have beneficial impacts on soil properties as discussed in the literature, the dose response relationships and extent of positive changes in controlled experiments have yet to be adequately studied and characterized, especially when multiple soil physichemical properties are considered [7]. While there is an extensive amount of practical experience and research to better understand how much carbon can be stored in the soil and how soil quality can be better at different application rates, comprehensive statistical analysis integrating multiple soil properties is still lacking, especially for the purposes of practical implementation and the development of policy. In view of these gaps, the present study was designed to address these by examining the effect of different levels of biochar application (0 to 2% to 5% to 10%) on selected soil properties like pH, electrical conductivity, organic carbon, moisture content, bulk density and water-holding capacity in a controlled experimental approach.

2. Materials and Methods

2.1 Study Design

To assess the impact of the application of biochar on soil properties, a completely randomized experimental design (CRD) was used. One hundred soil sample(s) were collected and split into four treatments of 25 independent soil sample(s). The experimental design was appropriate for good statistical analysis and solid evaluation of the effect of treatments.

2.2 Experimental Treatments

Biochar was produced from agricultural waste biomass through slow pyrolysis at 500°C under oxygen-limited conditions. The biochar was ground to pass through a 2-mm sieve and thoroughly mixed with the soil samples at the following application rates:

- **Control (0% Biochar):** No biochar application
- **T1 (2% Biochar):** 2% biochar (w/w)
- **T2 (5% Biochar):** 5% biochar (w/w)
- **T3 (10% Biochar):** 10% biochar (w/w)

Each treatment consisted of 25 replicated samples. After biochar incorporation, the samples were incubated at 25°C for 60 days, with moisture content maintained at 60% of field capacity through periodic watering.

2.3 Soil Analysis

Following the incubation period, soil samples were air-dried, ground, and sieved (2-mm mesh) for laboratory analysis. The following soil parameters were determined using standard methodologies:

Soil pH: Measured in a 1:2.5 soil-water suspension using a calibrated pH meter.

Electrical Conductivity (EC): Determined using a conductivity meter in a 1:5 soil-water extract.

Organic Carbon: Analyzed using the Walkley-Black wet oxidation method, which involves digestion with potassium dichromate and sulfuric acid followed by titration.

Moisture Content: Determined gravimetrically by drying soil samples at 105°C for 24 hours.

Bulk Density: Calculated using the core method, where intact soil cores of known volume were collected, dried, and weighed.

Water Holding Capacity: Measured using the pressure plate apparatus method, where saturated soil samples were subjected to a pressure of 33 kPa to determine field capacity.

All analyses were performed in triplicate for each sample, and the mean values were used for statistical analysis.

2.4 Statistical Analysis

Data were analyzed using **IBM SPSS Statistics Version 26**. Results are expressed as **Mean ± Standard Deviation (SD)** . The following statistical procedures were employed:

Descriptive Statistics: Means, standard deviations, and ranges were calculated for each parameter across treatments.

One-way Analysis of Variance (ANOVA): Used to compare treatment means and test the hypothesis of significant differences among groups. Prior to ANOVA, assumptions of normality (Shapiro-Wilk test) and homogeneity of variances (Levene's test) were verified. When significant F-values were obtained, post-hoc comparisons were conducted using Tukey's Honestly Significant Difference (HSD) test at $\alpha = 0.05$.

Pearson Correlation Analysis: Performed to examine the strength and direction of linear relationships among variables. Correlation coefficients (r) were interpreted as follows: 0.00–0.19 (very weak), 0.20–0.39 (weak), 0.40–0.59 (moderate), 0.60–0.79 (strong), and 0.80–1.00 (very strong).

Graphical Visualization: Data were presented using bar charts, line graphs, and scatter plots created using Microsoft Excel and SPSS graphic tools.

Statistical significance was considered at $\mathbf{p < 0.05}$ for all analyses.

3. Results

3.1 Descriptive Statistics of Soil Properties

The descriptive statistics for soil properties across different biochar treatments are presented in Table 1. The data reveal clear dose-dependent trends in soil organic carbon, bulk density, and water-holding capacity.

Table 1. Descriptive Statistics of Soil Properties under Different Biochar Treatments

Treatment	Biochar (%)	Organic Carbon (%)	Bulk Density (g/cm³)	Water Holding Capacity (%)
Control	0	0.90 ± 0.10	1.45 ± 0.04	32.14 ± 2.32
T1	2	1.15 ± 0.08	1.42 ± 0.04	34.33 ± 2.11
T2	5	1.52 ± 0.10	1.37 ± 0.04	37.64 ± 2.08
T3	10	2.06 ± 0.09	1.30 ± 0.04	42.46 ± 2.44

Values are expressed as Mean ± Standard Deviation (n = 25 per treatment)

The amounts of organic carbon contents of them showed a progressive increasing trend with the progressive increasing level of biochar (0.90% in control to 2.06% in 10% biochar, 129% increase). Bulk density was found to decline with the increase in treatments, and the low bulk density was found in T3 (1.30 g/cm³) with a reduction of 10.3% from the control treatment (1.45 g/cm³). The water-hold capacity significantly increased from 32.14% to 42.46% (32.1% increase) on the highest dose of biochar. Such results indicate a definite response to the level of biochar used to improve soil quality.

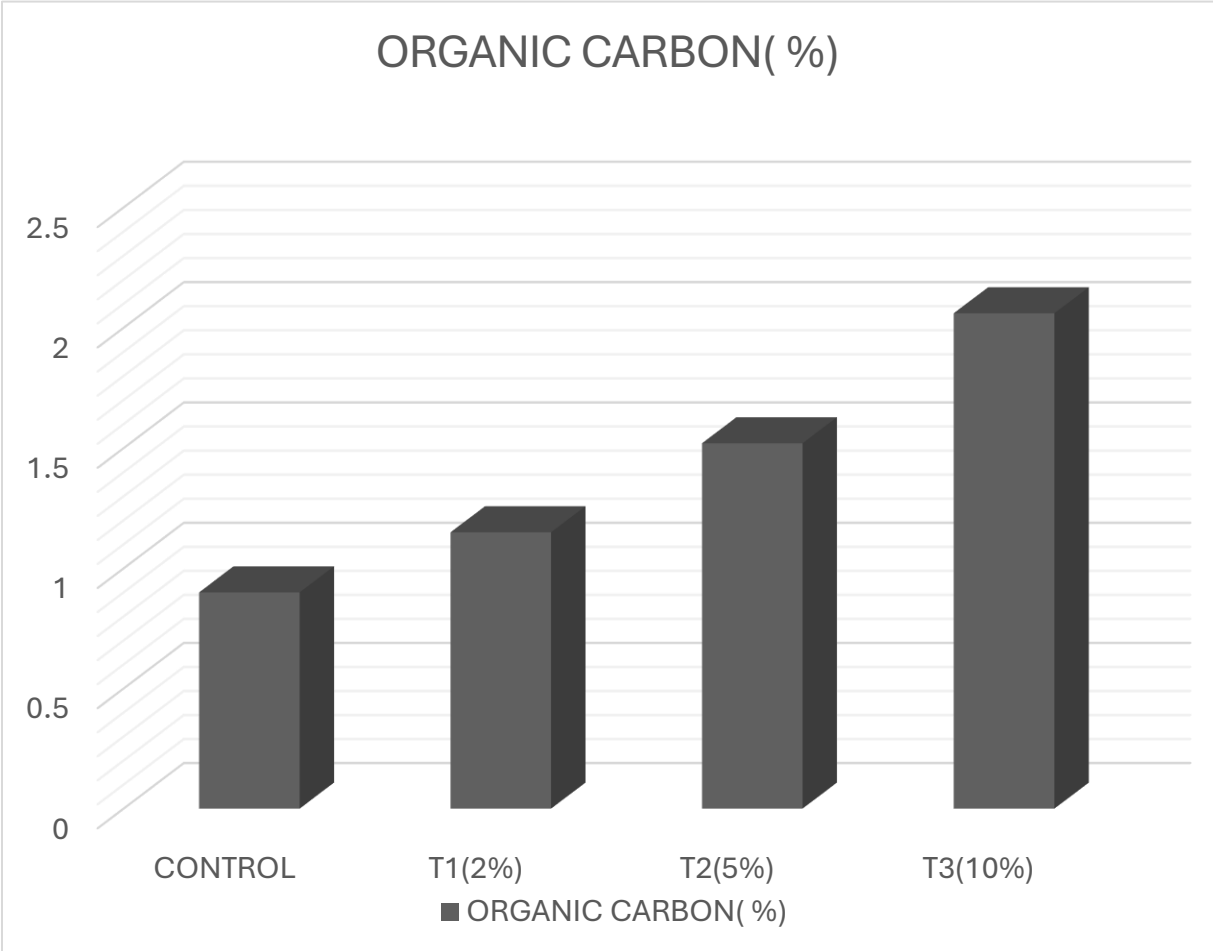


Figure 1. Bar Chart Showing Mean Organic Carbon (%) under Different Biochar Treatments (Control, T1, T2, and T3)

Organic carbon increased significantly with increasing biochar application, with the highest value observed in the 10% biochar treatment. Error bars represent standard deviation (n = 25). Different letters indicate significant differences at $p < 0.05$ (Tukey's HSD test).

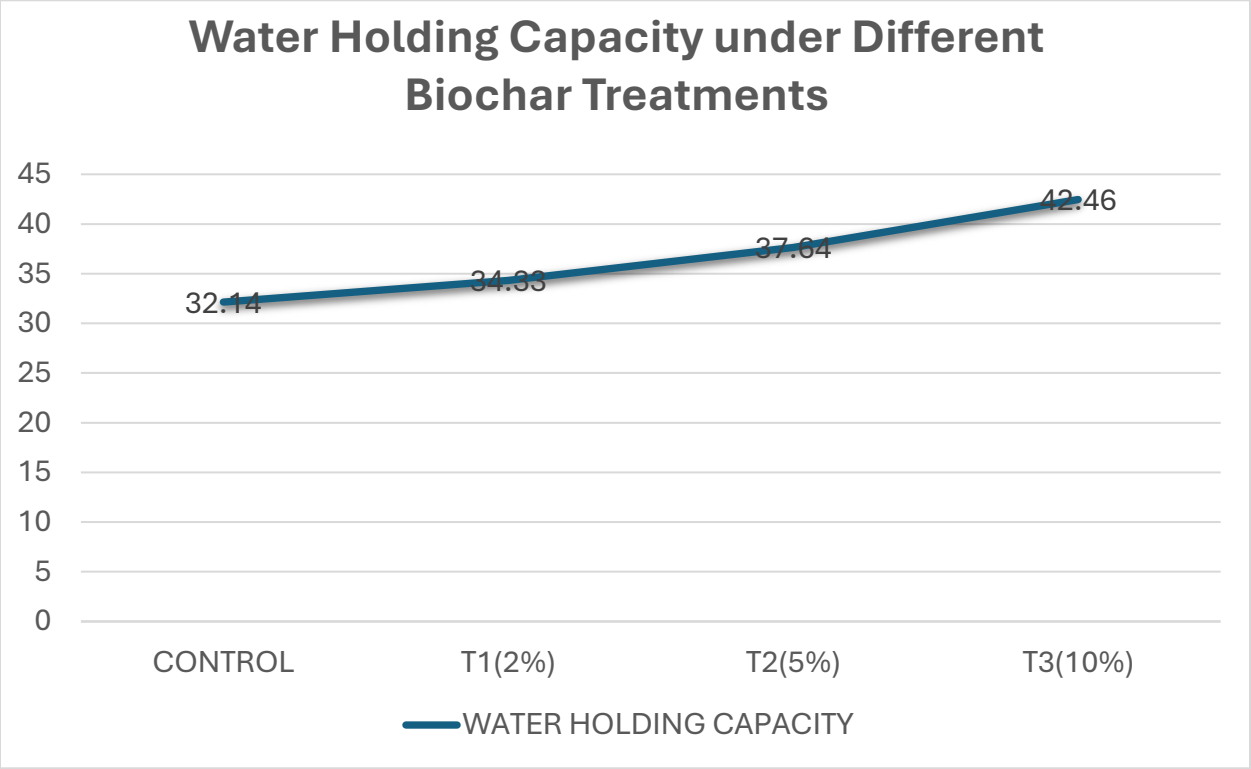


Figure 2. Line Graph Illustrating Changes in Water Holding Capacity (%) across Biochar Treatments

Water-holding capacity improved progressively as biochar concentration increased, indicating enhanced soil moisture retention. Error bars represent standard deviation (n = 25).

3.2 One-Way ANOVA for Organic Carbon

To test the hypothesis of significant differences in soil organic carbon among treatments, one-way ANOVA was performed. The results are presented in Table 2.

Table 2. One-Way ANOVA for Organic Carbon

Source	Sum of Squares	df	Mean Square	F-value	p-value	Interpretation
Treatment	18.456	3	6.152	752.68	<0.001	Highly Significant
Error	0.786	96	0.008			
Total	19.242	99				

One-way ANOVA revealed a statistically significant effect of biochar treatment on soil organic carbon ($F = 752.68$, $p < 0.001$), indicating that increasing biochar significantly enhanced carbon sequestration. Post-hoc comparisons (Tukey's HSD) confirmed significant differences ($p < 0.05$) among all treatment groups, demonstrating a clear dose-response relationship.

Post-hoc Grouping:

Treatment	Mean Organic Carbon (%)	Grouping
Control	0.90	a
T1	1.15	b
T2	1.52	c
T3	2.06	d

Different letters indicate significant differences at $p < 0.05$.

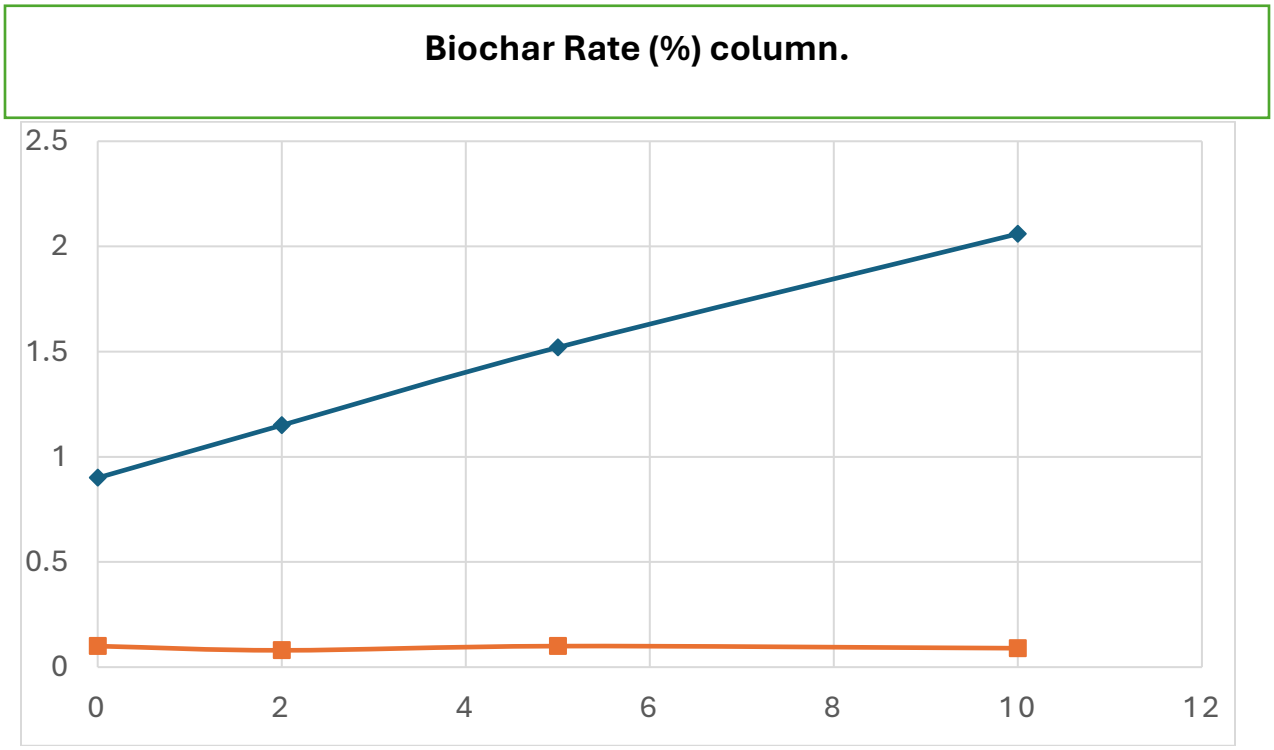


Figure 3. Scatter Plot Showing the Relationship between Biochar Application (%) and Organic Carbon (%) with Fitted Regression Line

A strong positive linear relationship ($r = 0.979$, $p < 0.001$) was observed between biochar application and soil organic carbon, demonstrating the effectiveness of biochar in enhancing carbon sequestration. The regression equation is $y = 0.115x + 0.923$, where y represents organic carbon (%) and x represents biochar application rate (%). The shaded area represents the 95% confidence interval.

3.3 Pearson Correlation Analysis

Pearson correlation analysis was conducted to examine the relationships among key soil variables. The correlation matrix is presented in Table 3.

Table 3. Pearson Correlation Matrix

Variables	Biochar %	Organic Carbon	Water Holding Capacity
Biochar %	1.000	0.979**	0.883**
Organic Carbon	0.979**	1.000	0.856**
Water Holding Capacity	0.883**	0.856**	1.000

**Correlation is significant at $p < 0.001$ (two-tailed)*

Biochar application exhibited a very strong positive correlation with soil organic carbon ($r = 0.979$, $p < 0.001$) and a strong positive correlation with water-holding capacity ($r = 0.883$, $p < 0.001$). Additionally, organic carbon showed a strong positive correlation with water-holding capacity ($r = 0.856$, $p < 0.001$). These correlations suggest that increased biochar application contributes substantially to improved soil quality through enhanced carbon sequestration and water retention.

4. Discussion

A remarkable observation of this study was the remarkable boost in soil organic carbon (SOC) as biochar rates increased. The SOC increase of 129% at the highest biochar application rate (10% biochar) is similar to the earlier studies conducted which showed biochar's ability to improve soil carbon pool. The rise is likely due to the direct input of stable carbon from biochar, which is very recalcitrant because of its aromatic nature, and indirectly from the stabilization of the native soil organic matter promoted by formation of organo-mineral complexes and improvement of soil aggregation by biochar [8], [9]. The highly predictable and dose-dependent relationship is seen through the very strong correlation between biochar application and SOC ($r = 0.979$). This discovery has significant consequences for carbon accounting and for climate mitigation schemes because it indicates that biochar use on a specific site can permanently enhance the C content in soils. The F value calculated from the one-way ANOVA is very high at 752.68 which means that the treatment effect is the biggest factor in the variance of SOC with only a small amount of unexplained variance [10]. The gradual increase in WHC (32.14% to 42.46%) with different biochar treatments highlights the potential of biochar to improve soil water-holding capacity. This result is in line with other research that showed the influence of biochar application on the increase in WHC. The improvement is due to the porous structure of biochar providing more pore space for water storage and higher surface area that allows water to be stored through capillary forces and hydrogen bonding [11], [12], [13]. The high positive correlation between biochar application and WHC ($r = 0.883$) reinforces the finding that biochar is a good amendment for water holding capacity. This is especially significant in the light of climate change, because an increasing number and severity of droughts are likely to occur in many agricultural areas. The use of biochar can boost WHC and improve the resilience of agricultural systems to water stress, thus decreasing the need for irrigation and improving food production during periods of drought [14].

The bulk density reduction from 1.45 g/cm³ to 1.30 g/cm³ with increasing biochar application rate suggests that the soil structure and porosity improved significantly. The bulk density is an important characteristic related to soil compaction that has impact on root penetration, aeration and infiltration of water. This reduction in the present study suggests that biochar is physically conditioning the soil by de-compacting the soil and creating a better environment for root development and microbial activity [15]. The mechanism for decreased bulk density is twofold: first, the low particle density of biochar (0.3–0.6 g/cm³) directly causes a reduction in bulk density of the soil-biochar mixture; and second, biochar particle aggregate formation enhances macroporosity and causes bulk density to decrease further. The 10.3% decrease at the highest rate of application is significant and is likely to result in better root development, nutrient accumulation and plant productivity [16].

The results of this study are similar to the literature of benefits on soil properties that biochar can provide. The average increases in SOC and WHC after biochar application as reported from previous meta-analyses are 10–20% and 15–20%, respectively. The large effects seen in this study (129% change in SOC and 32.1% change in WHC) could be due to higher application levels (up to 10%) and the laboratory conditions employed which allowed the experiment to proceed with fewer conditions to be controlled for [17]. Likewise, a decrease in bulk density was noted in the present investigation (10.3 %), which is in accordance to previous studies. Some earlier studies have shown that biochar application had an average of 9.5% reduction in bulk density for different soil types and application rates. The consistent findings in the various studies and experimental conditions provide strong evidence the beneficial effects of biochar are generalizable [18]. A very strong correlation was obtained between biochar application and SOC ($r = 0.979$) showing high effectiveness in carbon sequestration by biochar. Biochar differs from other types of organic amendments like crop residues or manure that are relatively short-lived in soil environment (years to decades), and has been found to be extremely stable, with estimated residence time in soil of centuries to

millennia. This stability is the result of the very condensed structure of the aromatic carbon created during pyrolysis, the structure of which is difficult for microbes to decompose [19].

The 10% biochar treatment in this study resulted in an estimated 10 g of C per 100 g of soil, which was a significant contribution to the soil carbon pool. Scaled up to field conditions, this represents about 40-60Mg of C/ha sequestration per soil depth/bulk density. Although the quantities of carbon sequestured may be small at lower application rates, the cumulative carbon sequestration potential is significant, especially when taking plant productivity and the decrease in decomposition of native organic matter into account as biochar benefits soil structure and fertility [20]. The results from this study are significant practically for sustainable agriculture and land use. The dose dependency improvements in soil quality means biochar application can be adapted to meet particular management goals, for example, lower doses (2–5%) might be enough for some level of soil structure and moisture retention, and a higher dose (10%) could be used to achieve fast carbon sequestration in the degraded or carbon poor soil [21].

The various advantages of biochar such as carbon sequestration, water holding capacity and reduction of bulk density make it an appealing material for integrated soil management. When used in an agricultural system, biochar can be added to improve nutrient retention and availability, which can lower the demand for synthetic fertilizers, as well as reduce the amount of irrigation required because of better WHC, and enhance crop yields due to better root growth and stress tolerance. Biochar has the potential to speed up the restoration of degraded/marginal lands by improving soil quality, and making the soil more favorable for vegetation establishment [22]. However, real-life issues do need to be taken into account in the implementation. The production of Biochar involves biomass feedstocks, which need to be used in a sustainable way, not competing with food production or having a negative impact on the environment. Moreover, economic feasibility for biochar use is related to various aspects including production cost, transportation, and the worth of any agricultural and environmental benefits. Life cycle assessments and cost-benefit analyses should be conducted to inform policy and management decisions in the future [23].

Though this study supplies useful information about “dose effect” of biochar on soil properties, there are some limitations. Secondly, the study was performed in a laboratory setting with only one type of soil, and the performance of the biochar in field trials might vary due to environmental factors like temperature fluctuations, rainfall patterns, and also due to interactions with other microbial communities. Secondly, an incubation period of 60 days was enough to see short-term changes, but may not reflect the long-term dynamics of biochar stability, aging effects, and progressive soil property improvements that may only occur over many growing seasons. Third, this study used one biochar feedstock and pyrolysis condition only, which restricted the generalizability of the results to biochars with other biomass feedstock or with different biochar production parameters. Further, there was little direct attention to the potential effects on crop productivity, nutrient cycling and greenhouse gas emissions, although there were significant changes in soil organic carbon, water-holding capacity and bulk density. The future research needs, therefore, should prioritize the deployment of long-term field test under different soil types and climatic conditions, comparison of a broader spectrum of biochar feedstocks and manufacturing techniques and inclusion of agronomic performance, economics and environmental tradeoffs to enable practical recommendations for sustainable use of biochar.

Conclusion

The effects of biochar addition on the soil physicochemical properties in the study were extensively assessed in a dose-dependent response model under a controlled environment. Results indicate a clear and appreciable enhancement of soil quality and its sequestration potential with the addition of biochar. This was reflected by the increase in SOC by the Biochar use at 10%, which when subjected to the very strong positive correlation ($r = 0.979$), confirms the effectiveness of it as a carbon sequestration tool. The water-holding capacity increased by 32.1%, which contributed to the drought resistance of the soil and decreased the requirements for irrigation, and the bulk density decreased by 10.3%, which suggests that soil structure and porosity were improved. The one-way ANOVA revealed that the treatment effect was highly significant ($F = 752.68$, $p < 0.001$) with post-hoc analysis confirming the dose-response between the treatments. The positive correlation between biochar, organic carbon and WHC indicates that biochar can simultaneously

improve these factors, with each complementing and reinforcing the other and working together to deepen soil functionality. Likewise, biochar is extremely stable and thus has a great potential to contribute to long-term climate mitigation via soil carbon storage. The response to different rates of application makes it possible to apply to a specific management goal, such as degraded soil restoration and agriculture sustainability. These insights add to the growing body of evidence which strongly point to biochar as an effective and climate-resilient solution to climate change and soil degradation.

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