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Improving the Hydraulic and Chemical Properties of Sandy Soil by Using a Mixture of Biochar and Clay

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ABSTRACT

In recent years, food demand has risen due to rapid population surge. Meeting this food demand means more land is supposed to be cultivated. Yet, there are many areas in Sindh, Pakistan, particularly "Thar," where crop yield is inadequate due to the sandy soil's poor water holding capacity (WHC), water retention, and higher hydraulic conductivity. Thus, this study evaluates the effect of biochar-clay mixture on sandy soil to improve its hydraulic and chemical properties. This study provides positive results of applying clay at three different rates (5, 10, and 20%) in sandy soil. When clay was mixed at these rates with 5% biochar, it not only improved the hydraulic properties of soil but also its chemical properties including soil organic carbon (SOC) and soil organic matter (SOM). The experimental findings improved the sandy soil's WHC and reduced its hydraulic conductivity. This clay and biochar mixture enhanced SOC, SOM, and Electrical Conductivity (EC) and decreased the pH in sandy soil. Thus, adding biochar and clay mixture proved to be a better soil amendment than only clay. Further investigation requires modification in biochar particle size before mixing it with the sandy soil.

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1. Introduction

The world population has increased in the last century to about 7.3 billion as per the latest UN estimate, and by 2050, it may ascend to 9.7 billion. This expansion, with lower incomes in underdeveloped nations, is driving up the demand for food globally. By 2050, an increase of 59% to 98% in the demand for food is expected. It will influence farming practices in unprecedented ways. Farmers must increase agricultural production by modifying existing practices, developing the cultivation land, or improving the soil characteristics.

Increasing land use is needed to double agricultural production until 2050 to fulfill anticipated demands for food (Pastor et al., 2019). A practical approach for overcoming hunger, particularly in developing countries, is cultivating sandy soils. It has long been assumed in agriculture that the productivity of sandy soils is less than that of soils of other texture classes. Owing to rapid water and nutrient loss, low organic carbon levels, high bulk density, and little microbial activity in sandy soils, vegetation growth is typically hampered (Alotaibi & Schoenau, 2019). The Poor surface area of sandy soils, i.e., 0.01-0.1 m^3g^{-1}, is the leading cause of poor water retention. Compared to sandy soils, water retention in average soils is higher because of the higher surface area in such soils, i.e., 5–750 m^3g^{-1} (Mertens et al., 2017).

In sandy desert areas, agriculture is entirely rain-fed. However, because of climate change, the rainfall span is shrinking year by year, and thus, it is necessary to boost the sandy soil's WHC (Ahmad, 2008; Belmonte et al., 2018). Also, balancing the rapidly growing affluent global population's food requirements with the world's finite resources is a crucial concern of our day (Davis et al., 2016). Growers are implementing many farming strategies to improve soil water retention and agricultural production in arid locations, and sandy soil additives like biochar and organic wastes may be a suitable alternative in improving crop development and soil properties (Baiamonte et al., 2020).

Mineral fertilizing has a limited chance of enhancing the low growth of sandy soils due to groundwater pollution. It is needed to raise their adsorption capacities. Conventional organic fertilizer (manure) intervention is only partially effective because organic materials are easily degradable in soils. Another option is using reasonably indestructible mineral substances (Reuter, 1994).

The previous findings show that the combined impact of clay soil and biochar is a perfect remedy for restoring sandy soil because it enhances organic matter, total Phosphorus (P), cation exchange capacity (CEC), pH, total Nitrogen (N), and water retention in sandy soil (Thi et al., 2021). There is less potential for water pollution when finely ground clay soil is added to sandy soil, by reducing the Nitrogen and Phosphorus nutrient leaching (Tahir & Marschner, 2017).

Biochar contains enough carbon and is prepared by pyrolysis when biomass is broken down under different conditions. As found in recent studies, it is extensively known for its capacity to mitigate climate change, control pollution, and its application as a soil amendment. There are numerous beneficial ways in which biochar is used as a soil additive, specifically in reducing nitrous oxide and carbon dioxide emissions, enhancing P and N absorption, and lowering nutrient loss (Pan et al., 2021).

The possible advantages of biochar as a soil amendment vary due to its aging and pyrolysis temperature. The soil's physical properties, including porosity and bulk density, are improved when biochar produced at higher temperatures (i.e., 500 to 600 ℃) is added. EC increases in all cases at a given temperature range while pH reduces. The biochar produced at 300 ℃ pyrolysis temperature effectively increases CEC and SOM (Alotaibi & Schoenau, 2019).

Previous findings demonstrate that, amidst the use of small portions of low-porous biochar, it is adequate to reach significant available water capacity (AWC) improvements in the arable sandy soil by adjusting the amendment fraction size (Gluba et al., 2021). Higher rates of application and smaller biochar particle sizes have more favorable impacts. Studies revealed that biochar has markedly enhanced soil porosity and increased tiny pores and extreme microspores. Compared to biochar biomass and preparation systems, the end users can easily manage the particle size of biochar; thus, the biochar particle size ought to be recognized as an essential core factor while enhancing the mixed amount of biochar (Fu et al., 2021).

A change in the desert soil's hydraulic properties is based on the properties of biochar. Sewage sludge biochar can enhance crop yield and soil microbial activity even at lower application rates (You et al., 2019). Biochar prepared from sewage sludge has been reported to improve nutrient balance and carbon sequestration (Gwenzi et al., 2016). It is beneficial in reducing water infiltration and increasing soil water retention in desert soil. Adding biochar to enhance hydraulic properties may give a possible answer to counter desertification (Zhang et al., 2016). The microbial population's organization and the soil's microclimate are altered with biochar addition (Liao et al., 2016).

Treating soil with biochar enhances its quality, improves irrigation systems, and decreases irrigation requirements, particularly in dryland areas (Baiamonte et al., 2020). Mixing soils with biochar adsorbs CO_2, ameliorates mineral deposits, and enhances P and N retention in soils, lowering the risk of water pollution (Pan et al., 2021).

Numerous studies exhibit the impact of applying only biochar in sandy soil. Nevertheless, research is scarce to evaluate the effects on the characteristics of sandy soil resulting from the concurrent utilization of biochar and clay. Hence, this study assessed the impact of adding biochar and clay in a mixture on several properties of sandy soil.

The primary objectives of this research were (i) to evaluate the effect of clay and biochar on the hydraulic and chemical characteristics of sandy soil and (ii) to examine the influence of varying application rates of clay in conjunction with biochar on the sandy soil's hydraulic and chemical properties. The present study posits two hypotheses: (i) adding clay combined with biochar in sandy soil will increase WHC, decrease hydraulic conductivity, improve water retention, increase EC, reduce soil pH, and significantly enhance SOC content. (ii) The combined impact of biochar and clay is expected to be more advantageous in augmenting the SOM.

2. Methods

2.1. Soil Additives

2.1.1. Clay

The experiment involved the utilization of clay soil as an amendment, with samples collected from the clay-rich regions of Sindh. The distribution of clay particle size is provided in Table 2.

2.1.2. Biochar

In a prior investigation conducted by (Laghari et al., 2021), biochar obtained through the sewage sludge pyrolysis at 600 °C was employed in combination with clay. The pH of the biochar was 8.59, indicating an alkaline nature. Table 1 enumerates several significant plant nutrients available in biochar.

Table 1
Nutrients Present in Biochar

	Fe	**K**	**Mg**	**P**	**Zn**
Nutrients (g/Kg)	118.05	8.79	9.11	54.20	1.12

2.2. Sampling of Sandy Soil

2.2.1. Sampling Site

The experiment involved the collection of sandy soil from Islamkot, Sindh, Pakistan. The field is situated within the Thar desert, alternatively referred to as the Great Indian Desert. This desert ranks as the ninth-largest subtropical desert globally, including a vast expanse of 200,000 km^2. A spade was used to sample the soil, starting from the top layer and extending to about 30 cm of depth. Subsequently, the soil samples were carefully enclosed in hermetically sealed plastic bags.

2.2.2. Sandy Soil Characterization

The samples of sandy soil were brought to the Energy and Environment Laboratory within the Agricultural Engineering Faculty of Sindh Agriculture University, Tandojam. Subsequent laboratory tests were conducted after drying, mixing, and sieving the soil through a 2 mm sieve size. The sandy soil texture was identified using the hydrometer method (Bouyoucos, 1962). The texture of sandy and clay soil is mentioned in Table 2.

Table 2. Soil texture composition of clay and sandy soil

Soil Type	**Soil Texture Composition (%)**		
	Sand	**Silt**	**Clay**
Sand-textured	91.6	7.5	0.9
Clay-textured	10.4	27.0	62.6

2.3. Pot Experiment

2.3.1. Preparation for Biochar

The biochar underwent first crushing and then sieving using a 2-mm sieve to get a particle size like that of sandy soil. The biochar particle size distribution consists of particles with dimensions of 2.00-0.84, 0.84-0.40, 0.40-0.25, and less than 0.25 mm, accounting for 37.26%, 25.86%, 17.72%, and 19.16% of the total particles, respectively.

2.3.2. Preparation of Fine Clay

The soil with a clay texture exhibited the presence of a portion of sand and silt particles. It was dried and mixed to isolate the clay particles from sand and silt. Subsequently, the soil was processed to pulverize the lumps. The clay soil sample underwent sieving using standard sieve sizes to separate clay, silt, and sand fractions. Clay particles smaller than 0.002 mm were gathered for incorporation into the sandy soil. The soil texture of clay soil was predetermined before separation using the sieve analysis method (Gee & Or, 2018). Table 2 displays the particle size distributions of the chosen soil.

2.3.3. Experimental Setup

Three different application rates, specifically 5%, 10%, and 20% were used to mix clay in sandy soil. These treatments were designated as T_1, T_2, and T_3, respectively. In each treatment labeled as T_4, T_5, and T_6, clay at previous rates, respectively, was mixed with 5% biochar in sandy soil in separate containers. However, in the case of treatment T_0, which solely consists of sandy soil. Twenty-one experimental designs were constructed in a Complete Randomized Block Design (CRBD), comprising three clay mixing rates, three application rates of clay and biochar mixture, and a control treatment. Each design had three replicates. The clay and biochar application rates were determined by utilizing a mass of 1000 grams of sandy soil in each container.

2.3.4. Incubation

After mixing, each sample was incubated using distilled water to maintain a WHC of 60% for two weeks. Upon completion of the incubation period, the laboratory studied each soil sample to ascertain the effectiveness of biochar and clay on their hydraulic and chemical characteristics.

2.4. Determination of Hydraulic Properties

2.4.1. Water Holding Capacity

The percolation method (Peterson., 1980) assessed the biochar and clay impact on the sandy soil's WHC under different treatments. A 25-gram soil sample was taken and placed on a filter paper; an estimated amount of water, 50 milliliters, drained freely from the soil sample to the measuring cylinder, passing across the filter paper, and the WHC was determined.

2.4.2.Water retention curve

A retention curve for each sample was drawn to find a relationship between water potential and volumetric water content. This study used a hanging water column method (Stolte & Veerman, 1997) to draw a WRC. A flexible rubber tube prepared a model apparatus by joining a burette and a Buchner funnel. Here, the water was removed from the soil sample by applying a negative pressure using a pressure difference in the rubber tube. Firstly, the 2 cm of water filled in the apparatus over the perforated plate of the funnel by covering it completely. Then, the burette was lowered, the filter paper placed on the funnel was stroked with a glass rod, and the soil was placed on the filter paper evenly with a thickness of 1-2 cm. In the next step, the sample was allowed to be saturated by moving the burette upward. The stopcock of the funnel was closed, and then the funnel and burette were raised as high as possible. At the beginning of the experiment, initial parameters Vi (volume of water in the burette) and Ho (corresponding height) were taken. Different volume (V) and height (H) values were noted by applying different levels of suction (cm of H_2O). Further, the water content (ϴ) was measured by calculating the bulk volume (cm^3) and dry weight (g) of the sample. After estimating the cumulative volumetric water content (cm^3/cm^3), a curve was plotted against suction (cm).

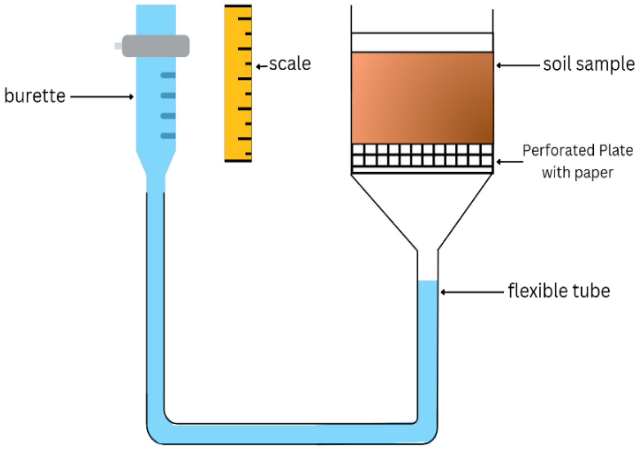

Figure 1. Hanging Water Column Model Used to Determine the Volumetric Water Content of Sandy Soil Samples at Varying Suction Heads. This Setup Consists of A Buchner Funnel and A Burette Joint, Together with The Help of a Rubber Tube.

2.4.3.Hydraulic Conductivity

To measure the hydraulic conductivity (K), a constant head method (Amoozegar, 2012) was used with a soil-permeability tester having a diameter of 5.5 cm. During this test, a constant water head of 42.5 cm was maintained. The volume of water collected for each soil sample was fixed for almost 5 minutes.

2.5. Determination of Chemical Properties

The EC and pH were analyzed using the standard electrometric method (Kargas et al., 2020; Minasny et al., 2011) using a soil-water suspension of 1:5 (w/v). SOC was determined with the Walkley-Black method, and the SOM of sandy soil under various treatments was determined by multiplying a factor of 1.724 by the SOC value of each sample (Meersmans et al., 2009).

2.6. Statistical Analysis

The Microsoft Excel 2013 version was used for statistical analysis. Using one-way analysis of variance (ANOVA), the statistical analysis for WHC, hydraulic conductivity, EC, pH, SOC, and SOM was completed. While two-way ANOVA with replications was used for the WRC.

3. Results

3.1. Hydraulic Properties

The outcomes of introducing amendments such as clay and biochar on the sandy soil's WHC are exhibited in Table 3. A consistent increase in soil WHC was estimated across all clay and combined clay and biochar treatment scenarios. Specifically, when biochar and clay were incorporated into the sandy soil at a rate of 5 and 20%, respectively, a significant enhancement of 46% in WHC was observed compared to the treatment under control conditions (Figure 2).

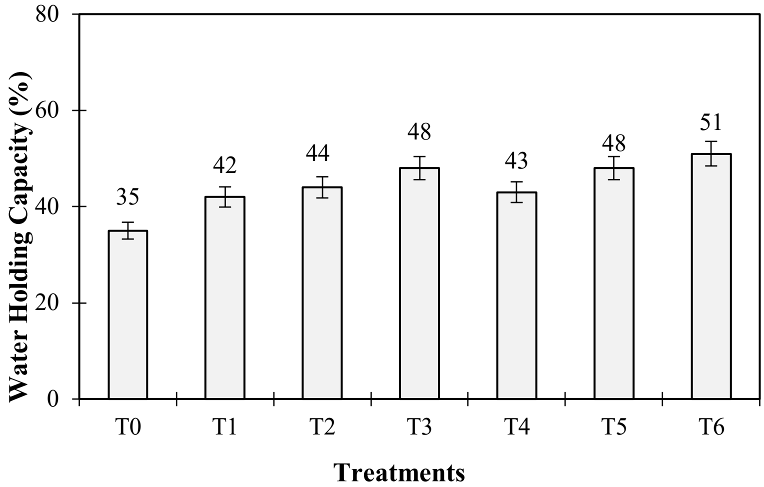

Figure 2. Effects of Biochar and Clay Application on WHC of Sandy Soil. To Indicates the Control Treatment with no Biochar and Clay Mixture. Compared to Clay-amended Samples (T1, T2, and T3), WHC Improved Greatly in Biochar-clay-Amended Samples (T4, T5, and T6)

Additionally, only clay treatments were observed to have a noteworthy effect on reducing the soil's hydraulic conductivity compared with similar rates of clay combined with biochar. Soil hydraulic conductivity, denoted as K values, experienced a significant reduction of 94% when only clay was applied at a 20% rate in T_3 compared to T_0 (Figure 3).

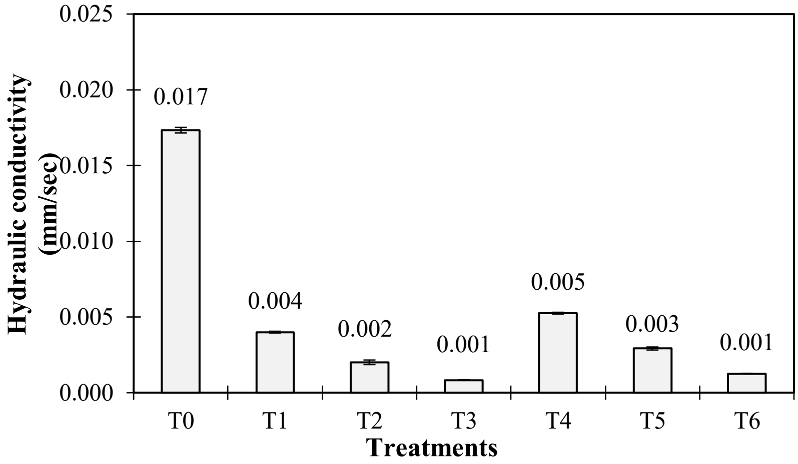

Figure 3: Effects of Biochar and Clay Application on Hydraulic Conductivity of Sandy Soil.

The rise in sandy soil's capacity to retain water after amendment is visually depicted via the water retention curve at various suction heads. The curves for each treatment clearly illustrate that increasing the number of suctions decreased the water retention, yet these suction heads were least effective in reducing the water retention in T_6. Compared to T_0, a substantial 27% and 46% increase was recorded in water retention at a suction head of 22 cm for the T_3 and T_6 treatments, respectively (Figure 4).

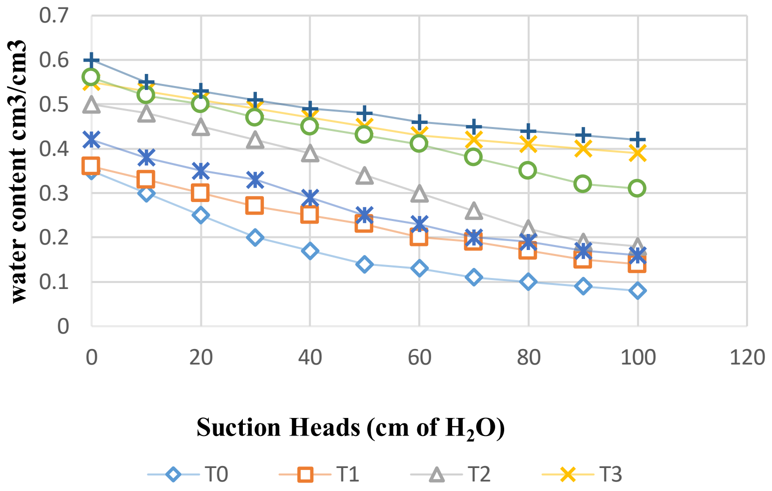

Figure 4: Water Retention Curve (WRC) Showing the Sandy Soil's Water Retention After Mixing Clay and Clay-biochar Against Different Suctions (cm of H2O).

3.2. Chemical Properties

3.2.1. Soil Organic Matter (SOM)

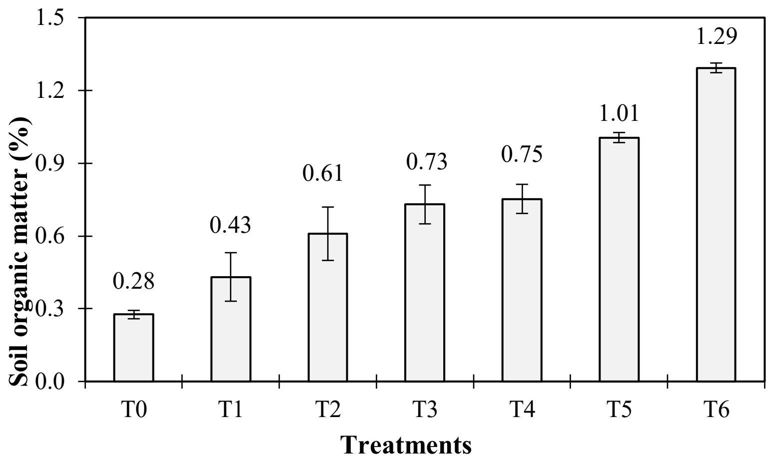

Figure 5: Increase in Soil Organic Matter (SOM) After Biochar and Clay Addition.

Table 3 summarizes the effects of varying clay and clay-biochar application rates on the sandy desert soil's chemical properties. Notably, when clay was applied at a rate of 20% combined with 5% biochar, a sandy soil sample named T_6 experienced a significant increase in SOM. It should be noted that the sandy soil samples amended with a mixture of biochar and clay showed a greater increase in SOM than those amended with clay. This increase can be attributed to the organic properties of biochar, which cause this increase. When comparing the overall results, T_3 followed T_6 in SOM content compared to all other treatments (Figure 5).

3.2.2. Soil Organic Carbon (SOC)

In addition to the SOM enhancement, the SOC content compared to the controlled treatment increased significantly for the T_6 and T_3 treatments. This increase was recorded more in the former than in the latter (Figure 6).

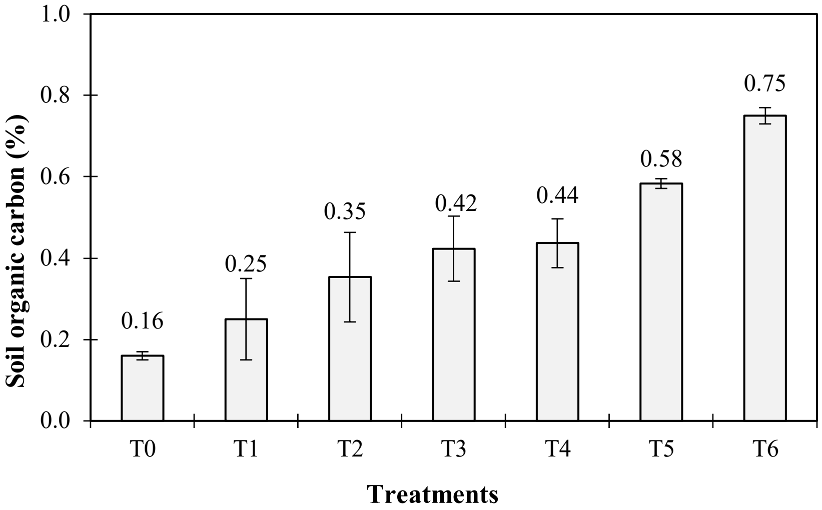

Figure 6. Improvement in soil Organic Carbon in Clay and Biochar Amended Samples.

3.2.3.PH

Yet, it is worth noting that the pH decreased more in treatments where a clay and biochar mixture was applied compared to the sandy soil samples under clay treatment. The treatments with clay and biochar mixture and those with clay mix only provided a decreased pH when comparing to the control treatment (Figure 7).

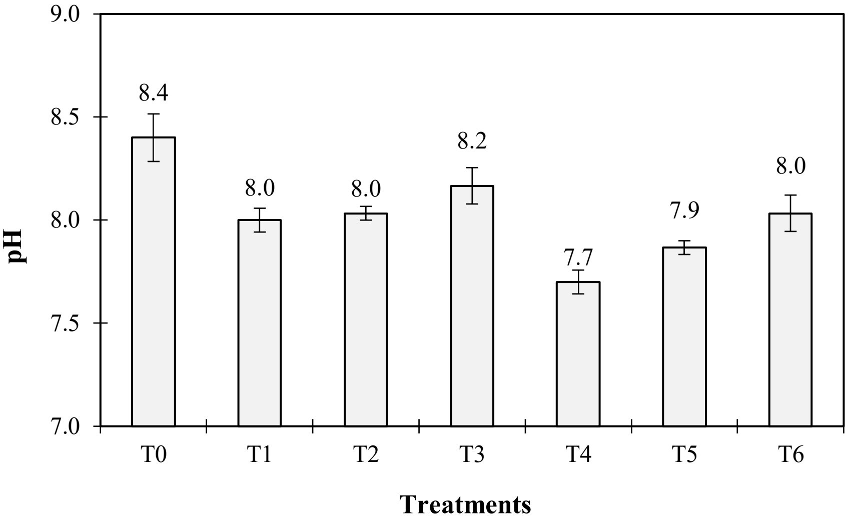

Figure 7. Effect of Biochar and Clay Mixture on PH of Sandy Soil.

3.2.4.Electrical Conductivity (EC)

An increase was observed in the EC of T_6 when a mixture of Biochar 5% and clay 20% was added. Other treatments had an increased pH after the biochar and clay mixture, but less than T_6. A significant difference was noticed in EC before and after the amendment (Figure 8).

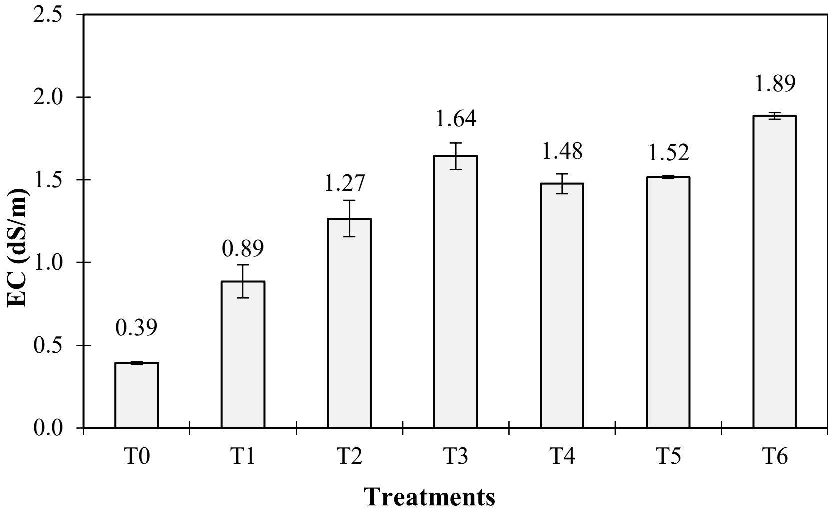

Figure 8. Effect of Biochar and Clay Mixture on Electrical Conductivity of Sandy Soil

Table 3
Effect of Biochar and Clay on Properties of Sandy Soil

Properties	T_0	T_1	T_2	T_3	T_4	T_5	T_6
WHC (%)	35.20	42.00	44.23	48.18	43.33	48.36	51.33
K (mm/sec)	0.017	0.004	0.002	0.001	0.005	0.003	0.001
pH (pH units)	8.4	8.0	8.0	8.2	7.7	7.9	8.0
EC (dS/m)	0.37	0.88	1.25	1.63	1.44	1.52	1.86
SOC (%)	0.16	0.25	0.35	0.42	0.43	0.58	0.75

K, Hydraulic Conductivity; WHC, Water Holding Capacity; SOC, Soil Organic Carbon; EC, Electrical Conductivity.

4. Discussions

In this investigation, the sandy desert soil exhibits a higher proportion of coarse particles, leading to a reduced WHC attributed to its coarse structure. Adding a combination of biochar at a concentration of 5% and clay at 20% increased the WHC from 35.2% in T_0 to 51.3% in T_6. The intrinsic clay and biochar properties caused this rise, enabling them to retain more water inside their pore spaces. By using clay at a concentration of 20%, WHC was enhanced to 48.18% for T_3. Nevertheless, incorporating clay at a dose of 5% did not yield significant enhancements in the WHC of sandy desert soil. These results show similarities to the results of a study of (Herawati et al., 2021), demonstrating that the biochar introduction at a concentration of 5% resulted in a WHC of 56% in the soil, compared to the control soil's capacity of 29%. A previous investigation by (Thi et al., 2021) proved that adding biochar at 0.5% to 1.5% and clay at 10.0% to 15.0% enhanced the capacity of sandy soil to retain more water significantly.

Meanwhile, the retention of water in sandy soil reached the value of 0.50 cm^3/cm^3 when biochar at 5% and clay at 20% were added. Furthermore, when a 20% clay application rate was employed, water retention improved to 0.46 cm^3/cm^3. The control treatment was recorded to have a water retention of 0.19 cm^3/cm^3, and the results of other treatments were compared with it. Those treatments in which combined clay and biochar were added exhibited higher water retention when the curves were plotted, and the treatments where only clay was added had lower water retention. (Atkinson, 2018) found water retention of about 0.05-0.40 cm^3/cm^3 in the study when he applied a pressure of 0.1 to 1.5 kPa to the samples of sandy soil. When the amendment of sandy soil was done with 2 mm biochar particles, it enhanced the retention reported in the study of (Fu et al., 2021). The 600 ℃ pyrolysis temperature produced the biochar mixed in the soil during a research study by (Javeed et al., 2021), which provided similar results in enhancing water retention.

The clay positively reduced its hydraulic conductivity when added to sandy soil. For control treatment T_0, the hydraulic conductivity was 1.7×10^{-2} mm.sec^{-1} for $T_{0,}$ which was reduced to 1×10^{-3} mm.sec^{-1} for treatments T_3 and $T_{6.}$ Here, the treatment with clay and biochar did not reduce the hydraulic conductivity effectively because of the finer particle size, which formed a slightly coarse texture for the whole treatment, causing water to flow easily. It was observed that the clay addition at a 20% rate resulted in the formation of more aggregates in T_3. Alignment of these results was found in the study of (Devereux et al., 2012) when the hydraulic conductivity was decreased from 4.3×10^{-3} to 2.3×10^{-3} cm.sec^{-1} at 5% biochar. The study of (Laghari et al., 2015) supports the reduction in hydraulic conductivity after incorporating biochar in desert soil. After adding biochar, (Zhang et al., 2016) recorded that k values from 1.038×10^{-3} reduced to 7×10^{-4} cm.sec^{-1}. (Reuter, 1994) found that hydraulic conductivity decreased when he mixed the soil with clay and biochar in sandy soil.

After its amendment, the chemical properties of sandy soil were changed. However, this change was more for those sandy soil treatments in which biochar was incorporated with clay. Each sandy soil sample treated with only clay exhibited a lesser decrease in pH than the samples treated with clay and biochar. Our study provided results that are similar to the findings of (Reuter, 1994), according to which pH reduction in clay-amended sandy soil samples was less than that of the samples amended with clay and biochar. Using biochar mixing rates from 60 and 30 t/ha, (Ulyett et al., 2014) recorded a decrease in pH from 7.2 to 7.1 and from 7.2 to 6.9, respectively. Alkaline biochar reduces the pH and is supported in the findings of (Javeed et al., 2021). The pH reduction is proven in the research of (Laghari et al., 2015) after mixing sandy soils with biochar.

Adding only clay and clay with biochar increased the EC of sandy soil samples. A combined mixture of biochar and clay caused an increase in EC compared to the clay amendments. An increase in EC by the combined application of clay and biochar also aligns with the study of (Javeed et al., 2021). In their research, (Alotaibi & Schoenau, 2019) proved that a biochar produced at 600 ℃ temperature, when applied in a mixture with clay into sandy soil, had an increasing effect on its EC. (Zhang et al., 2016) suggested that EC increased from 1.65 to 5.39 dS/m when sandy soil was mixed with biochar.

All treatments were recorded to increase SOC and SOM after clay addition. However, the mixture of biochar and clay was more effective in causing this increase. An increase in the SOC from 0.6% to 1.0% for control and biochar mixed soil, respectively, was recorded in the report of (Pituello et al., 2018). The increasing rates of soil amendments increases SOC, as supported by (Alotaibi & Schoenau, 2019). Biochar application enhances SOM, which is also proven in the findings of (Laghari et al., 2015). The SOM in sandy soils increases when clay and biochar application rates increase (Zhang et al., 2016). The clay-biochar mixture was found to have excellent results for SOM increase compared to clay application, as (Thi et al., 2021) recorded.

5. Conclusions

A mixture of clay and biochar upgraded the hydraulic as well as the chemical characteristics of sandy soil in this study. This improvement was exhibited in the water retention curve, hydraulic conductivity, and WHC. Moreover, it enhanced the SOC, SOM, and EC of sandy soil. A reduction in pH was recorded in each treatment compared to the control. Thus, biochar and clay can be added to sandy soil to improve its quality. This study recommends using biochar and clay mixtures in fields of sandy soil to obtain results similar to those of this pot experiment. The SOM content in sandy soil can be enhanced with more than 5% biochar rates. However, more research is needed to assess the effect of different particle sizes of biochar with clay on improving the hydraulic and chemical properties of sandy soil.

Authors Contribution

Lareb Bhirai: Writing original draft, methodology, data collection and analysis, revision, reviewing, editing, and finalizing draft.

Mahmood Laghari: Supervision of project, reviewing and editing draft, data analysis assistance.
Hafeez-Ur-Rehman: Supervision and methodology reviewing
Rajesh Kumar: Supervision, data analysis assitance, methodology reviewing, and editing.

Conflict of Interests/Disclosures

The authors declared no potential conflicts of interest w.r.t. the research, authorship and/or publication of this article.

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