COMPARATIVE ANALYSIS OF WATER RETENTION PROPERTIES OF BIOCHAR AMENDED WITH FINE GRAINED SOILS

by

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# ABSTRACT

MOHAMMAD KHALID. Comparative analysis of water retention properties of biochar amended with fine grained soils

(Under the direction of DR. MARIYA MUNIR)

Biochar has emerged as a promising soil amendment to enhance soil hydraulic properties, particularly improving water retention in fine-grained soils. This study investigates the impact of nine different commercial biochar types, applied at 3% and 6% concentrations, on the water retention characteristics of two native fine-grained soils from North Carolina. The soils were characterized as low-plasticity clay (CL) and low-plasticity silt (ML). Soil Water Retention Curves (SWRC) were modeled using the HYPROP and WP4C data, fitted using the van Genuchten (vG) and Brooks-Corey (BC) models. Results demonstrated that biochar amendments enhanced water retention, with having greater improvements at higher biochar concentrations. However, soils with higher organic content exhibited a relatively smaller increment in water retention. Moreover, the BC model consistently predicted slightly lower water retention values than the vG models. The results highlight the importance of biochar types and concentrations to optimize water retention characteristics and soil performance in diverse applications of roadside soil, agricultural soil, and environmental applications.

# TABLE OF CONTENTS

# LIST OF FIGURES

# LIST OF TABLES

**Introduction**

Biochar is an organic material produced through thermal processing of biomass under low oxygen (Hossain et al. 2020). In addition, biochar is known to have high porosity, large specific surface area (SSA), high pH value, and high nutrient content (Lehmann and Joseph, 2009; Ahmad et al., 2014); thus, proposed as a soil amendment for carbon sequestration, landfill cover material, improving soil fertility and removing heavy metals and organic pollutant such as polycyclic aromatic hydrocarbon (PAH) from soil (Waqas et al., 2015; Wong et al., 2017; Garg et al., 2019). Geo-environmental engineering structures and agricultural fields soils such as landfill covers, green roof, bioengineered slopes and embankments are influenced by soil water retention characteristics (SWRC) as it mostly governs the behavior of the soil (Fredlund and Rahardjo, 1993; Tamari et al., 1993). The relationship of water content and soil suction pressure is derived from SWRC (Ng and Pang, 2000; Vanapalli et al., 1996). Soil suction plays a critical role as a primary stress state variable influencing the mechanical behavior of soil (Fredlund and Rahardjo, 1993). The SWRC becomes critically important to understand in characterization of soil in geo-environmental engineering structures where partially saturated soils are involved. And it has been found that amendment of soil with biochar has the potential to alter the soil SWRC properties (Downie et al., 2009; Lei and Zhang, 2013).

It has been found that biochar amendment to soil increases the water retention capacity of the mixture (Yu et al., 2013). It has also been observed that the higher biochar content leads to higher water retention and the coarse textured soils have shown more pronounced effects than fine textured soils (Ajayi et al., 2016, Blanco-Canqui, 2017). For example, the study of Gamage et al. (2016) have found that sandy soil showed comparatively higher water retention than sandy loam soil. Also, biochar has the ability to remove contaminants from aqueous media through adsorption due higher surface area and porous structure (Jiang et al., 2018) and adsorption is the best suited method for the treatment of pollutants for example carcinogenic heavy metals (Khan et al., 2021, 2023).

Research has been done in the past to examine the effect of biochar amended soil on SWRC. Studies have reported that biochar amended soil SWRC is different from unamended soil while some studies have also found no effect of biochar addition on SWRC (Suliman et al., 2017). For example, no effect on sandy loam soil with biochar amendment was reported by (Hardie et al., 2014) and a similar result was found on Quincy sand from the study of (Streubel et al., 2011). The study conducted by Streubel et al., (2011) have also found increased water holding capacity of two silt loams but also reported no effects in two other silt loams. And they concluded that the contradictory results could be due to the higher clay content of the silt loams. Moreover, a reduction in water retention was also found from clay loam and some clay soils (Castellini et al., 2015, Aller et al., 2014). For SWRC modeling, the vG and BC models are most commonly used approach (Pan et al., 2019). Both methods are based on the assumption of uniform soil properties. However, when soil is mixed with additives that alter its physical characteristics, the water retention properties can change significantly (Wang et al., 2020, Bordoloi et al., 2018).

Geotechnical structures are made of soil and vegetation, with vegetation playing a key role in maintaining stability. Moreover, the performance and growth of vegetation mainly depends on properties of soil and SWRC plays a critical role (Li et al., 2016). Although, studies have been done on water retention properties of biochar amended soils, studies focusing on different types of commercial biochar, application rates and fine-grained soil types remain limited (Bordoloi et al., 2018; Ni et al., 2018). There is a need to explore different commercially available biochar types, application rates, and their effects on fine-grained soils. Understanding SWRC is crucial for soil stability and vegetation growth in geotechnical and agricultural applications. This study addresses these gaps by examining nine commercial biochars and comparing their effects using vG and BC models.

This study aims to examine the impact of nine different types of biochar on water retention properties in two types of fine-grained soils, with main objective of (1) investigating the water retention characteristics of nine different biochar amended with two soil and difference between the effects of vG model curve and BC model curve; (2) to understand the difference in model analysis of air entry points with both models; and (3) to find the effect of biochar on different parameters of vG and BC models of amended soil.

## Materials and Methods

### *Biochar and soil type characterization*

In this study, two distinct types of fine-grained soils from the Piedmont Region of North Carolina were selected to evaluate the effects of biochar amendment. Soil 1 contains a mixture of organic material and bulk soil particles, while Soil 2 lacks organic matter, as illustrated in Fig. 1. The bulk soil samples were crushed and passed through a 4.75 mm sieve (U.S. Mesh #4) to remove larger rocks and other coarse materials. Laboratory testing identified Soil 1 as low plasticity clay (CL) and Soil 2 as low plasticity silt (ML), based on the Unified Soil Classification System (USCS). These classifications provide a baseline for assessing the impact of biochar on the physical and water retention properties of the amended soils.

Nine different types of biochar used in this study were obtained from eight different vendors and are summarized in Table 1. A comprehensive physicochemical characterization of biochar and soil samples were done which includes sieve analysis, hydrometer analysis, dry bulk density, and pycnometer density. These samples were oven dried overnight followed by sieving through the U.S standard sieve sizes. Oven dried biochar and soil samples were used to get the constant weight to obtain the accurate mass fraction. The mixture of biochar amended soil was prepared by adding 3% and 6% by dry weight of the soil along with a control sample (0% biochar) to see the effects on the water holding capacity and different parameters of models at different mixture rates.

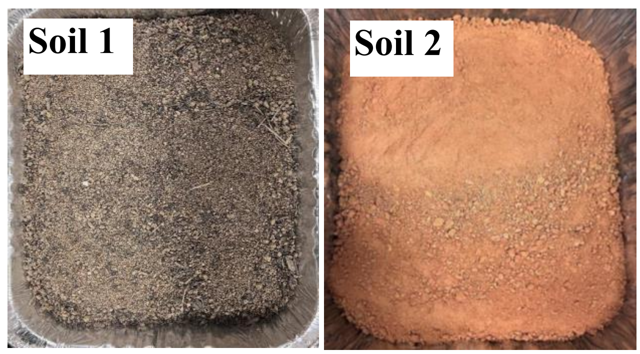

Figure 1 Different in organic content of both the soils.

Table 1 Biochar with different feedstock and pyrolysis temperature

| **Product Name** | **Company Name** | **Feedstock** | **Location** |
|---|---|---|---|
| Naked Char | American Biochar Company | Wood (Southern Yellow Pine) | Niles, MI |
| Aries Green | Aries Clean Technologies | Wood Chip | Franklin, TN |

| | | | |
|---|---|---|---|
| Organic Granular Pine Biochar; Organic Micronized Powder Pine Biochar | Blue Sky Biochar | Wood (Pine) | Thousand Oaks, CA |
| BN Small, BN Medium | Biochar Now | Wood (Pine) | Berthoud, CO<br>Loveland, CO |
| Char Bliss Premium Wood Biochar | Plantonix | Softwood | Ashland, OR |
| Soil Reef Biochar | Soil Reef LLC | Wood | Berwyn, PA |
| Biochar DG | The Andersons | Wood | Maumee, Ohio |
| Wakefield Premium Biochar | Wakefield Biochar | Wood (Pine) | Valdosta, GA<br>Columbia, MO |

***Unsaturated hydraulic conductivity and water retention curve***

The water retention curves were measured at room temperature (22 ± 1°C) using HYPROP and WP4C (METER Group, Pullman, WA). Where the range of measurement of water suction varies from 0.1 to -100 kPa for HYPROP which determines the hydraulic properties based on evaporation method and -0.01 to -300,000 kPa for WP4C for the dewpoint potentiometer for the higher values of suction. For the HYPROP measurements, the samples were poured and compacted into standard stainless-steel cylindrical ring of 250 ml (2.5 x 10−4 m3 volume, diameter 8cm, height 5cm, from meter group) in three layers with a piece of fabric filter and a plastic cap at the bottom. The samples were saturated with deionized water overnight and water was applied from the bottom as recommended in the HYPROP manual (UMS., 2015). The samples were saturated overnight before mounting onto the HYPROP instrument. Each set of tests usually last a week where the samples are allowed to evaporate at room temperature. Finally, the tests were terminated once the water in both tensiometers had cavitated.

After the HYPROP testing, the same sample was transferred into stainless steel trays to measure the water potential with dew point method. The testing was adopted to extend the water retention curve to the permanent wilting point (UMS, 2015, Kirste et al., 2019). The study of Dumenu et al. (2017) was followed for the test methodology of WP4C. Where the samples were allowed to dry at room temperature in the lab and were tested at various intervals until the mass of the sample reached a plateau. The WP4C was calibrated regularly with 0.5M potassium chloride solution from the Meter group. Fast mode was adopted to measure the suction of the samples. Prior to the testing, the mass of the samples was recorded. Finally, the dry mass of the sample was calculated once the testing was done.

***Models for prediction of water retention curves***

HYPROP-Fit software was used from the Meter group to generate the SWCC curve. The software incorporates the data of WP4C to generate the models. Van Genuchten (VG) water retention model - The closed form equation consists of four independent parameters which have to be estimated from observed soil water retention data.

$$\theta(h) = \theta_r + (\theta_s - \theta_r)[1+(\alpha h)^n]^{-m} \quad (1)$$

where, $\theta$ is the volumetric water content; h is the pressure head; $\theta_s$ and $\theta_r$ represent the saturated and residual water contents, respectively; $\alpha$, n and m are empirical shape parameters.

Brooks - Corey (BC) water retention model - This is a four-parameter water retention model. A Brooks-Corey model is a type of nonlinear curve fitting model for fitting water retention characteristics using experimental data. The Brooks-Corey functions can be defined as:

$$\theta(h) = \theta_r + (\theta_s - \theta_r)(\alpha h)^{-\lambda} \quad (2)$$

Where, $\theta_r$ is the residual water content ($cm^3/cm^3$), $\theta_s$ is the saturated water content ($cm^3/cm^3$), h is the matric potential (cm), $\lambda$ and $\alpha$ are empirical shape parameters.

***Surface morphology analysis***

Pore structure analysis of biochar was performed with Scanning Electron Microscopy Energy Dispersive X-Ray Analysis (SEM-EDAX) by using JEOL model 6460LV. Dried biochar particles were glued onto a glass strip using conductive double-sided tape. Gold coating was applied to secure the biochar particles. Finally, SEM was operated in multiple modes to analyze the biochar's pore structure. Images were captured of the selected biochar surfaces, and further analyses were conducted.

## Results and Discussions

### *Electron microscopy analysis of biochar*

Three-dimensional pore structure of biochar was analyzed by SEM and Fig. 2 shows the SEM imagery of all the biochar used for this study along with the soil samples. The surface structure of each biochar, number of surface pores as well as mesh formation varies from biochar to biochar. And this could be attributed to feedstock and production temperature as used biochar are different. Also, with the help of EDX, the elemental analysis of biochar and soils were done and the carbon contents are summarized in (Table 1 of Supplemental Information (SI)). The source of biochar material and the production temperature significantly influence the elemental composition of the samples, particularly the carbon (C) content. The carbon content in all biochar samples was found to be substantially higher, averaging around 87.4%, compared to soil samples, which exhibited average carbon contents of 51.4%, respectively.

The images from SEM analysis clearly shows the significantly high number of macropores which are shown in Fig. 2 except TA biochar. Both the soil samples did not show the presence of any macropores as it can be seen Fig. 3. The difference in the structure of the pores is not significantly different except WF biochar. Cell walls are also present in all the biochar except TA and both the soils. The SEM analysis also reveals the cracks and pores of the cell walls, where biochar shows the presence and absence of these characteristics. The biochar showed the higher pores, less water holding capacity will be implicated as intense water flux through the inner caliber will happen due to macropores which can be found from water holding capacity.

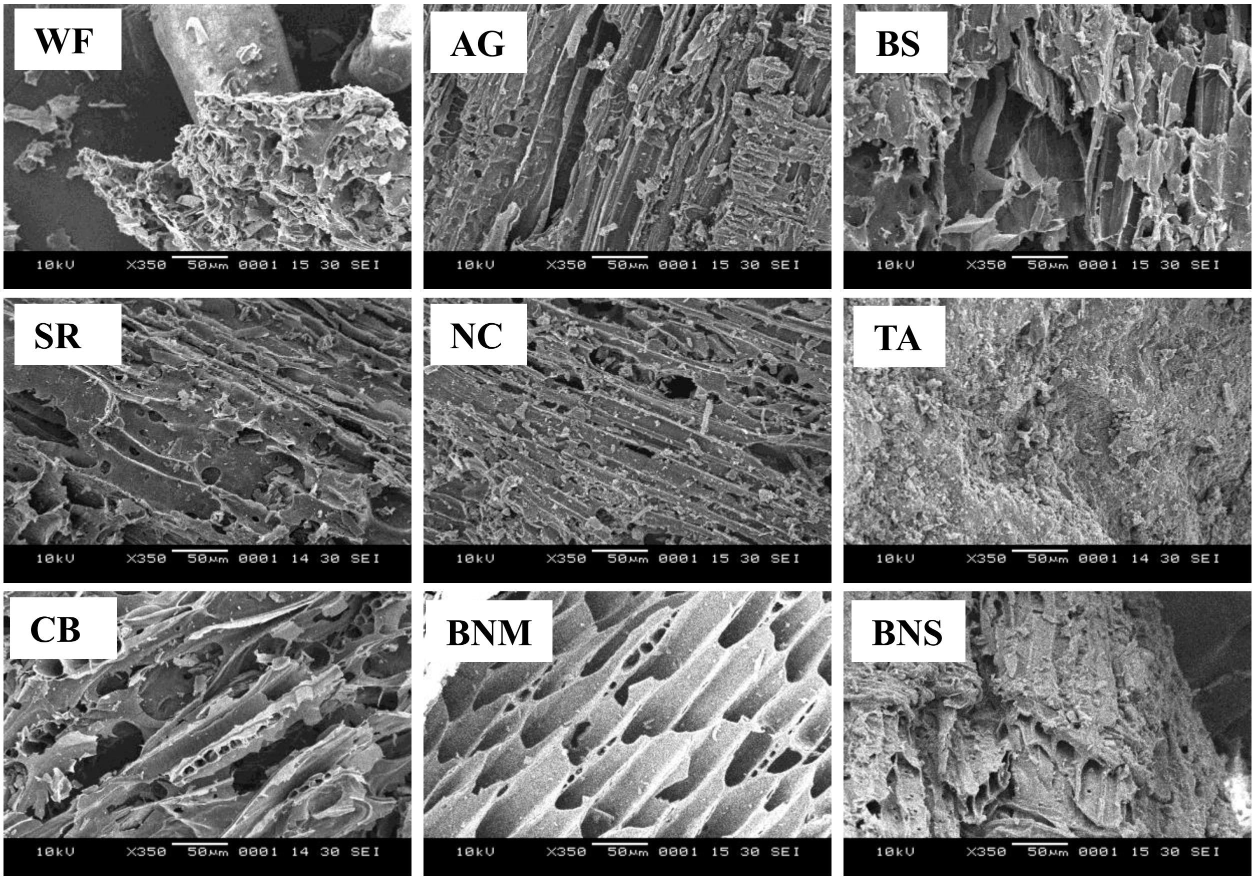


Figure 3 Scanning electron microscope of all the biochar particles with the scale bar of 50 µm on each panel. These images were recorded at 5.0 kV current probe, with identical magnification of each pair.

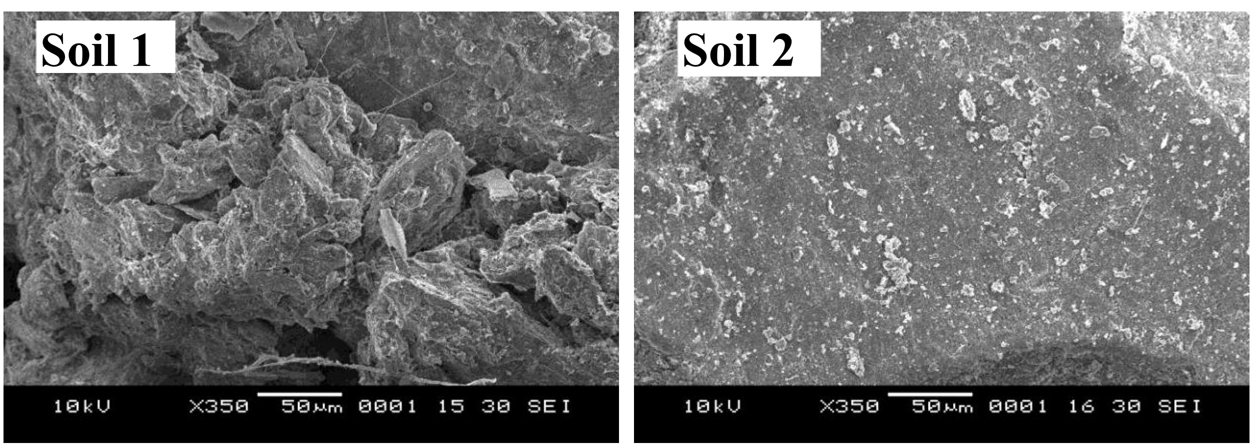


Figure 2 Scanning electron microscope of both soils' particles with the scale bar of 50 µm on both soils. The images of both soils were recorded at 5.0 kV current probe, with identical magnification of each pair

***Variation in water retention curve across biochar types***

SWRCs were modeled by using HYPROP-FIT software for both vG and BC models. All the biochar samples were tested at 3% and 6% biochar content for both soil 1 and soil 2 along with control samples (soil only). Biochar amended samples comparatively performed better than the control samples. Furthermore, the 6% amendment showed higher water retention than the 3% biochar amendment with both soils. The effect of biochar percentage was clearly observed in the saturation zone and transition zone (Fig.1-4 of SI). It was observed that all the biochar amended samples had higher water content values near the saturation zone and mostly gentle slope near the SWRC inflection point compared to both control samples which are shown in (Fig.1-4 of SI) with both the soils for vG and BC models. The difference in observed results with different biochar could be due to different wettability of biochar which is hydrophobic and hydrophilic properties. The water content at which tillage operations can result in production of greatest proportion of small aggregates, compared to both control samples (DEXTER AND BIRD, 2001). The inflection point or air entry point of the samples were determined from the intersection of tangents between saturated zone and transition zone (Fig. 5 SI). Higher water content at lower tensions also shows that addition of biochar increases the water retention abilities of the amended soil.

This has been proven in previous studies where biochar amendment increased the total porosity (Sun et al., 2015). Another explanation for the increase in water retention has been given due to increased content of organic matter within the matrix which results in a higher specific surface area and reduced soil bulk density (Basso et al., 2013; Rawls et al., 2003; Smith et al., 1985). Also, biochar type and particle size influence the water holding capacities. Soil amended with larger biochar particles (larger than 2mm) found to weaker whereas lower particle sized biochar (smaller than 0.25 mm) showed improved water holding capacity which could be attributed to large biochar particles reduce the dehydration rate (Chen et al., 2019).

This study found that the both tested soils exhibited distinct water retention capacities, primarily due to soil type (differences in organic content). Soil 1, which contained a higher amount of organic matter, demonstrated superior water retention compared to Soil 2, as organic material improves soil structure, enhances pore connectivity, and increases the ability to hold water. As a result, the influence of biochar on Soil 1 water retention was less pronounced. likely because the high organic content already contributed to moisture retention, making the additional impact of biochar less significant compared to its effect on Soil 2, which has a more silty texture. Also, both vG and BC models followed the same trend in terms of biochar performance. However, the BC models consider slightly lower values in modeling. Overall, the result shows that biochar is effective in retaining moisture within the biochar soil matrix.

***Impact of Biochar Characteristics on Hydraulic Properties***

Field water holding capacity (WHC) and permanent wilting point (PWP) were calculated based on the water pressure measured at -0.033 MPa and -0.15 MPa. The difference between (WHC) and (PWP) provides the available water capacity (AWC) for plants. The difference between water content at t -0.03 and -0.1 MPa gives the readily available water content (RAWC) (Hillel, 2013). Variations across WHC, PWP, and AWC for each soil-biochar mixture are shown in Table 2 and Table 3 for both the soils with the vG method.

In the dry (high suction) phase, the biochar amended soil samples show mixed results for water retention than the control samples for the soil 1 whereas with soil 2, most of the biochar showed comparatively higher water retention than the control sample. Biochar which showed the higher pores, less water holding capacity will be implicated as intense water flux through the inner caliber will happen due to macropores which can be found from water holding capacity. Also, the reason for the inconsistency could be due to the less amount of sample used for WP4C testing where soil would have a major effect in testing. Higher percentage of biochar mixture needs to be conducted to understand the performance at higher suction pressure. This study demonstrates that at higher suction pressure, during the dry period, organic content within the soil plays an important role. The water retention properties of soil also varied with different biochar types. WF, BS, CB, and BNS biochar were the best performing biochar and their performance was consistent with the both soil whereas TA and NC showed the lowest effect.

The findings align with the prior study of Fang et al. (2018) showing biochar's potential to plant growth and resilience. The porous structure and high surface area of biochar facilitate improved water retention and soil health promoting increased soil moisture availability for plant growth (Bruun et al., 2014). This helps in sustaining plants during the dry season, preventing soil loss due to erosion from flooding in the wet season. The enhanced soil properties could aid in habitat restoration, strengthening local biodiversity and healthy roadside landscapes (Moore et al., 2023). The biochar application rate 3% and 6% (w/w) in this study is comparatively lower than the previous studies. For example, the study of Garg et al. (2022) used 5%, 10%, and 15% biochar content to loam and sandy loam soil. In another, the study of Wong et al. (2017) used biochar content of 20% to found the effect on water holding capacity of the soil. Similarly, the other study of Wong et al. (2018) with clay soil, the biochar content to conduct Ksat was 20%.

Table 2 Effect of biochar on different water retention characteristics of soil 1 with vG method

| Treatment | Biochar content | WHC | PWP | AWC | RAWC |
|---|---|---|---|---|---|
| Soil only | | 38.28 | 38.28 | 12.63 | 10.17 |
| WF | 3% | 46.66 | 32.46 | 14.20 | 12.50 |
| | 6% | 47.20 | 32.12 | 15.08 | 12.82 |
| AG | 3% | 45.75 | 28.82 | 16.93 | 14.29 |
| | 6% | 49.77 | 33.31 | 16.46 | 13.49 |
| BS | 3% | 46.00 | 35.59 | 10.41 | 10.41 |
| | 6% | 45.62 | 30.73 | 14.89 | 13.34 |
| SR | 3% | 43.13 | 30.67 | 12.46 | 11.02 |
| | 6% | 50.78 | 35.74 | 15.04 | 12.49 |
| NC | 3% | 43.14 | 31.31 | 11.83 | 10.16 |
| | 6% | 44.76 | 30.73 | 14.03 | 11.49 |
| TA | 3% | 39.84 | 27.25 | 12.59 | 11.39 |
| | 6% | 43.05 | 29.62 | 13.43 | 10.79 |
| CB | 3% | 43.36 | 32.84 | 10.52 | 9.03 |
| | 6% | 49.61 | 33.01 | 16.60 | 14.70 |
| BNM | 3% | 44.47 | 28.38 | 16.09 | 13.38 |
| | 6% | 48.09 | 31.64 | 16.45 | 13.64 |
| BNS | 3% | 41.95 | 28.42 | 13.53 | 11.54 |
| | 6% | 43.21 | 29.07 | 14.14 | 12.03 |

Table 3 Effect of biochar on different water retention characteristics of soil 2 with vG method

| Treatment | Biochar content | WHC | PWP | AWC | RAWC |
|---|---|---|---|---|---|
| Soil only | | 37.72 | 33.55 | 4.17 | 3.83 |
| WF | 3% | 40.325 | 34.32 | 6.01 | 5.24 |

| | | | | | |
|---|---|---|---|---|---|
| | 6% | 42.31 | 34.24 | 8.07 | 7.06 |
| AG | 3% | 33.625 | 30.79 | 2.84 | 2.77 |
| | 6% | 42.955 | 36.01 | 6.95 | 5.97 |
| BS | 3% | 40.12 | 33.07 | 7.05 | 6.15 |
| | 6% | 37.425 | 29.25 | 8.18 | 7.33 |
| SR | 3% | 35.42 | 29.27 | 6.15 | 5.46 |
| | 6% | 40.9 | 34.22 | 6.68 | 5.89 |
| NC | 3% | 37.85 | 31.91 | 5.94 | 5.30 |
| | 6% | 37.115 | 30.26 | 6.86 | 6.10 |
| TA | 3% | 31.835 | 27.01 | 4.83 | 4.44 |
| | 6% | 30.74 | 26.63 | 4.11 | 3.82 |
| CB | 3% | 39.21 | 32.83 | 6.38 | 5.62 |
| | 6% | 37.425 | 29.25 | 8.18 | 7.33 |
| BNM | 3% | 42.78 | 40.66 | 2.12 | 2.07 |
| | 6% | 42.78 | 40.66 | 2.12 | 2.07 |
| BNS | 3% | 38.6 | 33.20 | 5.40 | 4.87 |
| | 6% | 41.86 | 36.89 | 4.97 | 4.47 |

***Air entry pressure and biochar performance***

Air entry pressure varies with different biochar and also with the different soil types which are shown in Table 4 and Table 5. Most of the biochar have shown lower air entry pressure than the control sample. Soil 1, which has higher porosity and higher organic content, shows lower air entry pressure than soil 2 indicating that the organic matter present within the soil samples affect the capillary forces. And this effect was obvious between both the soils. As the concentration of biochar increases the porosity of the biochar soil matrix also increases. Which results in lower air entry pressure at 6% concentration of biochar than 3% or control samples. And best performing biochar were SR, CB, and BNS. Also, mixed results or no improvement were observed at 3% and 6% biochar contents for few biochar such as TA and AG with both the soil. Comparatively lower air entry pressure has been found at 6% biochar content. The observed biochar modification impacted positively on soil hydrologic and agronomic response under different weather conditions.

When the results were compared with both the models, vG and BC models show similar trends in performance at both biochar application rates. However, the BC model shows comparatively lower air entry pressure than vG models.

With the increase of particle size, the air entry value decreases which can be attributed to increase in micropores with larger biochar size (Edeh and Masek, 2022). The air entry pressure is explicitly dependent on the porosity of the soil (Nuth and Laloui, 2008). Biochar enhances the porosity of the soil mixture, as shown by results at both 3% and 6% biochar application levels (Table 2 of SI). The performance of each biochar varies based on factors such as feedstock type, particle size, and soil properties. Notably, Soil 1, with its higher organic content and higher porosity values, exhibited lower air entry values compared to Soil 2. This is because biochar increases the porosity of the mixture, allowing air to infiltrate more easily through the sample.

Table 4 Air entry pressure of soil 1 with different biochar

| **Sample** | **vG** | | **BC** | |
|---|---|---|---|---|
| | ***3%*** | ***6%*** | ***3%*** | ***6%*** |
| **Soil** | 1.1 | 1.1 | 0.6 | 0.6 |
| **WF** | 1.2 | 0.5 | 1.0 | 0.6 |
| **AG** | 1.2 | 0.5 | 1.0 | 0.6 |
| **BS** | 1.4 | 1.2 | 1.1 | 1.0 |
| **SR** | 0.5 | 0.8 | 0.9 | 1.4 |
| **NC** | 0.9 | 1.0 | 1.0 | 0.7 |
| **TA** | 1.2 | 1.1 | 0.8 | 0.5 |
| **CB** | 0.5 | 1.1 | 1.1 | 1.2 |
| **BNM** | 1.2 | 1.1 | 0.5 | 0.5 |
| **BNS** | 0.6 | 0.5 | 0.4 | 0.5 |

Table 5 Air entry pressure of soil 2 with different biochar

| **Sample** | **vG** | | **BC** | |
|---|---|---|---|---|
| | ***3%*** | ***6%*** | ***3%*** | ***6%*** |
| **Soil** | 13.0 | 13.0 | 12.0 | 12.0 |
| **WF** | 10.0 | 8.0 | 5.0 | 7.0 |
| **AG** | 14.0 | 12.0 | 13.0 | 8.0 |

| | | | | |
|---|---|---|---|---|
| **BS** | 11.0 | 7.0 | 8.0 | 5.0 |
| **SR** | 6.0 | 4.0 | 5.0 | 4.0 |
| **NC** | 10.0 | 7.0 | 4.0 | 7.0 |
| **TA** | 11.0 | 13.0 | 7.0 | 10.0 |
| **CB** | 5.0 | 8.0 | 4.0 | 6.0 |
| **BNM** | 10.0 | 7.0 | 2.0 | 5.0 |
| **BNS** | 10.0 | 8.0 | 4.0 | 6.0 |

***Variability in vG and BC Model's Parameters***

The α and n values of vG model and α and lambda values of BC model for soil 1 and soil 2 are plotted in Fig. 4 and Fig. 5 respectively. The suction pressure at the point of air entry refers to α values and is proportional to the radius of the largest pore openings (Ghanbarian-Alavijeh et al.2010). Most of the biochar at 3% and 6% amendment shows that α values are comparatively lower than the control samples for soil 1. And similar results have been found with the study of Garg et al. (2022) where the fitted parameters for vG and BC showed lower with biochar amended soil and also with increase in biochar concentration. However, some inconsistent results have been found within 3% and 6% amendment. For example, AG biochar at 6% shows a very high alpha value than 3% and control samples. Similarly, CB biochar at 3% shows higher value than control and 6% biochar content. Both vG and BC follow the similar trend however α values for BC models were comparatively higher than vG models. The relative lower values of α of biochar amendment shows the largest pore diameter of biochar amended soil was smaller than the control samples. Conversely, most of the biochar amended with soil 2 showed higher α values than the control samples and also 6% biochar content comparatively showed enhanced α values. As, these properties are highly influenced by soil type, the study of Xing et al. (2021) found increased α when biochar was increased from 5% to 15%. Similar to soil 1, few biochar found to have inconsistent results. For example, BS at both biochar content had lower values and moreover 6% values were even more on the lower side. A similar trend can be found with both models with all the biochar and BC models comparatively have higher α values than vG model.

The n values from the vG model represents the "shape" parameter where steepness of the curve indicates the increase in the water volume at field capacity which are shown in Fig 1. Our study shows mixed results with soil 1 where some biochar showed higher values than the control sample whereas some of the samples were found on the lower side. And similarly, some biochar at 6% showed lower values than the 3% and control samples. Whereas, soil 2 which did not have organic content, showed that biochar content at 3% and 6% enhanced the n values of the soil. Moreover, 6% biochar comparatively showed even enhanced values than 3%. Also, soil 2 values are comparatively on the higher range than soil 1 values. While Dokoohaki et al. (2017) reported that biochar amendments reduce n values, other studies have found varying results, indicating that the influence of biochar on n values is not uniform. The difference in the results are attributed to biochar feedstock types, application rates, and soil properties, as reported by Lei and Zhang (2013) and Hardie et al. (2014).

The pore size distribution index (λ) of biochar soil mixture was assessed with the BC model and results are shown in Fig. 4 and Fig. 5. Some of the biochar amendment with soil 1 showed comparatively higher values than the control samples and also enhanced values at 6%. Although, few biochar amendments have shown lower values than the control samples. However, the obtained values from soil 2 showed all the biochar amendments increased the lambda values.

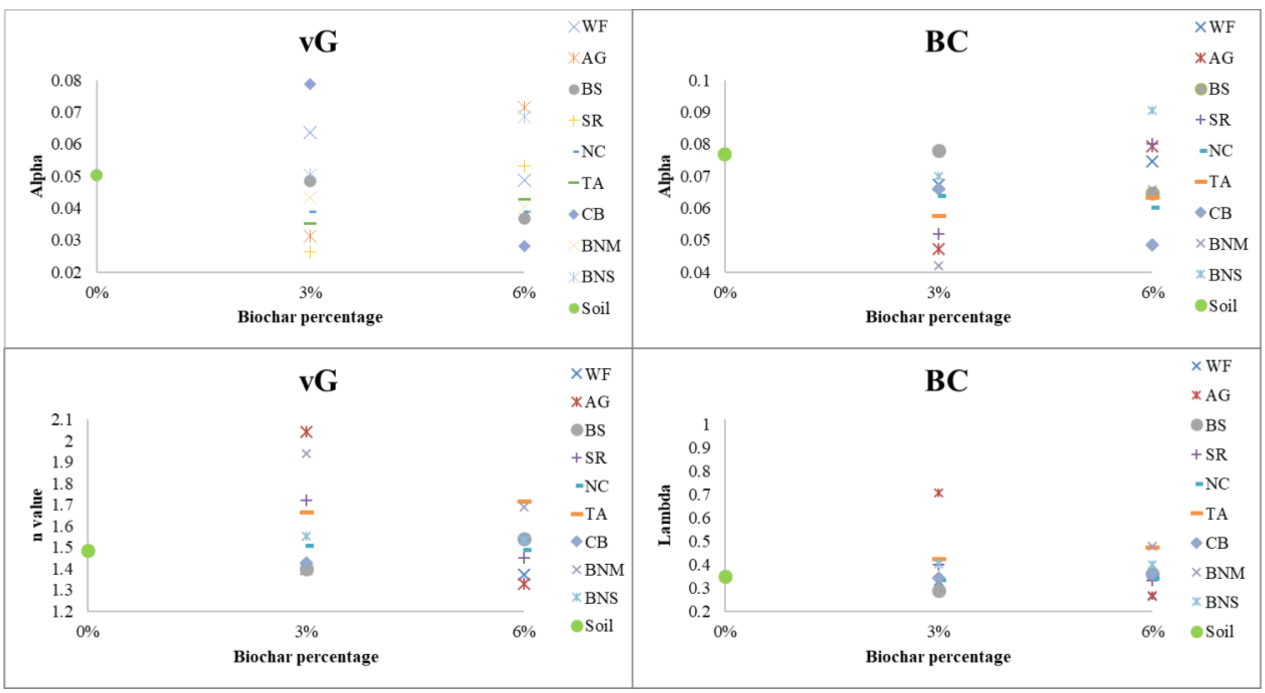


Figure 4 Model parameters of soil 1

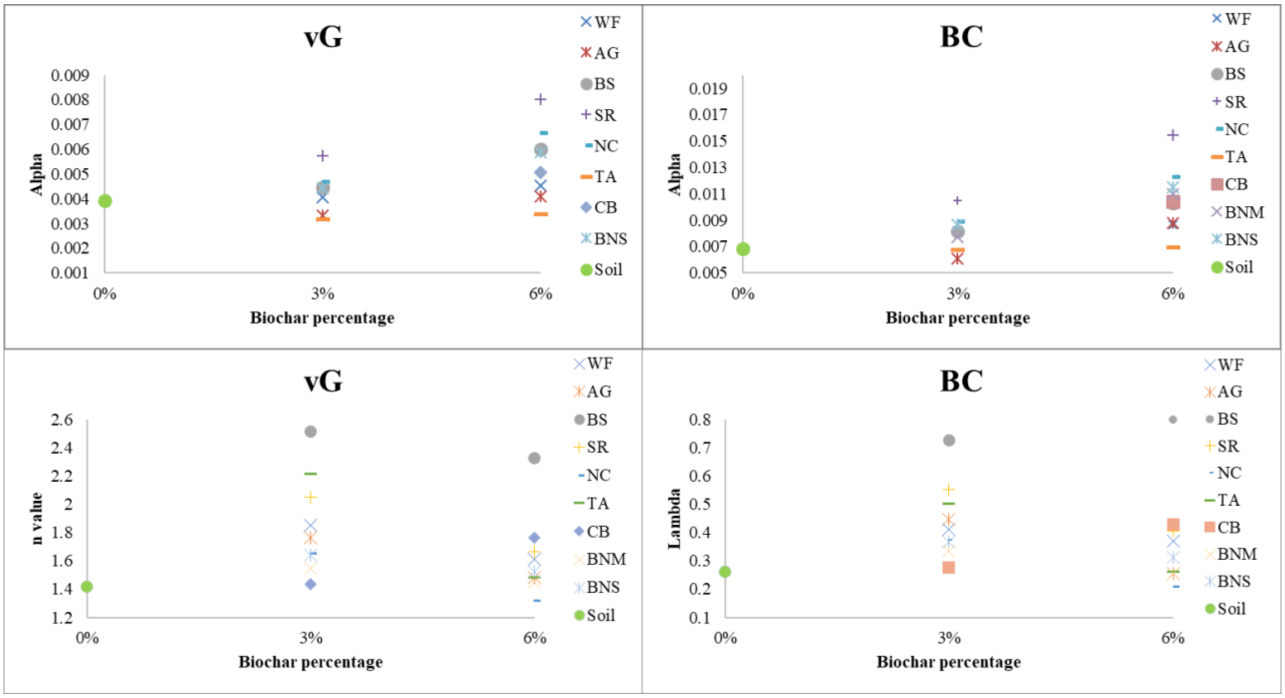


Figure 5 Model parameters of soil 2

**Conclusion**

This study aimed to determine the water retention characteristics, air entry pressure, and model parameters of vG and BC models curves for two fine-grained soils amended with biochar. The effects of nine commercial biochars were evaluated at 3% and 6% concentrations. Results show that biochar amendment enhance water retention properties of these soils. Soil 1, which is a clay rich soil, exhibited higher water retention due to having organic content, leading to less benefits from biochar addition. However, the silt-dominant soil (Soil 2) showed higher improvements, indicating biochar's effectiveness is more pronounced in soils with lower organic matter.

From the plotted models, air entry pressure was calculated using gravimetric water content and suction pressure. The results revealed that biochar amendments, particularly at 6%, reduced air entry pressure compared to control and 3% treatments, facilitating improved water infiltration. The BC model consistently predicted lower air entry pressures and water retention values than the vG model, reflecting differences in their assumptions about pore-size distribution. Also, both model parameters were influenced by biochar amendments with both soils. In soil 2, biochar increased $\alpha$ values, improving air entry potential, while in soil 1 it reduced $\alpha$ values. Soil 2 also exhibited higher $n$ values, indicating better pore connectivity. The BC model indicated higher $\lambda$ values for biochar-amended samples compared to control, especially in soil 2, suggesting that biochar enhances the soil's ability to retain water at varying moisture levels. With most biochar types enhancing performance in both soils, though soil 2 benefiting more significantly from the amendments.

It has been found that 6% biochar amendment generally outperforms 3% biochar concentration. However, performance varied across different biochar types due to differences in feedstock, pyrolysis conditions, and particle size. Both the vG and BC models showed consistent trends, though the BC model showed slightly lower water retention. As the demand for sustainable approaches to soil amendment continues to grow, biochar could be a potential solution. However, factors such as feedstock selection, application method, long-term impact, and contaminant leaching must be carefully considered, especially in areas with varying local soil types. So, before biochar application, soil properties need to be assessed to select the most suitable biochar. Future research should focus on field studies and evaluate biochar performance under diverse environmental conditions to ensure its long-term effectiveness.

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