



Impact of Biochar Particle Shape and Size on Saturated Hydraulic Properties of Soil

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Abstract

BACKGROUND: Different physical and chemical properties of biochar, which is made out of a variety of biomass materials, can impact water movement through amended soil. The objective of this research was to develop a decision support tool evaluating the impact of the shape and the size distribution of biochar on soil saturated hydraulic conductivity (K_{sat}).

METHODS AND RESULTS: Plastic beads of different size and morphology were compared with biochar to assess impacts on soil K_{sat} . Bead and biochar were added at the rate of 5% (v/w) to coarse sand. The particle size of bead and biochar had an effect on the K_{sat} , with larger and smaller particle sizes than the original sand grain (0.5 mm) decreasing the K_{sat} value. The equivalent size bead or biochar to the sand grains had no impact on K_{sat} . The amendment shape also influenced soil hydraulic properties, but only when the particle size was between 3-6 mm. Intra-particle porosity had no significant influence on the K_{sat} due to its small pore size and increased tortuosity compared to the inter-particle spaces (macro-porosity).

CONCLUSION: The results supported the conclusion that both particle size and shape of the amended biochar impacted the K_{sat} value.

Key words: Biochar size distribution, Saturated hydraulic conductivity, Tortuosity

Introduction

The saturated hydraulic conductivity (K_{sat}) of soil is a function of soil texture, soil particle arrangement, clay content, organic matter content, soil aggregation, bioturbation, shrink-swelling, and overall soil structure (Hillel, 1998; Moutier *et al.*, 2000; Vervoort and Cattle, 2003; West *et al.*, 2008). The K_{sat} is one of the main physical properties that aid in predicting complex water movement and retention pathways through the soil profile (Keller *et al.*, 2012; Quin *et al.*, 2014). It is also widely used as a metric of soil physical quality (Reynolds *et al.*, 2000).

It appears that the impact of biochar on the soil hydraulic properties is a complex interaction of the physical properties of soils and biochars. Several studies have reported that the incorporation of biochar to soil increased the K_{sat} (Herath *et al.*, 2013; Moutier *et al.*, 2000; Oguntunde *et al.*, 2008), but other studies have observed decreased K_{sat} following biochar additions (Brockhoff *et al.*, 2010; Uzoma *et al.*, 2011; Githinji *et al.*, 2014). In contrast, Barnes *et al.* (2014) found that biochar addition decreased by 92% the K_{sat} in sand, but increased K_{sat} by 328% in clay-rich soil. However, it is unclear which physical characteristics of biochar have the greatest effect on

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the transport and the interaction of water within the soil profile.

The shape and size of external biochar pores is a function of particle size and particle morphology. The biochar particle size and particle morphology depend on the shape of raw materials, which can be processed into a range of shapes from platy to spherical (Abel *et al.*, 2013; Yargicoglu *et al.*, 2014). The particle size of biochar also impacts the hydraulic conductivity due to the increase of tortuosity when it added to soil as biochar consists of mostly different particle size distributions (Lim *et al.*, 2016). Those features could affect the pore distribution of soil after addition of biochar to soil and, the important flow characteristics like hydraulic conductivity (Sperry and Peirce, 1995; Lim *et al.*, 2016).

Biochar porosity has been divided into micropores (<2 nm), mesopores (2-50 nm), and macropores (>50 nm) based on internal diameter (Rouquerol *et al.*, 1994; Rouquerol *et al.*, 1999). However, Gray *et al.* (2014) reported this classification system does not adequately account for micrometer size pores that dominates soil water retention and transport (typically >15,000 nm).

Pores between 1 and 100 μm in diameter are regarded to contain the majority of pore volume within biochar (Sun *et al.*, 2012; Gray *et al.*, 2014). Hydraulic conductivity in saturation condition is significantly influenced by the presence of large macropores (>100 nm) (Bouma *et al.*, 1977; Bouma, 1982). An interconnected network of macropores will facilitate the rapid downward movement of water through soil profile (Mallants *et al.*, 1997; Vervoort and Cattle, 2003). For soil applications, the presence of macropores in biochar could also affect the hydraulic conductivity of soil.

This research is an investigation of the influence of the shape and the size of biochar particles on hydraulic conductivity. The objectives of this research were (1) in order to determine the influence of biochar particle size on the K_{sat} when two different types of biochar were added to coarse sand and (2) to determine whether coarse sand amended with spherical and non-spherical beads can be used to predict K_{sat} values of soils amended with biochar.

Materials and Methods

Sand

Coarse sand was obtained from QUIKCRETE Company

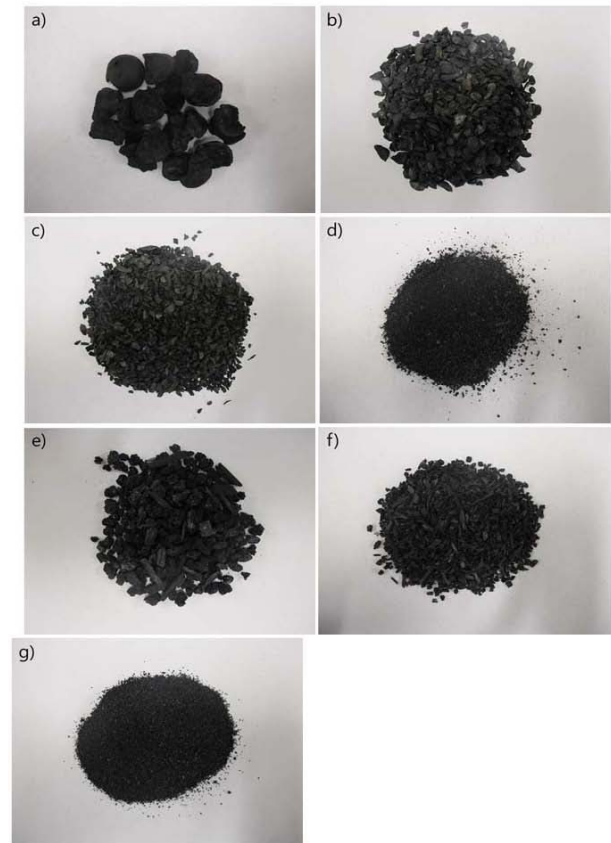


Fig. 1. Photos by different particle sizes of Macadamia nutshell (a-d) and Pine chip (e-g) biochar used in this experiment: a) 18 mm, b) 8.0-4.0 mm, c) 4.0-2.0 mm, d) <2.0 mm, e) 8.0-4.0 mm, f) 4.0-2.0 mm, g) <2.0 mm.

(Atlanta, GA USA). Particle size distribution of coarse sand was determined by manual dry sieving of a 500 g subsample of homogenized sand. Dry sieving was performed using seven different sized sieves arranged in decreasing sizes of 4.0, 2.0, 1.0, 0.5, 0.25, 0.1, and 0.05 mm and agitating for 10 min. The sand was 4% >2mm, 9% 1-2 mm, 39% 0.5-1 mm, 43% 0.25-0.5 mm, and 5% <0.25mm (median 0.5 mm) by weight.

Biochars and beads

The biochars used in the experiments were derived from pine wood chips (bark and limbs, *Pinus ponderosa* and *P. banksiana*), and macadamia nutshell (*Macadamia integrifolia*). Dry sieving 100 g of the biochars (10 min agitation) resulted in size fractions from 8 to 4 mm, from 4 to 2 mm, and <2 mm (Fig. 1). The average diameter of macadamia nutshell remaining on the 8 mm sieve size after sieving was 18 mm. Spherical and non-spherical beads (15.0, 8.0, 3.0, 1.0, and 0.1 mm) were purchased from various commercial companies (Fig. 2).

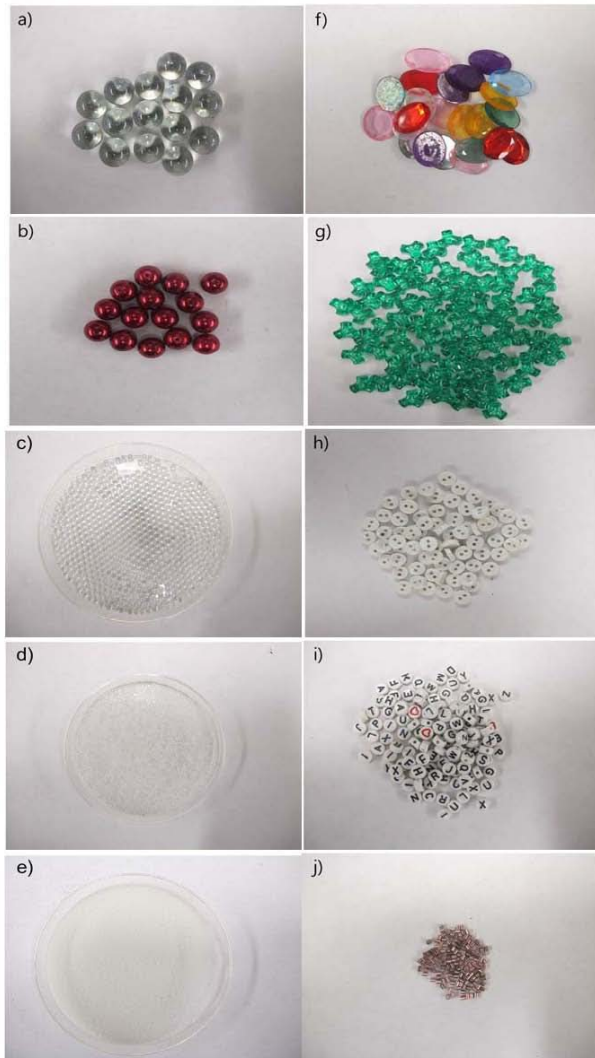


Fig. 2. Photos by different particle sizes of spherical beads (a-e) and non-spherical beads (f-i): a) 15.0 mm, b) 8.0 mm, c) 3.0 mm, d) 1.0 mm, e) 0.1 mm, f) 13.0 mm (13.0×18.0×2.0 mm), g) 10.0 mm (10.0×10.0×4.0 mm), h) 7.0 mm (7.0×7.0×2.0 mm), i) 6.0 mm (6.0×6.0×4.0 mm), j) 2.5 mm (2.5×2.5×2.0 mm).

Preparation of columns

The two biochars and spherical or non-spherical beads were each combined at 5% volume per weight with coarse sand and thoroughly mixed to provide a homogeneous mixture. It should be noted, that we normalized the additions to volume, such that the density difference of beads and biochar would be minimized.

To determine the hydraulic conductivity, the coarse sand and biochar or bead mixtures were gently packed into a soil column (6 cm diameter×20 cm high) to approximately a 5 cm height with light tamping and vibration of the PVC column to eliminate any gaps and voids during packing. Four independent

replicates of each soil treatment were prepared.

Saturated Hydraulic Conductivity

Saturated hydraulic conductivity (K_{sat}) was measured using a falling head method (Klute and Dirksen, 1986). A piece of filter paper was placed on the soil surface to minimize soil disturbance when filling with water. Tap water was gently poured into column until it was full (20 cm height of column) and hydraulic testing was performed after steady flow conditions were attained, usually after 3-4 repetitive flushing of the entire column. The average drop in hydraulic head over a known time period was used to calculate the K_{sat} value for each sample by the following equation (Klute and Dirksen, 1986):

$$k = \frac{L}{t} \ln\left(\frac{h_o}{h_f}\right),$$

where L is the length of the soil sample (3-6 cm), t is the time period (sec), h_o is the initial height of water in the column referenced to the soil column outflow (cm), and h_f is the final height of water also referenced to the soil outflow (cm). Since the diameters of the column and water column were equivalent these factors cancelled out from the equation.

Bulk density

The bulk density of each individual column was determined by dividing the known mass of the oven dried sample added to the columns by the measured sample volume. This soil volume measurement occurred immediately after the hydraulic conductivity assessments.

Statistical analysis

Averages and standard deviations of the quadruplicates were calculated. The one-way analysis of variance (ANOVA) is used to determine whether there were any significant differences between the means of the independent treatment groups (R Core Team, 1980).

Results and Discussion

Bulk density

Biochar had a statistically significant influence on the bulk density of coarse sand after amendment ($p < 0.05$; Table 1). This decrease in bulk density following biochar incorporation has also been observed in other studies (e.g., Mukherjee *et al.*, 2014; Pathan *et al.*,

Table 1. The change of coarse sand bulk density after different size of biochar and bead were added to coarse sand

| Treatment | Biochar/bead additions | | | Bulk density of 5% (v/w) amended soil mixtures g/cm ³ |
|--------------------|------------------------|------------------------|-----------------------------------|---|
| | Size mm | Addition rate % v/w | Bulk density g/cm ³ | |
| Control | - | - | - | 1.68 (0.03)ab |
| Macadamia nutshell | > 8.0 | 5.0 | 0.36(0.02) | 1.61 (0.03) e |
| | 8.0 - 4.0 | 5.0 | 0.51 (0.03) | 1.59 (0.02) e |
| | 4.0 - 2.0 | 5.0 | 0.48 (0.05) | 1.59 (0.02) de |
| | < 2.0 | 5.0 | 0.51 (0.04) | 1.60 (0.02) ab |
| Pine chip | 8.0 - 4.0 | 5.0 | 0.26 (0.08) | 1.58 (0.04) e |
| | 4.0 - 2.0 | 5.0 | 0.30 (0.09) | 1.60 (0.02)cde |
| | < 2.0 | 5.0 | 0.51 (0.05) | 1.58 (0.04)cde |
| Spherical bead | 15.0 | 5.0 | 1.45 (0.07) | 1.68 (0.03) ab |
| | 8.0 | 5.0 | 1.32 (0.08) | 1.68 (0.02) ab |
| | 3.0 | 5.0 | 1.36 (0.10) | 1.65 (0.01)abcd |
| | 1.0 | 5.0 | 1.36 (0.11) | 1.66 (0.02)abc |
| | 0.1 | 5.0 | 1.59 (0.09) | 1.68 (0.02) ab |
| Non-spherical bead | 13.0 | 5.0 | 0.24 (0.05) | 1.60 (0.01)cde |
| | 10.0 | 5.0 | 0.76 (0.04) | 1.63 (0.01)abcde |
| | 7.0 | 5.0 | 0.30 (0.03) | 1.61 (0.01)cde |
| | 6.0 | 5.0 | 0.79 (0.05) | 1.63 (0.02)bcde |
| | 2.5 | 5.0 | 1.33 (0.07) | 1.68 (0.02) ab |

The values in parentheses are the standard deviation for the 4 assessments of the corresponding bulk densities. Values for the soil mixtures with the same letter are not statistically different from one another.

2003; Laird *et al.*, 2010) and is expected due to the lower particle density of the biochar materials compared to soils (Laird *et al.*, 2010; Brewer *et al.*, 2014; Rogovska *et al.*, 2014). The bulk density of the 6 to 13 mm non-spherical bead/sand mixture decreased similarly to the sand/biochar mixture; the 2.5 mm non-spherical bead/sand mixture is not different (Table 2). In contrast, the sand amended with spherical beads had a higher bulk density than that of the non-spherical bead/sand mixtures, likely linked to a possible improved packing and geometric packing arrangement.

Hydraulic Conductivity

The K_{sat} of coarse sand amended with spherical beads were significantly affected ($p < 0.05$) as compared to the K_{sat} of coarse sand (Fig. 3). Increasing the size of spherical beads in the sand from 1.0 to 15 mm decreased the K_{sat} . For example, the K_{sat} values of coarse sand added with 1 mm and 15 mm spherical beads were decreased to 206, and 112 mm/h, respectively as compared to 229 mm/h for sand.

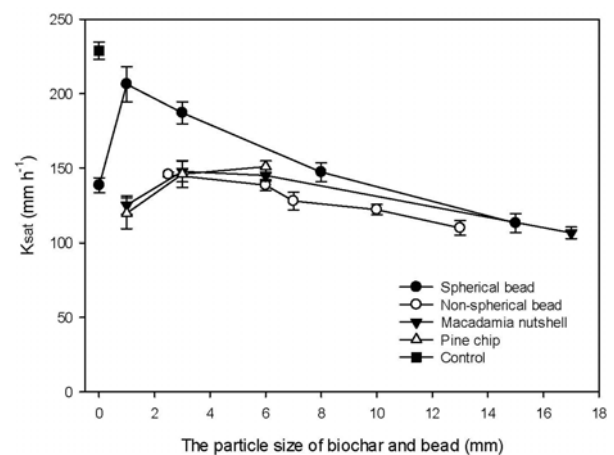


Fig. 3. The comparison of saturated hydraulic conductivity between biochar (pine chip and macadamia nutshell) and beads (spherical and non-spherical bead) treated with different particle sizes on the coarse sand.

Those reasons might be attributed to greater tortuosity and increased length of the water pathway following amendment of larger sized beads to sand as compared to the unamended sand, for which >85% of

the particles were <1.0 mm, with a median size of 0.5 mm (McKeague *et al.*, 1982; Kameyama *et al.*, 2012). It should be noted for the case of 0.1 mm beads also reduced K_{sat} , possibly as the result of clogging existing pores. Keren *et al.* (1980) attributed the reduction in hydraulic conductivity of soils following gypsum additions was due to small gypsum particles mechanical plugging existing pores.

The K_{sat} was also significantly affected by non-spherical bead and its particle size representing what could be affected by particle shape. Those K_{sat} value showed similar patterns with the K_{sat} of biochars in the condition of 3 and 6 mm, corresponding intermediate sizes of from 2-4 mm and 4-8 mm, indicating do not following the K_{sat} curve of the spherical bead added into coarse sand. It might be attributed to similar non-spherical shapes as shown Fig. 1 and Fig. 2. It could be also inferred that it does not well match with those methods such as Campbell (1985), and Smettem and Bristow (1999), and Saxton *et al.* (1986) models in predicting of K_{sat} , presumably because application of biochar and the shape of biochar play an important role in predicting and modeling of K_{sat} .

In the soil treated with biochar, there are two possible theoretical pathways in water flow through soil profiles (Barnes *et al.*, 2014). One is water migration through the pores within the biochar, the other is water migration through external space between sands or biochar-sand mixtures.

Firstly, there are potential water pathways through the pores within the biochar particle. The size distribution of pores of biochar appear a different range of from sub-nano (<1 nm) to macro (>50 nm), and their ability are well known for improving water holding capacity (Yu *et al.*, 2006; Atkinson *et al.*, 2010; Joseph *et al.*, 2010). From soil capillary forces, a given height of water rise in a capillary column can be related to the pore radius by the following equation:

$$h = \frac{2\gamma \cos(\theta_{contact})}{gr(p_{water})}$$

Where h is the height of rise in the capillary column (pore, m), γ is the surface tension of water [at 25°C=71.97 kg/sec²], $\theta_{contact}$ is the contact angle (assumed=0° rad), g is the acceleration due to gravity (9.8 m/sec²), p_{water} is the density of water (999.97 kg/m³), and r is the radius of the pore (m) (Hillel, 1998). Therefore, the largest pore that will be holding

water at a soil moisture potential at the wilting point (-1500 kPa) is 0.2 μ m. In other words, soil pores <200 nm are not of agronomic significance, since this soil moisture will not be plant or microbe available, as well as not contributing significantly to saturated water flow.

According to pore classification in relation to pore function, it is mentioned that pore sizes of between 0.005 and 0.5 μ m are recognized as retention and diffusion ions in solutions as residual pores, and pore sizes of between 0.5 and 50 μ m are capable of holding of water against gravity and release as storage pores, and pore sizes above 50 μ m play a drainage in excess water as transmission pores (Lal and Shukla, 2004). In other words, only pore sizes above 50 μ m play a critical role for water transport.

Gray *et al.* (2014) found that the sizes of biochar's macropore were centered in the low micrometer range and Shaaban *et al.* (2013) reported average pore diameter for rubber wood sawdust biochar treated at 300, 500, and 700°C was 7, 13, and 7 nm, respectively. All these median pore sizes are significantly below those pores theoretically available at the soil wilting point. Besides, Barnes *et al.* (2014) mentioned water pathway within biochar has greater tortuosity and the restriction of water flow due to the size of the smallest pore as well as the lack of interconnectivity. These facts justify the lack of significant impacts of biochar's intra-particle pores in water transport.

Secondly, there is also water pathway through external spaces between sands or biochar-sand mixtures. The size of external pores counts on particle size, particle morphology, and compaction (Juang and Holtz, 1985; Gray *et al.*, 2014). Bigelow *et al.* (2004) found that the K_{sat} values in coarse sand increased 6 times due to the higher presence of macro-porosity in the coarse sand (0.347 cm³/cm³) compared to fine sand (0.182 cm³/cm³), although the total porosity in fine sand, was higher in the fine sand (0.45 cm³/cm³ compared to 0.38 cm³/cm³). This result highlights the importance of pore size in regards to controlling K_{sat} . For example, according to Jong *et al.* (2007), the required time for water to move 30 mm through a channel with a 5 cm water head water was 200 sec for a 200 μ m channel compared to 1,400 sec for a channel of 50 μ m of diameter. Thereby, K_{sat} depends on the presence and proportion of macropores (50 μ m) existing within sands or biochar-sand and meanwhile the water pathway through internal pores

of biochar was largely restricted or had a little impact on the K_{sat} values.

Particle shape was also important parameter in ground-water flow such as hydraulic conductivity (Coelho *et al.*, 1997). Sperry and Peirce (1995) reported porous media consisted of irregular particles showed lower hydraulic conductivity for the larger (700 to 840 μm) particles, though particle shape had no observable influence for the smaller (150 to 180 μm) particles on hydraulic conductivity. Those results could be extrapolated on the basis of two things. The first thing is that non-spherical bead might put in denser configurations than spherical bead, creating smaller pore passage sizes and greater tortuosity. The other thing is when beads pour into a column, the shape the bead affects the angle of repose. For example, Friedman and Robinson (2002) found while the minimum and maximum angle of glass beads were 22.1 and 23.1 degrees respectively, those of soil grains were between 34 and 37 degrees. In other word, the angle of repose is influenced by the shape and roughness of the particles and is greater for non-spherical particles, which makes the K_{sat} increase (Sperry and Peirce 1995; Yun *et al.*, 2005).

Conclusions

Saturated hydraulic conductivity (K_{sat}) is influenced by the particle size distribution and the shape of bead and biochar treated with coarse sand. The application of larger particles sizes compared to the median sand (0.5 mm) decreased K_{sat} , while non-spherical particles had a more significant impact on decreasing K_{sat} than the spherical counterparts. The application of smaller particles size materials also decreased the K_{sat} value, most likely due to the mechanical clogging of original water pathways. The downward migration of water through inner holes within biochar in the well-drained coarse sand had little impact on the K_{sat} value. This data also demonstrated that an important consideration for biochar additions in altering hydraulic properties is the overall particle morphology also must be considered. However, further research is needed to understand the duration of these effects.

Notes

The authors declare no conflict of interest.

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