Influence of Biochar Particle Size and Shape on Soil Hydraulic Properties

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Abstract: 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}). Plastic beads of different size and morphology were compared with biochar to assess impacts on soil K_{SAT}. Bead and biochar at the rate of were 5% (v/w) were added to a 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 grains (0.5mm) 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 3-6mm. 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). The results support the conclusion that both particle size and shape of the biochar amendment will impact the K_{SAT} value.

Keywords: Biochar size distribution, saturated hydraulic conductivity, tortuosity.

1. 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 [1-4]. The K_{SAT} is one of the main physical properties that aid in predicting complex water movement and retention pathways through the soil profile [5-6]. It is also widely used as a metric of soil physical quality [7].

It appears that the impacts 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} [2, 8-9], but other studies have observed decreased K_{SAT} following biochar additions [10-12]. In contrast, Barnes *et al*. [13] found that biochar addition decreased by 92% the K_{SAT} in sand, but increased K_{SAT} by 328% in clay-rich soil. Similarly, Lim *et al*. [14] reported that the K_{SAT} decreased when biochar was added to a sandy-textured soil. Hydraulic conductivity and increased when biochar was added to a clay loam. However, it is unclear which physical characteristics of biochar have the greatest effect on 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 [15-16]. The particle size of biochar also impacts the hydraulic conductivity due to the increase of tortuosity when it added to soil [14]. Those features could affect the pore distribution of soil after addition of biochar to soil and the important flow characteristics like hydraulic conductivity [14, 17].

Biochar porosity has been divided into micropores (<2nm), mesopores (2-50nm), and macropores (>50nm) based on internal diameter [18-19]. However, Gray *et al*. [20] reported this classification system does not adequately account for micrometer size pores that dominate soil water retention and transport (typically >15,000nm).

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Pores between 1 and 100µm in diameter are regarded to contain the majority of pore volume within biochar [20, 21]. Hydraulic conductivity in saturated conditions is significantly influenced by the presence of large macropores (>100nm) [22-23]. An interconnected network of macropores will facilitate the rapid downward movement of water through soil profile [3, 24]. 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 to determine (1) the influence of biochar particle size on the K_{SAT} when two different types of biochar were added to coarse sand and (2) whether coarse sand textured soil amended with spherical and non-spherical beads can be used to predict K_{SAT} values of soils amended with biochar.

2. MATERIALS AND METHODS

2.1. Sand

Coarse sand was obtained from QUIKCRETE Company (Atlanta, GA USA). Particle size distribution of coarse sand was determined by manual dry sieving of a 500g sub sample of homogenized sand. Dry sieving was performed using sieve sizes of 4.0, 2.0, 1.0, 0.5, 0.25, 0.1, and 0.05mm and agitating for 10min. The sand was 4% >2mm, 9% 1-2mm; 39% 0.5-1mm; 43% 0.25-0.5mm; and 5% <0.25mm (median 0.5mm) by weight.

2.2. Biochars and Beads

The biochars used in the experiments were derived from pine wood chips (bark and limbs; *Pinus ponderosa and Pinus banksiana*), and macadamia nutshell (*Macadamia integrifolia*). Dry sieving 100 g of the biochars (10 min agitation) resulted in size fractions from 8 to 4mm, from 4 to 2mm, and <2mm (Figure **1**).

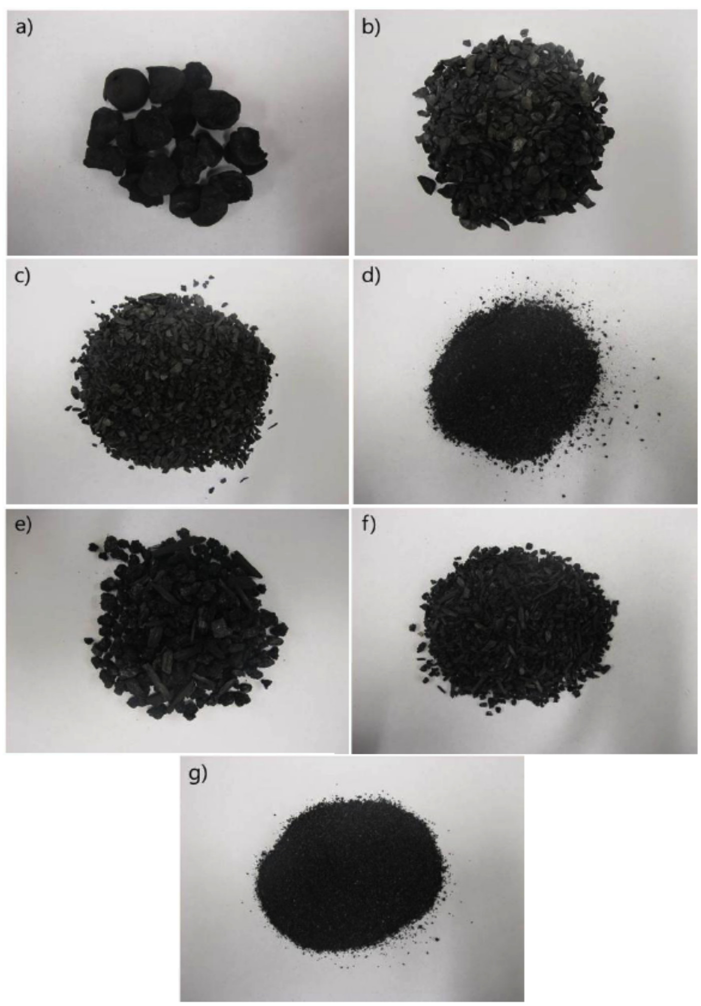

Figure 1: Photos of different particle sizes of Macadamia nutshell (a-d) and Pine chip (e-g) biochar used in this experiment: (a) 18mm, (b) 8.0-4.0mm, (c) 4.0-2.0mm, (d) <2.0mm, (e) 8.0-4.0mm, (f) 4.0-2.0mm, (g) <2.0mm.

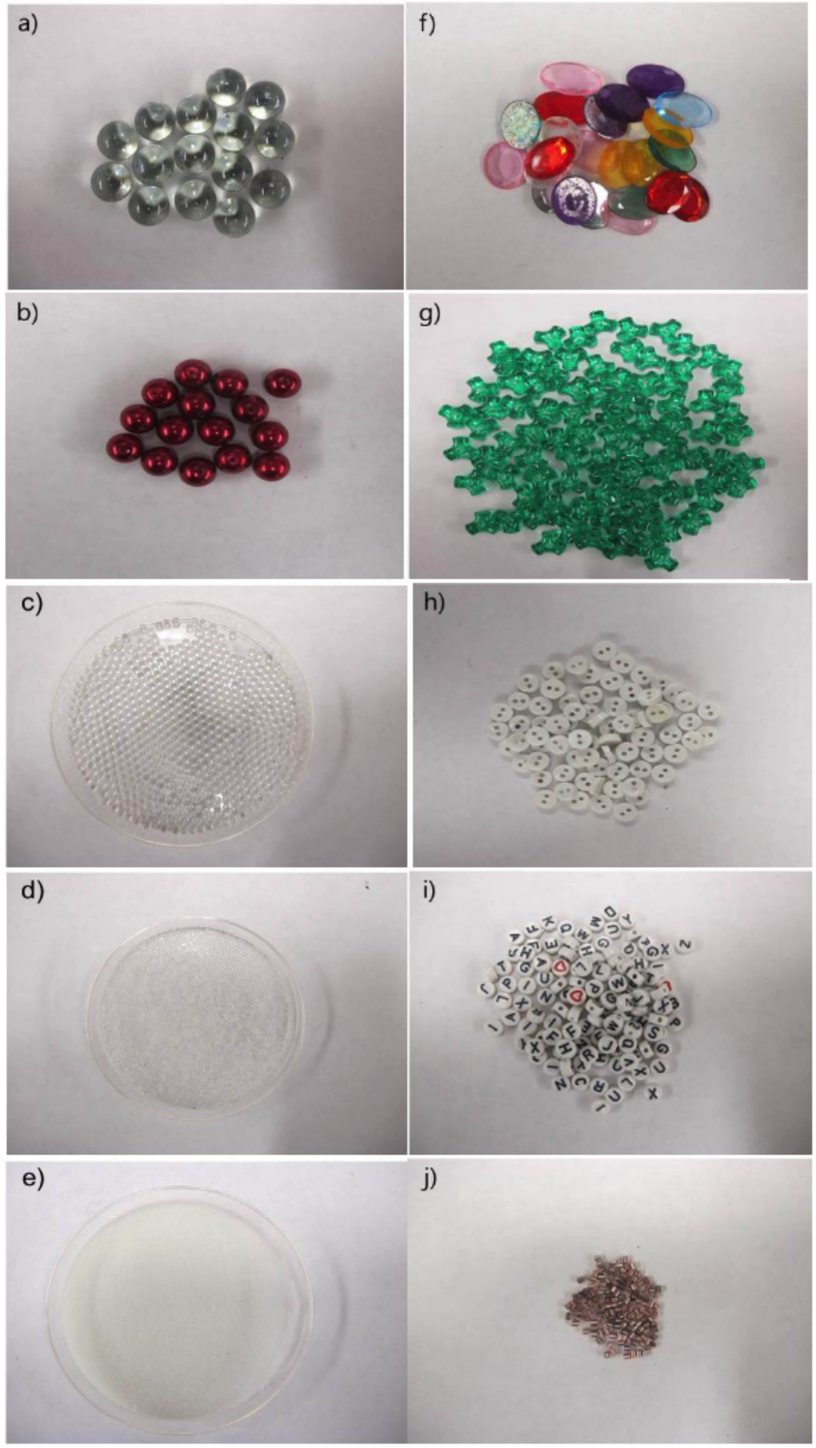

Figure 2: Photos of different particle sizes of spherical beads (a-e) and non-spherical beads (f-i): (a) glass 15.0mm, (b) plastic 8.0mm, (c) glass 3.0mm, (d) glass 1.0mm, (e) glass 0.1mm, (f) glass 13.0mm (13.0x18.0x2.0mm), (g) plastic 10.0mm (10.0x10.0x4.0mm), (h) plastic 7.0mm (7.0x7.0x2.0mm), (i) plastic 6.0mm (6.0x6.0x4.0mm), and (j) plastic 2.5mm (2.5x2.5x2.0mm).

The average diameter of macadamia nutshell remaining on the 8mm sieve size after sieving was 18mm. Spherical and non-spherical beads (15.0, 8.0, 3.0, 1.0, and 0.1mm) composed of glass and plastic were purchased from various commercial companies (Figure **2**).

2.3. Preparation of Columns

The various biochar and bead treatments 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 bead 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 (6cm diameter x 20cm high) to approximately a 5cm 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.

2.4. Saturated Hydraulic Conductivity

Saturated hydraulic conductivity (K_{SAT}) was measured using a falling head method [25]. 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 (20cm 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 [25]:

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

where L is the length of the soil sample (3-6cm), 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.

2.5. 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.

2.6. 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 [26]. Fisher protected least significant differences were then used to compare treatment means at the 95% (p=0.05, *Bonferroni* adjustment) significance level using the "*agricolae"* package in *R* [27].

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
	Size	Addition Rate	Bulk Density	
	mm	% v/w	g cm^{-3}	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.

3. RESULTS AND DISCUSSION

3.1. 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. 28-30] and is expected due to the lower particle density of the biochar materials compared to soils [30-32]. The bulk density of the 6 to 13mm non-spherical bead/sand mixture decreased similarly to the sand/biochar mixture; the 2.5mm non-spherical bead/sand mixture is not different than what? (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 optimized geometric packing.

3.2. 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 (control) (Figure **3**). Increasing the size of spherical beads in the sand from 1.0 to 15mm decreased the K_{SAT}. For example, the K_{SAT} values of coarse sand added with 1mm and 15mm spherical beads were decreased to 206, and 112mm h^{-1}, respectively as compared to 229mm h^{-1} for sand. A potential reason for the decrease might be greater tortuosity. This results in an 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 <1.0mm, with a median size of 0.5mm [33-34]. It was observed that 0.1mm beads also reduced K_{SAT}, which could be a result of the clogging existing pores by the smaller amendment. This is analogous to Keren *et al*. [35], who attributed the reduction in hydraulic conductivity of soils following gypsum additions to small gypsum particles mechanically plugging existing pores.

Our observations demonstrated that the K_{SAT} was also significantly affected by particle shape, as illustrated by the addition of the non-spherical beads. All K_{SAT} values of the non-spherical beads were lower than the equivalent sized spherical beads (Figure **3**). However, this difference was reduced with increasing particle size. This result indicates that the particle size pedo transfer functions for K_{SAT} [e.g. 36-38] should solely be applied to biochar with spherical particle sizes. This data demonstrates that the shape of the added biochar particles does play an important role in predicting and modeling of resulting K_{SAT}.

In the soil treated with biochar, there are two possible theoretical pathways for water to flow through a soil profile [13]. 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 to cover a range

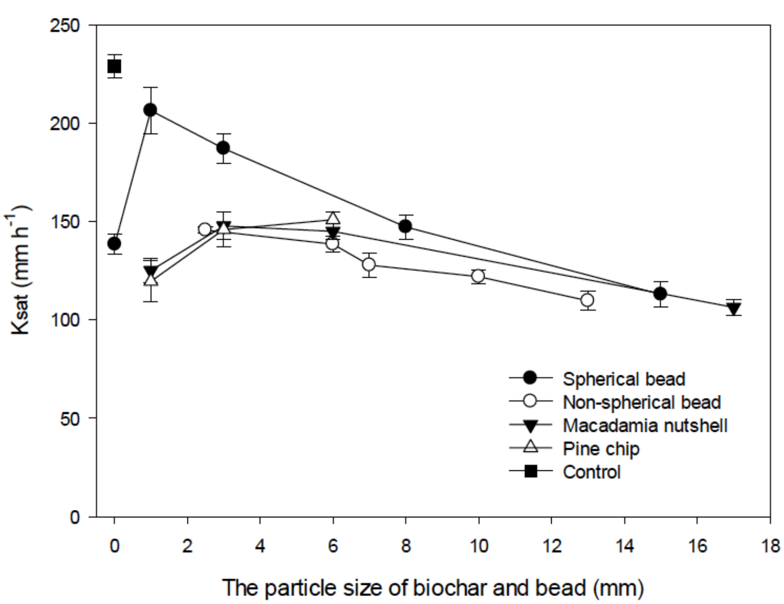

Figure 3: The comparison of saturated hydraulic conductivity between biochar (pine chip and macadamia nutshell) and beads (spherical and non-spherical bead) treated with different particle sizes on the medium sand.

from sub-nano (<1nm) to macro (>50nm) in size. As we add more macroporosity, biochar additions will increase plant available water holding capacity [39-41]. 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:

$$h = \frac{2\gamma \cos(\theta_{contact})}{g\, r\, (\rho_{water})}$$

where h is the height of rise in the capillary column (pore) (m), γ is the surface tension of water is the density of water (999.97 kg m^{-3}), and r is the radius of the pore (m)[1]. Therefore, the largest pore that will be holding water at a soil moisture potential at the wilting point (-1500 kPa) is 0.2µm. In other words, soil pores <200 nm are not of agronomic significance, since this soil moisture will not be plant or microbe available nor will it contribute 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 0.2µm are known as pores responsible for residual soil moisture (held more tightly than the plant wilting point). Pore sizes of between 0.5 and 50µm are capable of holding of water against gravity and release as storage pores, and pore sizes above 50µm result in drainage and water transmission pores [42]. In other words, only pore sizes above 50,000nm play a critical role for water transport.

Gray *et al*. [20] speculated that the pore size of biochar is centered in the low micrometer range. Whereas, Shaaban *et al*. [43] reported average pore diameter for rubber wood sawdust biochar treated at 300, 500, and 700 $^{\circ}C$ was 7, 13, and 7nm, respectively. All these median pore sizes are significantly below those pores theoretically available at the soil wilting point. Besides, Barnes *et al*. [13] mentioned water pathway within biochar has greater tortuosity and restricts water flow due to the physical size and lack of pore interconnectivity. These explanations justify the lack of significant impacts of biochar's intra-particle pores in water transport.

Second, there are water pathways through external spaces between sands or biochar-sand mixtures. The size of external pores depends on particle size, particle morphology, and compaction [20, 44]. Bigelow *et al*. [45] found that the K_{SAT} values in coarse sand increased 6 times due to higher macro-porosity in the coarse sand (0.347cm^3 cm^{-3}) compared to fine sand (0.182cm^3 cm^{-3}), although the total porosity in fine sand was higher in coarse sand (0.45cm^3 cm^{-3} compared to 0.38cm^3 cm^{-3}). This result highlights the importance of pore size in regards to controlling K_{SAT}. For example, according to Jong *et al*. [46], the required time for water to move 30mm through a channel with a 5cm water headwater was 200 sec for a 200µm diameter channel compared to 1400sec for a channel of 50µm of diameter. Thereby, K_{SAT} depends on the presence and proportion of macropores (50µm) within sands or biochar amended soils sand and the water pathway through internal pores of biochar was largely restricted and has little impact on the K_{SAT} values.

Particle shape has been observed to be an important factor in ground-water flow [47]. Sperry and Peirce [17] reported porous media composed of irregular particles showed lower hydraulic conductivity for the larger (700 to 840µm) more spherical particles, though particle shape had no observable influence on hydraulic conductivity for smaller (150 to 180µm) particles. These results can be explained by two factors. First, non-spherical beads might result in denser configurations than spherical beads, creating smaller pore passage sizes and thus greater tortuosity. Second, when beads are poured into a column the bead shape will affect the angle of repose. For example, Friedman and Robinson [48] 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 words, the angle of repose is greater for non-spherical particles, which results in higher porosity and thus an increase in K_{SAT} [17, 49].

K_{SAT} is influenced by the particle size distribution and the shape of bead or biochar amendment. The application of larger particles sizes compared to the median grain size (0.5mm) decreased K_{SAT}, while non-spherical particles had a more significant impact on decreasing K_{SAT} than the spherical counterparts. Addition of materials from 13-17mm reduce K_{SAT} by approximately one-half regardless of the shape. The application of materials with smaller particle sizes than the median grain size of the soil 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 the overall particle morphology of biochar added to sand is a vital consideration with respect to altering hydraulic properties. However, further research is needed to understand the duration of these effects.

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