Properties of biochar are thought to determine whether phosphorus (P) sorption or increased P availability occur following biochar application to sandy acidic soil; the effect of soil properties on P retention in biochar-amended acid soils remains largely unexplored. Our objective was to determine effects of hardwood biochar and poultry litter biochar on P sorption and release from two soils differing in P retention properties at three rates of biochar addition. Soils as well as soil + biochar mixtures were treated with 12 levels of solution P concentrations. Phosphorus concentration and the amount of P sorbed for each level of P addition at the end of the incubation showed that after P addition corresponding to the soil P storage capacity (SPSC) as determined prior to biochar application, P retention abruptly declined for all treatments irrespective of biochar type. Biochar did not diminish the capacity of the two soils to tenaciously bind P added as a soluble inorganic source. Also, the maximum P retention capacity of the soil ($S_{\max}$) increased as amount of biochar applied increased. Biochar-enhanced P sorption at high solution concentrations would be environmentally beneficial only if the sorption were strongly hysteretic such that subsequent P release is minimal as concentrations approach background levels. X-ray diffraction analysis of the biochar after incubating at high P solution concentration did not reveal formation of a stable crystalline P phase. This study provides evidence that the amount of P that can be “safely” added to soils amended with biochar depends significantly upon the P retention property of the soil, and not only the biochar characteristics.

1 Title: Relative influence of soil- vs. biochar properties on soil phosphorus retention

4 Running head: Biochar and phosphorus retention

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Abstract

Properties of biochar are thought to determine whether phosphorus (P) sorption or increased P availability occur following biochar application to sandy acidic soil; the effect of soil properties on P retention in biochar-amended acid soils remains largely unexplored. Our objective was to determine effects of hardwood biochar and poultry litter biochar on P sorption and release from two soils differing in P retention properties at three rates of biochar addition. Soils as well as soil + biochar mixtures were treated with 12 levels of solution P concentrations. Phosphorus concentration and the amount of P sorbed for each level of P addition at the end of the incubation showed that after P addition corresponding to the soil P storage capacity (SPSC) as determined prior to biochar application, P retention abruptly declined for all treatments irrespective of biochar type. Biochar did not diminish the capacity of the two soils to tenaciously bind P added as a soluble inorganic source. Also, the maximum P retention capacity of the soil ($S_{\max}$) increased as amount of biochar applied increased. Biochar-enhanced P sorption at high solution concentrations would be environmentally beneficial only if the sorption were strongly hysteretic such that subsequent P release is minimal as concentrations approach background levels. X-ray diffraction analysis of the biochar after incubating at high P solution concentration did not reveal formation of a stable crystalline P phase. This study provides evidence that the amount of P that can be “safely” added to soils amended with biochar depends significantly upon the P retention property of the soil, and not only the biochar characteristics.

45 **Keywords**

46 Biochar feedstock; hardwood biochar; phosphorus saturation ratio; poultry litter biochar; soil P
47 storage capacity; X-ray diffraction

48

49 **Abbreviations**

50 EPC₀, equilibrium phosphorus concentration; HWB, hardwood biochar; PLB, poultry litter
51 biochar; PSR, phosphorus saturation ratio; S_{max}, phosphorus sorption maximum; SPSC, soil
52 phosphorus storage capacity; XRD, X-ray diffraction analysis.

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1. Introduction

Biochar is a product of either thermal pyrolysis (temperature range of 300-1000°C) or gasification created by heating carbon-rich biomass (feedstock) under conditions of limited or no air (Lehmann, 2007a). It is reported to have several functions including carbon (C) sequestration (and thus climate change mitigation), soil amendment and management, environmental remediation, waste management and renewable energy generation (Barrow et al., 2012). During the past few years, biochar has attained considerable importance as an easily accessible input for agriculture (Biederman and Harpole, 2013) and as an amendment for achieving environmental objectives (Chen et al., 2011). Biochar is not only rich in C but also plant nutrients (Ippolito et al., 2012); one of the most important aspects of biochar use is its ability to supply nutrients to plants in nutrient-deficient, low-fertility and degraded soils (Novak et al., 2009; Woolf et al., 2010).

The consequences of biochar application on nutrient retention (Spokas et al., 2009; Kloss et al., 2014) and/or nutrient availability (Laird et al., 2010a, Wang et al., 2012), are recognized as potentially important. However, studies have shown inconsistent results as to whether biochar application enhances P sorption or release (Atkinson et al., 2010; Yao et al., 2012; Xu et al., 2014). Numerous studies have reported that P availability was enhanced by biochar application (Lehmann et al., 2003; Kloss et al., 2014; DeLuca et al., 2015), but it has also been reported that biochar could sorb phosphates (Lehmann, 2007b; Chintala et al., 2014; Schneider and Haderlein, 2016). Biochar has also been suggested as a P-retaining fertilizer with potential to release P in soils (Peng et al., 2012; Streubel et al., 2012; Yao et al., 2013). The retention and release of P from soil with biochar application might depend on chemisorption among soil and biochar particles (Zhang et al., 2016) or geo-chemical processes such as solubilization or adsorption

beyond electrostatic attraction or repulsion. Among these complex processes, retention of P is often best described by sorption mechanism which might improve the availability and plant uptake of P due to higher anion exchange capacity in soil (DeLuca et al., 2015; Novak et al., 2009). Other researchers have reported that P retention in biochar-amended soils can relate to P adsorption by calcium carbonate associated with the biochar ((Zhang et al., 2016; Kumari et al., 2014). The availability of P by biochar application in soils has been attributed to a biochar-induced pH change in soils (DeLuca et al., 2015) and strong competition between electrostatic repulsive forces induced by biochar dissolved organic matter and P sorption sites in soils (Schneider and Haderlein, 2016). Long-term studies are not available that clearly define the fate and transport of nutrients following biochar addition to a soil (Jeffery et al., 2011) and its associated trade-off with environmental pollution (eutrophication) (Jeffery et al., 2015). In addition, there is a need to account for the variability in P retention and release characteristics among biochars from diverse feedstocks.

The underlying mechanisms of P adsorption and release from soil due to biochar application need to be investigated further. The hypotheses of this research are that i) additions of biochar with EPC_0 greater than that of soil will not contribute to P retention at environmentally relevant solution P concentrations, and ii) increases in P sorption maximum (S_{max}) of a soil will depend on the amount of biochar added and the specific biochar feedstock. The objective of this study was to determine the effects of commercially available hardwood biochar (HWB) and poultry litter biochar (PLB) added at varying rates (1%, 2%, and 5%) on P sorption and release from two soils with differing P-retention capacities.

2. Materials and Methods

2.1 Soil sampling and preparation

Two types of soil samples were collected from relatively un-impacted sites in Florida with respect to P fertilizer and/or manure application. One of them, an E horizon of a Candler soil (Hyperthermic, uncoated Typic Quartzipsamments), generally has low P retention capacity. The other, with a higher P retention capacity, is from the Bt horizon of the Apopka soil series (Loamy, siliceous, subactive, hyperthermic grossarenic Paleudults). The soil profiles sampled were representative of these series. They were sampled at locations within the University of Florida Ordway-Swisher Biological Station in Putnam County, Florida, USA. After collection, samples were mixed thoroughly, air-dried and passed through a 2-mm sieve before use. The air-dried soil samples were further used for the biochar batch experiments.

2.2 Biochar feedstocks and production

Two different types of commercially available biochar were used for the batch experiment. One was a pure coarse biochar obtained from Charcoal Green. It was made from the wood of trees such as maple (*Acer* spp.), oak (*Quercus* spp.), and pine (*Pinus* spp.), slowly pyrolyzed at 650-700°C (Bakshi et al., 2014). The deciduous trees (maple and oak; “hardwoods”) were main contributors for this biochar preparation compared to pines, hence the product was labelled “hardwood biochar” (HWB). The term “HWB” is maintained in this article, with the above qualifications, to maintain consistency with the product label. The HWB was crushed, homogenized, and sieved through a 2-mm sieve before use. The other type of biochar was from poultry litter (the term “PLB” is maintained in this article), a granular activated biochar produced from broiler manure and bedding materials used in poultry operations, including wood shavings, saw dust, straw, and other materials as described by Lima et al., 2014.

The PLB was produced utilizing broiler manure litter obtained from United States Department of Agriculture, Agriculture Research Services (USDA-ARS) and Poultry Research Unit (Starkville, MS, USA) by Lima and her co-workers. The original litter materials serving as the PLB feedstock used in this study had up to 30% of wood shavings (Lima and Marshall, 2005). The ash content of the original feedstock was 21.2% in broiler litter. The poultry litter was pyrolyzed at 700°C for 1 h followed by a 45 min steam activation at 800°C at different water flow rates from 1 to 5 mL min⁻¹. A detailed description of biochar activation is available in Lima et al., 2014.

2.3 Experimental design

The HWB and PLB were added to samples from each of the two soils (Candler and Apopka) at rates of 1, 2 and 5% (w/w). Soil and each mixture (in triplicate) were incubated at 25°C for 14 days. A constant moisture content (60%) was maintained throughout the whole incubation period. The incubation period of 14 days was used to obtain stabilized pH values (by measuring the pH values of soil and biochar mixtures at each day starting from the first day of incubation). At the end of the incubation period, 12 concentrations of P in the form of KH₂PO₄ solution were added to each of the treatments. Various chemical analyses and P sorption isotherms were conducted on the biochars, and the incubated soil-biochar mixtures.

2.4 Chemical analyses of biochar and soil-biochar mixtures

The HWB and PLB samples were both characterized for selected chemical properties (Table 1 and Table S1). We used parameters as reported by Bakshi et al., 2014 and Lima et al., 2014 since the biochar in our study were subsamples from the Bakshi et al., 2014 and Lima et al., 2014 studies. The two biochars were analyzed for pH, electrical conductivity (EC), total P (TP) and water soluble P (WSP). The pH was determined using a standard pH meter in saturated paste

(Mukherjee et al., 2011) of 0.5 g of biochar in 50 mL of deionized water and allowing equilibration by stirring for 72 h using a mechanical stirrer. The EC was measured in a similar manner using a conductivity meter. A 1:10 soil to water ratio was used to determine WSP. The extraction procedure was performed by shaking 2 g of soil with 20 mL of DDI water for an hour and filtering through a 0.45 μ m filter paper. The ignition method was used to determine TP in soils (Andersen, 1976). The P in extracting solutions was determined using an auto-analyzer (USEPA, 1983; Method 365-1), following the Murphey and Riley (1962) procedure. The TP was analyzed using an inductively coupled plasma (ICP) spectrophotometer.

Biochars were analyzed for Mehlich 3-extractable P, Fe, and Al (Mehlich, 1984), in addition to extractable Ca, Mg, K, Zn, Mn, Cu, Ni and Na, by extracting with 0.2 M CH_3COOH + 0.25 M NH_4NO_3 + 0.015 M NH_4F + 0.13 M HNO_3 + 0.001 M EDTA for five minutes at a 1:8 soil to solution ratio (Mehlich, 1984). Elemental concentrations in extracting solutions were determined using an ICP. The Mehlich 3 extractant has been used for soils across a broad range of pH and composition. It is a widely used soil test measure for the southeastern USA where the soils of this study were located.

2.5 Mineralogical analyses

The two biochar samples were analyzed by XRD to determine mineral composition (Harris and White, 2008). Samples were ground in an agate mortar and pestle, after which they were loaded as a powder into cavity mounts designed for XRD analysis. They were scanned from 2-60° 2 θ at a rate of 2° per min using Cu K α radiation. The scans were performed on a computer-controlled x-ray diffractometer (Ultima IV X-Ray Diffractometer, Rigaku Corporation, Japan) equipped with stepping motor and graphite crystal monochromator. Additionally, both the

biochar samples were mixed (1:10, S:L) with 100 mg L⁻¹ P solution, incubated under laboratory condition for 14 days, washed with deionized water and analyzed by XRD.

2.6 Phosphorus sorption procedure

Phosphate sorption was measured on soil-biochar mixtures using 2.0 g of air-dried, homogenized soil treated with 20 mL of 0.01 M KCl solution containing 0.0, 0.01, 0.1, 0.5, 1.0, 2.0, 4.0, 5.0, 10.0, 25.0, 50.0, and 100.0 mg P L⁻¹ (Graetz and Nair, 1995; Dari et al., 2015) in 50-mL centrifuge tubes. The tubes were placed on a mechanical shaker for a 24-hour equilibration period. At the end of the equilibration period, the soil samples were centrifuged at 4066 g for 10 min and the supernatant was filtered through a 0.45-μm membrane filter. The filtrate was analyzed for soluble reactive P by the colorimetric method (Murphy and Riley, 1962) using a TechniconTM Autoanalyzer (EPA 365.1). All extractions and determinations were done at room temperature (25°C ± 1°C). The Langmuir K_L (Langmuir, 1918) or P bonding strength was calculated from Langmuir isotherm model (Nair and Reddy, 2013). The equilibrium P concentration (EPC₀) values (Graetz and Nair, 1995) were also calculated. The Freundlich adsorption coefficient or K_F was calculated from non-linear Freundlich isotherm model (Freundlich and Hatfield, 1926) and linear K_D was calculated from the linear isotherm model.

2.7 Phosphorus saturation ratio (PSR) and Soil P storage capacity (SPSC)

The P retention characteristics of soil-biochar mixes will be related to the “soil phosphorus storage capacity” (SPSC, as defined more specifically below), which has been shown to represent the amount of P that can be added to acidic soils prior to P release at concentrations of environmental concern (Nair and Harris, 2004). The SPSC incorporates the “phosphorus saturation ratio” (PSR), the molar ratio of extractable P to the sum of Fe and Al, which typically shows a threshold above which P solution concentrations abruptly start to increase. P retention in

these sandy soils is a function of only Fe and Al below the threshold value as explained by Chakraborty et al., 2012, Nair and Harris, 2014 and Nair, 2014 for upland soils, and by Nair et al., 2015 for wetland soils with high organic matter content.

2.7.1 PSR calculation

The PSR (Eq. 1) of a soil was calculated from P, Fe and Al as:

$$\text{PSR} = (\text{Extractable-P}/31) / ((\text{Extractable -Fe}/56) + (\text{Extractable -Al}/27)) \quad (1)$$

Where, P, Fe, and Al are expressed in moles (Sims et al., 2002). The extracting reagent can be an oxalate extractant (0.01 M oxalic acid + 0.175 M ammonium oxalate solution equilibrated for four hours at a pH of 3.0; McKeague and Day, 1966) or a soil test solution such as Mehlich 1 (M1) or Mehlich 3 (M3) (Nair et al., 2004). The PSR (Eq. 2) using the Mehlich 3 extractant was calculated as:

$$\text{PSR} = (\text{M3-P}/31) / ((\text{M3-Fe}/56) + (\text{M3-Al}/27)) \quad (2)$$

2.7.2 SPSC calculation

SPSC (Eq. 3) was calculated using the threshold PSR as:

$$\text{SPSC} = (\text{Threshold PSR}-\text{Soil PSR}) * (\text{Fe} + \text{Al}) * 31 \text{ mg kg}^{-1} \quad (3)$$

Threshold PSR for Florida soils = 0.1 (Nair, 2014).

2.8 Statistical analyses

Mean and standard deviations values were calculated using standard methods in Excel 2013. The data were analyzed using the general linear model procedure in the statistical package SAS (SAS Institute, 2001). The significant difference between treatments (soils and soil+biochar mixtures) means for various soil parameters were determined using a Student's t-test at 1% level of significance ($\alpha = 0.01$).

3. Results

3.1 Soil and biochar characterization

The pH of the Candler (a low P-retentive soil) was 5.5 and that of the Apopka (a higher P retentive soil) was 4.8. Both the soils had lower pH compared with the HWB (9.3) and PLB (9.8). The two biochars had very different elemental concentrations in the M3 solution with the PLB having the higher nutrient concentrations (Table S1). Mehlich 3-P in the HWB was 478 mg kg⁻¹ compared with the PLB which had an M3-P concentration of 14,545 mg kg⁻¹. The HWB had a much lower TP content (1898 mg kg⁻¹) compared with the PLB (25,615 mg kg⁻¹). Based on P, Fe, and Al concentrations in a M3 extract, the PSR and SPSC values were calculated (Eqs. 1, 2 and 3) for both Candler and Apopka soils. The SPSC for the Candler soil was lower than that of Apopka (45 mg kg⁻¹ vs. 150 mg kg⁻¹, respectively).

X-ray diffraction analysis revealed that the two biochars (Figs. S1 and S2) were drastically different in composition. The HWB was dominantly amorphous with the exception of containing the salt KCl (the mineral sylvite). The PLB also contained sylvite, but, in addition, had XRD peaks for the mineral whitlockite. The presence of whitlockite (beta-tricalcium phosphate), which can also have Mg in the structure, is consistent with the very high total P content of the PLB (25,615 mg kg⁻¹). Quartz and calcite were also indicated for the PLB.

3.2 P sorption parameters

The EPC₀ values for Candler and Apopka soils were 0.10 and 0.30 mg L⁻¹, respectively (Tables 2 and 3). Apopka soils had higher S_{max} values (202 mg kg⁻¹) compared with the Candler (120 mg kg⁻¹) soils (Tables 2 and 3). The S_{max} values for soil and biochar mixtures increased after biochar addition; the S_{max} values increased from 120 mg kg⁻¹ to 402 mg kg⁻¹ (0% to 5% HWB addition) and 202 to 419 mg kg⁻¹ (0% to 5% PLB addition) in Candler soils (Table 2).

Similarly, the $S_{\max}$ values of Apopka soils increased to 419 mg kg⁻¹ and 722 mg kg⁻¹ by increasing biochar rate from 0% to 5% for HWB and PLB, respectively (Table 3). Langmuir K_L , as well as K_F and K_D , generally showed an increasing trend with an increase in biochar additions to both Candler (Table 2) and Apopka (Table 3) soils.

4. Discussion

Since the EPC_0 values were statistically greater for both biochars compared to the two soils, these biochars are likely a P source when added to the soils. The $S_{\max}$ values for both biochar-soil mixtures (Tables 2 and 3) were greater than those of soils (either Candler or Apopka) alone and increased with increase in the amount of biochar added to the soil. Xu et al. (2014) noted a similar response of increasing P sorption at a higher biochar application.

Addition of a component to a soil that has higher available P (e.g., M3-P as inferred from soil test) than the soil itself (the case for our studied materials) presumably would elevate the available P of the system. Lehman et al. (2002) also observed increased available P while applying a secondary forest charcoal to a Ferralsol. The M3-P concentration was reported to increase by 3.3 mg kg⁻¹ in a 56-day laboratory incubation study for loamy sand surface soil when corn cob biochar was added in the presence of P fertilizer (Nelson et al., 2011). The trend supports the greater availability of P as inferred from M3-P extraction with increasing magnitude of added biochar. The K_L , K_F , and K_D generally increased with increase in the amount of biochar added (Tables 2 and 3).

4.1 Effects of biochar application on P sorption and release

After certain limits of P addition, depending on the initial (prior to biochar addition) SPSC of the soil, P began to be released from both soil types (low P retentive Candler soils and high P

retentive Apopka soils) for all treatments, irrespective of the nature or loading rate of the biochar (Figs. 1a, 1b, 2a, and 2b). The two biochars in this study probably represent extremes in nutrient concentrations in biochar from different feedstocks, suggesting that biochar prepared from almost any feedstock would likely behave similarly with respect to P release based on soil characteristics. A key point is that biochar did not diminish the limit to which the soils tenaciously retained P that was applied in soluble inorganic form. In effect, these results suggest that the SPSC could overestimate P loss risk when determined for a soil after biochar application. Also, biochar additions significantly enhanced P sorption, in proportion to the addition rate (from 0 to 5%), once the P loading exceeded threshold values corresponding closely to the zero SPSC value of the soil as determined prior to biochar application (Figs. 1 - 4). The $S_{\max}$ values of soils increased with an increase in biochar additions. The amount of P sorbed in the solid phase was greater for PLB as compared to HWB for all rates of biochar application irrespective of the soil type in the study (Figs. 3a, 3b, 4a, and 4b). Similar changes in $S_{\max}$ with biochar additions were reported by Xu et al. (2014). The result of our study suggests that biochar could be beneficial after heavy P loadings by enhancing P sorption when P concentrations greatly exceed background, environmentally acceptable levels. However, the benefit would be temporary (barring strong hysteresis) when P concentrations in soil solutions approach environmentally acceptable levels. EPC_0 increased with biochar additions suggesting that P held by the biochar is a temporarily-retained pool that could eventually be released into the soil (Tables 2 and 3). This finding is supported by XRD analysis which did not show any stable P form for the HWB and a sparingly soluble P form (whitlockite) for the PLB that could continue to release P over a long period of time.

4.2 *Implications of biochar application to different soils*

Biochar application increased P retention at higher solution P concentrations. Therefore, biochar additions to a heavily P-impacted soil might reduce P loss from the soil if the sorption were strongly hysteretic. There are published reports that biochar application can reduce leaching of P (Novak et al., 2009; Laird et al., 2010b; Chen et al., 2011; Nelson et al., 2011; Yao et al., 2011; Biederman and Harpole, 2013; Raave et al., 2014). However, the biochars used in the current study with higher EPC_0 values than the soils, suggest that they will constitute a P source at native background solution P concentrations.

The PLB imparted the highest P retention capacity of the materials studied (soils and HWB) despite its very high P content. This result may be due to the fact that the P in the PLB is in a 3-dimensional crystalline phase (whitlockite) and not competing with solution P for surface adsorption sites. The buffering capacity of the soils does not appear to be affected by the addition of biochar irrespective of the amount of P in the material. The threshold PSR, and therefore the SPSC, is not serving as an indicator of P release potential from these biochar-amended soils. These findings are contrary to our expectations of P release from biochar-amended soils compared to soils amended with manure or commercial fertilizers. Additional studies comparing P release from soils amended with manure and biochar derived from manure will be necessary to explain these results.

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Figure Captions

Figure 1: Initial phosphorus concentration added and phosphorus in soil solution for the Candler soil (lower phosphorus retention than the Apopka) and soil-biochar [(a) hardwood biochar (HWB) and (b) poultry litter biochar (PLB)] mixtures.

Figure 2: Initial phosphorus concentration added and phosphorus in soil solution for the Apopka soil (higher phosphorus retention than the Candler) and soil-biochar [(a) hardwood biochar (HWB) and (b) poultry litter biochar (PLB)] mixtures.

Figure 3: Phosphorus in solution and phosphorus sorbed in the solid phase for the Candler soil (lower phosphorus retention than the Apopka) and soil-biochar [(a) hardwood biochar (HWB) and (b) poultry litter biochar (PLB)] mixtures.

Figure 4. Phosphorus in solution and phosphorus sorbed in the solid phase for the Apopka soil (higher phosphorus retention than the Candler) and soil-biochar [(a) hardwood biochar (HWB) and (b) poultry litter biochar (PLB)] mixtures.

Table 1: Mean values (values in parentheses represent the standard error) of selected properties of the biochars used in the study.

Property	HWB	PLB	Source
Pyrolysis temperature (°C)	650-700	700-800	Bakshi et al., 2014; Lima et al., 2014
pH §	9.3 (0.6)	9.8 (0.9)	This study
EC ($\mu\text{S cm}^{-1}$)	443 (4.8)	565 (8.5)	This study
CEC ($\text{Cmol}_c \text{ kg}^{-1}$)	33.8 (18.3)	N/A	Bakshi et al., 2014; Lima et al., 2014
AEC ($\text{Cmol}_c \text{ kg}^{-1}$)	3.5 (1.3)	N/A	Bakshi et al., 2014; Lima et al., 2014
Total C (g kg^{-1})	720 (21)	338.1 (13.2)	Bakshi et al., 2014; Lima et al., 2014
Total Oxygen (g kg^{-1})	N/A	107.9 (2.1)	Lima et al., 2014
Total Hydrogen (g kg^{-1})	N/A	11.9 (0.4)	Lima et al., 2014
H/C	N/A	0.04	Lima et al., 2015
Total N (g kg^{-1})	10.2 (1.6)	32.6 (2.1)	Bakshi et al., 2014; Lima et al., 2014
Total P (g kg^{-1})	1.9 (0.2)	25.6 (1.8)	This study
WSP (mg kg^{-1})	2.30 (0.9)	1.10 (0.5)	This study
Ash content (%)	18.8 (0.3)	60.9 (0.7)	Bakshi et al., 2014; Lima et al., 2014
Volatile matter (%)	13.2 (1.2)	17.3 (2.3)	Bakshi et al., 2014; Isabel Lima, Personal Communication
Surface area ($\text{m}^2 \text{ g}^{-1}$)	0.78 (0.03)	274 (8.2)	Bakshi et al., 2014; Lima et al., 2014

Mineralogy	calcite, quartz	sylvite, whitlockite & quartz	This study
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HWB, hardwood biochar; PLB, poultry litter biochar; EC, electrical conductivity; CEC, cation exchange capacity; AEC, anion exchange capacity; WSP, water soluble P.

N/A = not available

§ After 72-h equilibration.

Table 2: Phosphorus sorption parameters[†] for Candler (low P retentive) soil and (soil+biochar) mixtures

Treatments	EPC ₀ (µg mL ⁻¹)	S _{max} (mg kg ⁻¹)	Langmuir K _L (L kg ⁻¹)	Freundlich K _F (L kg ⁻¹)	Linear K _D (L kg ⁻¹)
Candler soil	0.10 ^A	120 ^A	0.00 ^A	2.3 ^A	0.00 ^A
Soil + 1% HWB	2.30 ^{Ba}	320 ^{Ba}	0.01 ^{Ba}	6.5 ^{Ba}	0.01 ^{Ba}
Soil + 2% HWB	2.39 ^{Ba}	348 ^{Bb}	0.10 ^{Bb}	23.5 ^{Bb}	0.09 ^{Bb}
Soil + 5% HWB	3.13 ^{Bb}	402 ^{Bc}	2.13 ^{Bb}	65.7 ^{Bc}	1.10 ^{Bb}
Soil + 1% PLB	3.23 ^{Ca}	545 ^{Ca}	0.10 ^{Ca}	11.2 ^{Ca}	0.02 ^{Ca}
Soil + 2% PLB	3.20 ^{Cb}	611 ^{Cb}	1.40 ^{Cb}	45.6 ^{Cb}	0.10 ^{Ca}
Soil + 5% PLB	3.88 ^{Cc}	648 ^{Cc}	3.50 ^{Cc}	96.7 ^{Cc}	0.90 ^{Cb}

* Uppercase letters represent significant differences ($p<0.01$) among means for each treatment (soil and rate of HWB and PLB addition); lowercase letters represent significant differences ($p<0.01$) between means for each treatment for a given biochar (either HWB or PLB), using Tukey’s least significant difference method. HWB, hardwood biochar; PLB, poultry litter biochar.

[†]EPC₀, equilibrium P concentration; S_{max}, P sorption maxima of soil; Langmuir K_L, Langmuir P boding strength; Freundlich K_F, Freundlich adsorption coefficient; Linear K_D, linear adsorption coefficient.

Table 3: Phosphorus sorption parameters[†] for Apopka (high P retentive) soil and (soil+biochar) mixtures

Treatments	EPC ₀ ($\mu\text{g mL}^{-1}$)	S _{max} (mg kg^{-1})	Langmuir K _L ($\text{L kg}^{-1} \text{P}$)	Freundlich K _F ($\text{L kg}^{-1} \text{P}$)	Linear K _D ($\text{L kg}^{-1} \text{P}$)
Apopka soil	0.30 ^A	202 ^A	0.10 ^A	4.6 ^A	0.05 ^A
Soil + 1% HWB	2.65 ^{Ba}	340 ^{Ba}	0.02 ^{Ba}	7.8 ^{Aa}	0.12 ^{Ba}
Soil + 2% HWB	2.97 ^{Ba}	378 ^{Ba}	0.13 ^{Bb}	32.5 ^{Bb}	0.14 ^{Ba}
Soil + 5% HWB	3.52 ^{Bb}	419 ^{Bb}	3.02 ^{Bc}	87.4 ^{Bc}	1.7 ^{Bb}
Soil + 1% PLB	3.40 ^{Ca}	564 ^{Ca}	0.11 ^{Ca}	13.4 ^{Ca}	0.11 ^{Ca}
Soil + 2% PLB	3.75 ^{Cb}	656 ^{Cb}	1.61 ^{Cb}	57.8 ^{Cb}	0.11 ^{Ca}
Soil + 5% PLB	4.33 ^{Cc}	722 ^{Cc}	3.72 ^{Cc}	102.3 ^{Cc}	1.0 ^{Ca}

* Uppercase letters represent significant differences ($p < 0.01$) among means for each treatment (soil and rate of HWB and PLB addition); lowercase letters represent significant differences ($p < 0.01$) between means for each treatment for a given biochar (either HWB or PLB), using Tukey's least significant difference method. HWB, hardwood biochar; PLB, poultry litter biochar.

[†]EPC₀, equilibrium P concentration; S_{max}, P sorption maxima of soil; Langmuir K_L, Langmuir P binding strength; Freundlich K_F, Freundlich adsorption coefficient; Linear K_D, linear adsorption coefficient.

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