Open Journal of Applied Sciences, 2026, 16(9), 3237-3251
https://www.scirp.org/journal/ojapps
ISSN Online: 2165-3925
ISSN Print: 2165-3917

Biochar Rate Effects on Soil Water Retention in an Agroecosystem on an Alluvial Silt-Loam Soil in Southeast Arkansas

Hank Martin, Kristofor R. Brye*, Diego Della Lunga, Jonathan B. Brye, James Burke

Department of Crop, Soil, and Environmental Science, University of Arkansas, Fayetteville, USA
Email: *kbrye@uark.edu

How to cite this paper: Martin, H., Brye, K.R., Della Lunga, D., Brye, J.B. and Burke, J. (2026) Biochar Rate Effects on Soil Water Retention in an Agroecosystem on an Alluvial Silt-Loam Soil in Southeast Arkansas. *Open Journal of Applied Sciences*, **16**, 3237-3251.
https://doi.org/10.4236/ojapps.2026.169177

Received: August 19, 2026
Accepted: September 13, 2026
Published: September 16, 2026

Abstract

Biochar application to agroecosystems has become popular as a soil-health-improving, agricultural conservation practice that has been reported to positively affect numerous near-surface soil properties. However, biochar effects have often been inconsistent among cropping systems, management practices, and soil textures. The aim of this field study was to assess the effects of biochar application rate (*i.e.*, 0, 2,000, and 4,000 kg ha^{-1} yr^{-1}) after three consecutive years of annual pre-plant application (*i.e.*, 0, 6,000, and 12,000 kg ha^{-1} total) with minimal surface incorporation on near-surface soil properties and soil water retention, based on soil wetting curves, in a furrow-irrigated, cotton (*Gossypium hirsutum*)-corn (*Zea mays*) rotation on an alluvial silt-loam soil in southeast Arkansas. At the end of the 2025 corn growing season, all soil properties in the top 15 cm did not differ ($P > 0.05$) among biochar rates when treated as a discrete or continuous variable. Evaluated with the slope and intercept parameters from the linear and natural-logarithm regression fits characterizing the relationships between soil water potential and soil water content, soil water retention was unaffected ($P > 0.05$) by biochar rate. Biochar applications require continued evaluation across different crop management practices and soil textures to improve our understanding of the potential effects of biochar on crop productivity, various soil properties, and general soil health.

Keywords

Biochar, Water Retention, Soil Degradation, Cotton-Corn Production, Arkansas

1. Introduction

Soil degradation occurs when a soil system's structure, functionality, efficiency, or resilience is diminished, resulting in topsoil loss, loss of structural integrity, and eventually low plant productivity [1]. Anthropogenic actions have often accelerated soil degradation through excessive pesticide use, unnecessary tillage, deforestation, over-grazing, and industrial activities [1]. In agroecosystems, soil degradation that decreases agricultural yields can increase nutrient losses, greenhouse gas (GHG) emissions, and food prices for consumers [1]. Measures aimed at remediating and preventing soil degradation must be implemented widely to realize the pedosphere's essential ecosystem services in agriculture.

Agriculture is the primary industry impacted by soil degradation, as an estimated 29% of degraded soil worldwide is cropland [2]. Excessive tillage, which often occurs with agricultural practices in conventional tillage systems, can exacerbate the loss of soil organic matter (SOM) and soil organic carbon (SOC) through accelerated biotic and abiotic decomposition, which, in turn, can also cause the loss of soil nutrients, such as nitrogen (N), phosphorus (P), and sulfur (S) [2]. For decades, extensive efforts have been made to prevent agriculture-associated soil degradation through various conservation practices, such as reduced tillage, planting perennial crops, using cover crops between growing seasons, alternatives to chemical pesticides, and applying organic amendments [3] [4]. Many of the conservation practices focus on minimizing soil disturbance, keeping the soil in place, and preserving SOM [5].

Soil organic matter loss is particularly damaging not only for the potential associated loss of soil nutrients, but for the negative impacts SOM loss imparts on soil aggregation, structural stability, and soil water retention [6]. The presence of SOM decreases the soil's bulk density (BD), improves soil structure, and increases soil porosity, which, in turn, can increase soil water-holding capacity [6] [7]. Thus, SOM loss impairs the soil's ability to retain water, which is critical as useable freshwater for irrigation is already scarce in many regions and irrigated agriculture accounts for 69% of global groundwater withdrawals [8]. Consequently, increasing soil water retention would likely contribute to reducing the amount of freshwater needed for maximizing production in irrigated agriculture.

As an organic soil amendment gaining popularity and a recognized conservation practice, biochar is a C-rich substance derived from burning organic material in an anoxic environment at varying temperatures via pyrolysis [9]. As a result of pyrolysis, the remaining C in biochar is considered somewhat recalcitrant, thus semi-resistant to weathering and breakdown by oxidation after soil application [9]. Notably, biochar possesses the potential to improve the health and quality of degraded soils [10]. Biochar is also often noted for large nutrient contents and large surface area and porosity, which generally allows biochar to positively impact not only plant growth and soil health, but also provide a means of climate-change mitigation from expected lower GHG production and release [11]. Application of biochar has been observed to decrease BD and increase total porosity in coarse soils [12]. Biochar has also been reported to reduce nitrous oxide (N_2O) fluxes in a silt-loam soil cropped to a cotton (*Gossypium hirsutum*)-corn (*Zea* *mays*) rotation in southeast Arkansas [13].

When applied to soil, biochar can slowly release abundant nutrients that can then be absorbed by plant roots [11] [14]. However, biochar nutrient contents can differ depending on the pyrolysis temperature, with N losses occurring at 400˚C, and 600˚C favoring K concentration in the remaining biochar material [11]. The biochar's initial feedstock also has a controlling influence on the resulting biochar nutrient content, as biochar variations prepared with different woody feedstocks have shown to result in different biochar C, N, and oxygen concentrations [15]. Biochar's large surface area from increased internal porosity allows biochar to adsorb chemicals and sequester organic substances [7], as well as retain water [6]. Increased soil water retention is dependent not only on biochar composition, but also on biochar's interaction with the soil texture the biochar is applied to, with biochar considered effective at increasing soil water content in sandy soils, less effective in loamy soils, and potentially counter-effective in clayey soils [16].

More recently, Burke *et al.* [17] evaluated the effects of two or three years of annual biochar application on soil profile water contents at three locations in eastern Arkansas. Results showed that biochar applications are more consistently effective at increasing soil water content in dryland farms (irrigated by rainwater) compared to farms that utilize furrow irrigation [17].

Despite the recent study by Burke *et al.* [17], few studies have examined the cumulative effects of multiple years of consecutive biochar application on soil water retention in irrigated agroecosystems, particularly in the highly agriculturally productive Lower Mississippi River Valley (LMRV) region of eastern Arkansas [13] [17]. The objective of this field study was to evaluate the cumulative effects biochar application (*i.e.*, 0, 2000, and 4000 kg ha^{-1}) on near-surface soil properties and soil water retention, based on soil wetting curves, after three consecutive years of surface application with light incorporation in a furrow-irrigated cotton-corn rotation on an alluvial silt-loam soil in southeast Arkansas. It was hypothesized that the 4000 kg ha^{-1} rate treatment would have lower BD, but greater SOM, pH, extractable soil nutrients, TC, and soil C:N ratio compared to the 2000 kg ha^{-1} rate and unamended control (*i.e.*, 0 kg ha^{-1} rate) due to biochar's large porosity, nutrient adsorption ability, and large C concentration. It was also hypothesized that the 4000 kg ha^{-1} rate treatment would have greater water retention characteristics compared to the 2000 kg ha^{-1} rate and unamended control due to biochar's increased porosity and water-holding capacity.

2. Materials and Methods

2.1. Site Description

The study was conducted on a private farm in Desha County, southeast Arkansas within Major Land Resource Area (MLRA) 131B, Arkansas River Alluvium, which is an alluvial plain composed of variable soil textures, bottom-land hardwood deciduous forests, and cypress (*Taxodium distichum*) swamps [13] [18]. The specific study area was located approximately 46 m downslope (<1%) from the northern edge into production-scale field and was approximately 49 m long and 11.4 m wide with 12, 0.7-m wide raised beds [13]. The soil mapped throughout the study area was a Hebert silt loam (fine-silty, mixed, active, thermic Aeric Epiaqualfs), which is a poorly drained and slowly permeable soil developing in silty alluvium [18].

The 30-year (*i.e.*, 1991 to 2020) average annual precipitation in the region was 130 cm, with the greatest monthly rainfall generally occurring in April (*i.e.*, 14 cm) [13] [19]. The 30-year monthly average air temperature is 17.8˚C, with the largest average monthly air temperature generally occurring in July (*i.e.*, 27.7˚C) [13] [19].

2.2. Experimental Design, Treatments, and Plot Layout

The study area was comprised of four blocks (*i.e.*, replications) with three annual biochar rate treatments (*i.e.*, 0, 2000, and 4000 kg ha^{-1} yr^{-1}) randomly assigned per block [13] [17]. Total biochar amounts applied were 0, 6,000, and 12,000 kg ha^{-1} total. Consequently, the experimental design was a randomized complete block (RCB) with a factorial design to assess potential effects of biochar rate on soil water retention [13] [17]. The biochar treatment rates corresponded to 0, 7.75, and 15.5 kg of surface-applied biochar per plot, and biochar was broadcast-applied to the soil surface one week before planting in plots that were 10 m long and four raised beds wide (*i.e.*, 3.8 m), which represented the experimental unit [13] [17] The biochar was derived from a softwood pine (*Pinus* spp.) feedstock (EnviraPAC, Monticello, AR) and was composed of a mixture of coarse and powder-like particles [13] [17]. The biochar material applied had 93% organic C and 0.7% total N [20]. During planting, the applied biochar was lightly mixed in the upper ~5 cm of soil by the mechanical action of the planter [13] [17]. The minimal incorporation was preferred by the landowner to preserve the integrity of the raised beds for future use and to allow unobstructed water flow through the adjacent furrows [13] [17].

2.3. Field Management

The field study initially began in Spring 2023 with the first of three consecutive years of consistent biochar treatment (*i.e.*, 0, 2000, and 4000 kg ha^{-1}), where biochar was applied to the same plots in Spring 2024 and 2025 as well [13] [17]. Burke *et al.* [17] summarized selected initial biochar properties. The study area has a history of minimum tillage and furrow-irrigation each year when needed with nearby well water (*i.e.*, groundwater) [13] [17]. The typical annual tillage performed was one pass of a roller bedder to form or re-form the raised beds and a subsequent pass with a bed conditioner to level the tops of the beds for planting [13] [17].

During the 2023 and 2024 growing seasons, cotton was planted on top of the raised beds in April at a rate of ~168,000 seeds ha^{-1} to a depth of ~2.5 cm, with an in-row spacing of ~15 cm; the raised-bed width was 65 to 70 cm and the bed height was ~9 cm [13] [17]. In both growing seasons, ~120 to 130 kg N ha^{-1} were applied as a combination of either 32% urea ammonium nitrate (UAN), diammonium phosphate (DAP), or ammonium sulfate after planting [13] [17]. In addition, in both growing season, 44 kg ha^{-1} of phosphorus (P) were applied as DAP, 101 kg ha^{-1} of potassium (K) were applied as muriate of potash, 24 kg ha^{-1} of sulfur (S) were applied as ammonium sulfate, and 1.1 kg ha^{-1} of boron (B) were applied as elemental B [13] [17].

During the 2025 growing season, corn was planted in late March at a rate of ~84,000 seeds ha^{-1} to a depth of ~5cm, with an in-row spacing of ~6.4 cm [13] [17]. Immediately after planting in 2025, 112 kg ha^{-1} of ammonium sulfate, 196 kg ha^{-1} of DAP, 140 kg ha^{-1} of muriate of potash, and 1 kg ha^{-1} of chelated zinc were broadcast-applied [13] [17]. In late April 2025, 252 kg ha^{-1} of urea were broadcast, followed by a final urea broadcast application of 112 kg ha^{-1} in early June, and pesticides were applied each year on an as-needed basis to control weeds [13] [17]. Fertilizers and pesticides were applied with a ground rig or via airplane when necessary. Additional field management details were reported in Brye [13] and Burke *et al.* [17].

2.4. Soil Sample Collection and Processing

At the end of the 2025 corn growing season, one soil sample was collected with a 4.8-cm-diameter, stainless steel core chamber and slide hammer from the top 15 cm of one raised bed in each plot per treatment (n = 4 per treatment) for BD determination and chemical analyses [13]. Soil samples were oven-dried for at least 48 hours at 70˚C, ground, and sieved though a 2-mm mesh screen [13].

Soil pH and electrical conductivity (EC) were determined potentiometrically in a 1:2 soil mass:water volume suspension [21]. Plant-available Ca, Mg, K, and P concentrations were determined following Mehlich-3 extraction in a 1:10 soil mass:extractant volume and analysis by inductively coupled, argon-plasma spectrophotometry [22]. SOM concentration was measured after 2 hours of combustion at 360˚C by weight-loss on-ignition [23]. TC and total N (TN) concentrations were measured on a VarioMax CN analyzer (Elementar Americas Inc., Mt. Laurel, NJ) by high-temperature combustion [24] [25]. All measured TC was assumed to be organic due to no effervescence when treated with dilute hydrochloric acid. The soil C:N ratio was calculated from the measured TC and TN concentrations.

A second soil sample was collected with a 5-cm-tall core chamber, which was manually tapped into the soil with a rubber mallet, from the top 5 cm of one raised bed in each plot per treatment (n = 4 per treatment) for water-retention measurements. Samples were air-dried for at least 5 days at ~21˚C, then ground and sieved with light pressure though a 2-mm mesh screen.

2.5. Water Retention Procedures

Following prior procedures [4] [26]-[28], 10, 5.0 ± 0.1 g subsamples of air-dried, ground, and sieved soil from each of the 12 plots were placed into small, plastic cups, after which 1, 2, 4, 6, 10, 12, 15, 20, 30, and 40 drops of distilled water were added, respectively, to achieve a representative range of gravimetric soil water contents. Any dispersive effects from using distilled water were assumed to affect all soil samples equally. Following the addition of distilled water, the soil samples were manually mixed with a metal spatula to uniformity and subsequently transferred to pre-weighed, small, plastic measurement capsules (*i.e.*, 4.0 cm in diameter and 1.1 cm tall; Decagon Devices, Inc., Pullman, WA). Soil was placed to fill approximately half the height of the measurement capsule, after which the capsule was capped and allowed to equilibrate overnight at room temperature (*i.e.*, ~21˚C). The following morning, the soil water potential of each sample was then measured with a Decagon WP4C Dewpoint Potentiameter (Decagon Devices Inc.). After each water potential measurement, the capsule, cap, and moist soil were weighed and oven-dried at 70˚C for at least 12 hours. After oven-drying, the capsule, cap, and dry soil were reweighed to calculate the gravimetric water content of each sample based on the initial air-dried mass of soil. The resulting water potential measurement associated with each gravimetric soil water content was used to represent the soil wetting curve for all replicate samples.

The relationship between soil water potential (*i.e.*, dependent variable) and gravimetric soil water content (independent variable) was characterized via linear regression using Excel (version 2607, Microsoft Corp., Redmond, WA) by fitting trendlines through all data points for each replication of the three biochar treatments (n = 4) [26] [28]. A simple linear regression equation was determined for both the raw (*i.e.*, non-transformed) and natural-logarithm (LN)-transformed gravimetric soil water content data points. The linear and LN slopes and intercepts of the resulting regression relationships were recorded for each biochar plot for subsequent statistical analyses [26] [28].

2.6. Statistical Analyses

Based on the RCB design, a one-factor analysis of variance (ANOVA) was performed in SAS (version 9.4, SAS Institute, Inc., Cary, NC) to determine the effect of biochar treatment (*i.e.*, 0, 2000, and 4000 kg ha^{-1}) on soil BD, pH, EC, extractable soil nutrient (*i.e.*, Ca, Mg, K, and P) concentrations, SOM, TC, and TN concentrations, and the soil C:N ratio in the top 15 cm after three consecutive years of consistent management. All soil properties were analyzed with a gamma distribution. A one-factor ANOVA was also performed in SAS, based on a RCB design, to determine the effect of biochar treatment on the linear and LN slope and intercept parameters from the regression fits characterizing the relationship between the measured soil water potential and gravimetric soil water content from the top 5 cm. The slope parameters were analyzed with a gamma distribution due to the skewed data distribution, while the intercept parameters were analyzed with a normal distribution.

Treating the biochar rates as a continuous variable, rather than a discrete variable as with the ANOVA analyses, linear regression analyses were also performed on all soil properties and the slope and intercept parameters from the linear and LN fits characterizing the relationship between the measured soil water potential and gravimetric soil water content (Microsoft Excel 16). Significance was judged at $P \leq 0.05$ for all analyses.

3. Results and Discussion

3.1. End-of-Season Soil Properties

After the three consecutive years of pre-plant biochar additions (*i.e.*, 2023, 2024, and 2025), soil BD, pH, EC, extractable Ca, Mg, K, and P, and SOM, TC, and TN concentrations and C:N ratio in the top 15 cm did not differ ($P > 0.05$) among biochar treatments when biochar treatments were treated as a discrete or continuous variable (**Table 1**). However, soft, woody feedstocks, which served as the main component of the biochar used in this study, and softwood-derived biochar have been shown to increase soil K levels [29]. In addition, during pyrolysis, K is mostly preserved and converted into highly soluble salts [30] that are easily released upon biochar interaction with soil and soil moisture fluctuations. Potassium is also often one of the most abundant plant macronutrients in many soils [31], which may have masked biochar-addition effects on soil K.

Table 1. Summary of the effect of biochar (B) treatment [*i.e.*, 0 (0B), 2000 (2B), and 4000 (4B) kg ha^{-1}] on bulk density (BD), soil pH, electrical conductivity (EC), Mehlich-3 extractable soil nutrient (*i.e.*, Ca, Mg, K, and P) concentrations, soil organic matter (SOM), total carbon (TC), and total nitrogen (TN) concentrations, and the soil C:N ratio (C:N ratio) in the top 15 cm after three consecutive years (*i.e.*, 2023, 2024, and 2025) of biochar addition (n = 4 per treatment) in a furrow-irrigated, cotton-corn rotation in southeast Arkansas.

Soil Properties	*P*	Biochar Treatment			Regression Results		
		0B	2B	4B	Slope	Intercept	*P*
BD (g cm^{-3})	0.87	1.12	1.15	1.16	0.00001	1.125	0.59
pH	0.77	6.15	6.25	6.30	0.00004	6.14	0.41
EC (dS m^{-1})	0.95	0.303	0.306	0.317	0.00001	0.30	0.76
Ca (mg kg^{-1})	0.80	1536	1590	1563	0.007	1549.4	0.73
Mg (mg kg^{-1})	0.85	225.0	226.7	235.2	0.003	223.9	0.58
K (mg kg^{-1})	0.78	119.6	111.0	129.9	0.0024	116.3	0.73
P (mg kg^{-1})	0.53	74.1	65.0	58.2	−0.004	74.4	0.26
SOM (%)	0.38	2.19	2.04	2.06	−0.00003	2.16	0.25
TC (%)	0.49	1.19	1.07	1.09	−0.00002	1.16	0.33
TN (%)	0.54	0.12	0.11	0.11	−0.00001	0.11	0.30
C:N ratio	0.37	10.2	9.9	10.2	−0.00001	10.14	0.87

Though biochar is known to be a generally recalcitrant C source [9], the first-year applied biochar (*i.e.*, 2023), which also resulted in twice the biochar-C application in the high- compared to the low-biochar-rate treatment, likely had started to decompose by year three (*i.e.*, 2025) to stimulate microbial activity [32], specifically as carbon dioxide (CO_2) emissions [33], to contribute to numerically, though not significantly, decreasing TC concentrations as biochar rate increased (**Table 1**). Brye [13] reported season-long CO_2 emissions numerically increased as biochar rate increased, but season-long CO_2 emissions differences were not significant among biochar rates (*i.e.*, 0, 2,000, and 4,000 kg ha^{-1}). The numerically, though not significantly, decreasing soil C:N ratio after three consecutive years of biochar application was a positive influence on soil health by creating a more conducive soil environment for microbial activity [34] [35] and may have been reflective of the decomposition of the first year of biochar addition after three cropping season years. The lack of a significant effect of biochar rate on soil properties reflected larger variability among individual treatment replications and were likely related to the minimal biochar incorporation that occurred each application year [13].

3.2. Water Retention Properties

Combining data across all three biochar treatments and four replications, the relationship between measured water potential and gravimetric water content in disturbed fine-earth material was curvilinear, where the water potential increased exponentially as gravimetric water content increased (**Figure 1**). Similar patterns have been reported in other studies on loamy soils in eastern Arkansas portion of the LMRV [4] [27] [28].

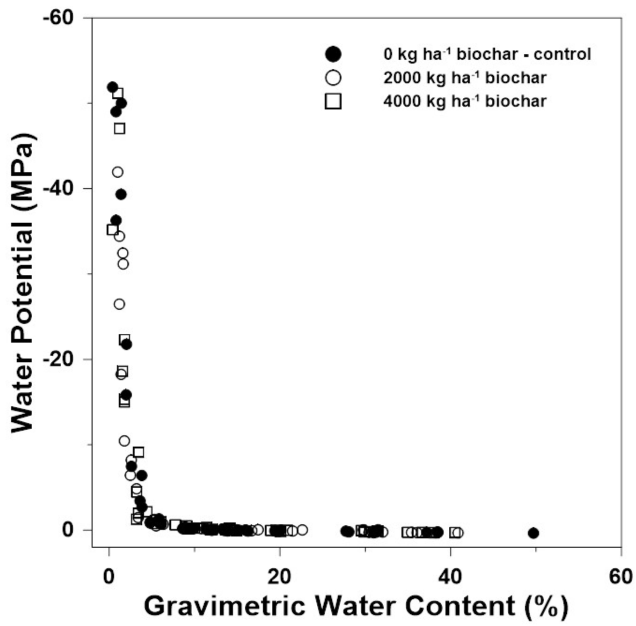

Figure 1. Relationship between soil water potential and gravimetric soil water content for three biochar treatments and all replications within a treatment (n = 4) for the top 5 cm after three consecutive years (*i.e.*, 2023, 2024, and 2025) of biochar addition in a furrow-irrigated, cotton-corn rotation in southeast Arkansas.

Similar to most end-of-season soil properties, but contrary to the original hypothesis, whether treated as a discrete or continuous variable, the slope and intercept parameters characterizing the both the linear and LN relationship between the measured soil water potential and the gravimetric soil water content did not differ ($P > 0.05$) among biochar treatments after three years of biochar application and three cropping seasons (**Table 2**). The predictive ability of the linear trendlines was not large, where coefficients of determination (r^2) values ranged from 0.21 to 0.37, while the r^2 values were somewhat larger for the LN relationships, which ranged from 0.49 to 0.79 across individual replications.

Table 2. Analysis of variance summary of the effect of biochar (B) treatment [*i.e.*, 0 (0B), 2000 (2B), and 4000 (4B) kg ha^{-1}], treated as a discrete variable, on the slope and intercept parameters from the linear and natural logarithmic (LN) fits characterizing the relationship between the measured soil water potential and gravimetric soil water content and the slope and intercept parameters from linear regression analysis treating biochar rates as a continuous variable in the top 5 cm after three consecutive years (*i.e.*, 2023, 2024, and 2025) of biochar addition (n = 4 per treatment) in a furrow-irrigated, cotton-corn rotation in southeast Arkansas.

Model	Parameter	P	Biochar Treatment			Regression Results		
			0B	2B	4B	Slope	Intercept	P
Linear	Slope	0.47	0.67	0.49	0.52	−0.00004	0.64	0.34
	Intercept	0.33	−16.61	−12.29	−12.86	0.0009	−15.80	0.23
LN	Slope	0.23	10.33	7.74	8.34	−0.0005	9.81	0.20
	Intercept	0.16	−29.28	−21.99	−23.41	0.001	−27.83	0.15

Soil water retention, as characterized by soil wetting curves, was unaffected by three consecutive years of biochar treatment to an alluvial, silt-loam soil in southeast Arkansas. Results of the current study were consistent with Gaskin *et al.* [36] who concluded that high rates of biochar application (*i.e.*, 22 Mg ha^{-1}) are needed in order to increase soil water retention in loamy-sand soils in Tifton, Georgia. In addition, numerous studies have reported that biochar application has only minimally impacted soil water retention [16] [27] [29], as fresh (*i.e.*, young and unweathered) biochar is known to show some hydrophobicity, despite having large porosity, that could have prevented or restricted water from entering the soil pores, which has been observed in sandy soils [37] [38]. Furthermore, aged (*i.e.*, weathered) biochar has been reported to retain less water than fresh biochar in fine-loamy soils in Iowa [39].

Burke *et al.* [17] tracked estimated volumetric soil water contents at the 15-, 30-, and 45-cm depths over time at three locations in the eastern Arkansas portion of the LMRV. Burke *et al.* [17] reported soil water contents generally differed among biochar rates in the deeper soil depth, which was likely due to the study plot's low BD and relatively low clay content (6%) that allowed furrow-irrigation water and rainwater to infiltrate to deeper depths where biochar had been applied. In the same plots as the soil samples were collected from for the current study, Burke *et al.* [17] reported that soil water contents varied among biochar-soil depth treatment combinations, where, at times, biochar application resulted in lower soil water contents than in the unamended control. In addition, biochar did not appear to maintain greater soil water contents at the 15-cm depth as the soil dried out from evaporation and a profile redistribution following furrow-irrigation events compared to the unamended control. Biochar effects appear to be minimized under irrigated conditions, thus are likely more beneficial for increasing soil water retention under dryland production systems [17].

There are several plausible explanations why there was no significant impact on water retention after three consecutive years of biochar application. Biochar has been reported to fill pores in sandy soils, which allows sandy soils to retain more water with biochar addition, due to biochar's own porosity, than if biochar had not been applied [40]. However, biochar pores themselves can become clogged by silt and clay particles over time, preventing water from entering and being stored in biochar pores [41]. Biochar was minimally mixed into the upper few centimeters of soil after biochar application, which is not deep enough for biochar to have a substantial impact on soil water retention, with 10 cm being the suggested biochar mixing depth [42]. Furthermore, biochar application to reduced-tillage conditions is challenging, as biochar incorporation into fine-textured soils is greatly limited unless thoroughly mixed into the soil [43].

3.3. Practical Implications

Though inconsistency exists, such as with the results of the current study and the minimal surface incorporation that occurred following annual biochar application, in general, biochar has been shown to increase soil water retention by various metrics, thus biochar is likely a useful organic amendment to impose positive effects for soil and water conservation. However, due to biochar's potential to retain less water as the biochar ages, or decomposes and weathers *in-situ* [39] [41], biochar may be better used as a short-term method of increasing soil water retention and be coupled with other conservation practices, such as reduced tillage and cover crops. In addition, similar to the results of the current study, biochar's effectiveness at increasing soil water retention is likely soil-texture dependent, where positive biochar effects may manifest more in coarse- than fine-textured soils, as coarse-textured (*i.e.*, sandy) soils already have lower water-retention capability, thus microporous biochar likely has a greater relative effect on soil water retention in sandy than in loamy or finer-textured soils [44].

Though even light incorporation may be challenging when a producer is also trying to maintain minimum or reduced tillage year after year, biochar incorporation into the 10 to 15 cm of soil profile is likely necessary to reduce potential off-site transport of the biochar via surface runoff during rainfall and/or irrigation events. Incorporation may also be necessary to maximize biochar's ability to decrease the upper soil profile's BD and increase soil porosity, infiltration, and water-retention capacity, particularly in regions, such as the LMRV, where many agricultural fields have a water-restricting, plow pan within 10 to 15 cm of the soil surface that limits vertical water flow after surface infiltration. Any added benefit that biochar could provide to improve vertical water flow with the soil profile after surface infiltration, such as through improving soil structure and aggregate-size distribution and increasing water-stable aggregation, will help off-set the decades long trend of declining groundwater recharge and increasing groundwater depletion due to a lengthy history of irrigated agriculture in the LMRV.

4. Conclusions

The current study evaluated the cumulative effects biochar application (*i.e.*, 0, 2000, and 4000 kg ha^{-1} yr^{-1}; 0, 6,000, and 12,000 kg ha^{-1} total in three years) on near-surface soil properties and soil-wetting-curve-derived soil water retention characteristics in a furrow-irrigated cotton-corn rotation on disturbed, fine-earth, silt-loam soil in southeast Arkansas. After three consecutive years of surface application, but with minimal incorporation during planting, results showed that, contrary to the initial hypotheses, soil BD, SOM, pH, extractable soil nutrients, TC, and soil C:N ratio in the top 15 cm did not differ among biochar application rates when biochar rate was treated as a discrete or continuous variable. In contrast to the initial hypothesis, both the slope and intercept parameters characterizing the relationship between soil water potential and gravimetric soil water content from both linear and natural-logarithm regression fits were unaffected biochar application rate when biochar rate was treated as a discrete and continuous variable.

Results of the current study demonstrate how biochar application can have variable effects on soil physical, chemical, and hydrologic properties, at least an alluvial, silt-loam soil in the southeast Arkansas portion of the LMRV. Biochar application may have had a greater positive impact on soil physical, chemical, and hydrologic properties if the biochar had been more extensively incorporated or biochar had been applied to a coarse-textured soil. The effects of single and repeated biochar applications require continued evaluation across different crop management practices and soil textures to develop a more complete picture of the potential effects of biochar on general soil health.

Author Contributions

H.M.—contributed original manuscript preparation; K.R.B.—contributed the conception, methods development, statistical analyses, and manuscript review; D.D.—contributed the conception, methods developments, and manuscript review; J.B.B.—contributed the methods development and manuscript review; J.B.—contributed methods development and manuscript review.

Acknowledgements

The authors gratefully acknowledge the private landowners for allowing the field research to be conducted on their property.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Shokri, N., Robinson, D.A., Afshar, M., Alewell, C., Aminzadeh, M., Arthur, E., *et al.* (2025) Rethinking Global Soil Degradation: Drivers, Impacts, and Solutions. *Reviews of Geophysics*, **63**, e2025RG000883. https://doi.org/10.1029/2025rg000883

[2] Kopittke, P.M., Harper, S.M., Asio, L.G., Asio, V.B., Batalon, J.T., Batuigas, A.M.T., *et al.* (2025) Soil Degradation: An Integrated Model of the Causes and Drivers. *International Soil and Water Conservation Research*, **13**, 744-755. https://doi.org/10.1016/j.iswcr.2025.07.010

[3] Gomiero, T. (2016) Soil Degradation, Land Scarcity and Food Security: Reviewing a Complex Challenge. *Sustainability*, **8**, Article 281. https://doi.org/10.3390/su8030281

[4] Lebeau, S., Brye, K.R., Daniels, M.B. and Wood, L.S. (2023) Cover Crop Effects on Infiltration, Aggregate Stability, and Water Retention in the Lower Mississippi River Valley. *Agrosystems, Geosciences & Environment*, **6**, e20341. https://doi.org/10.1002/agg2.20341

[5] United States Department of Agriculture, Natural Resources Conservation Service (USDA-NRCS) (2016) Residue and Tillage Management, Reduced Till. https://www.nrcs.usda.gov/sites/default/files/2022-09/Residue_And_Tillage_Management_Reduced_Till_345_CPS.pdf

[6] Lal, R. (2020) Soil Organic Matter and Water Retention. *Agronomy Journal*, **112**, 3265-3277. https://doi.org/10.1002/agj2.20282

[7] Cen, R., Feng, W., Yang, F., Wu, W., Liao, H. and Qu, Z. (2021) Effect Mechanism of Biochar Application on Soil Structure and Organic Matter in Semi-Arid Areas. *Journal of Environmental Management*, **286**, Article 112198. https://doi.org/10.1016/j.jenvman.2021.112198

[8] Gleick, P.H. and Cooley, H. (2021) Freshwater Scarcity. *Annual Review of Environment and Resources*, **46**, 319-348. https://doi.org/10.1146/annurev-environ-012220-101319

[9] Chagas, J.K.M., de Figueiredo, C.C. and Ramos, M.L.G. (2022) Biochar Increases Soil Carbon Pools: Evidence from a Global Meta-Analysis. *Journal of Environmental Management*, **305**, Article 114403. https://doi.org/10.1016/j.jenvman.2021.114403

[10] Novak, J.M., Lima, I., Xing, B., Gaskin, J.W., Steiner, C., Das, K.C., Ahmedna, M., Rehrah, D., Watts, D.W., Busscher, W.J. and Schomberg, H. (2009) Characterization of Designer Biochar Produced at Different Temperatures and Their Effects on a Loamy Sand. *Annals of Environmental Science*, **3**, 195-206.

[11] Ding, Y., Liu, Y., Liu, S., Li, Z., Tan, X., Huang, X., *et al.* (2016) Biochar to Improve Soil Fertility. A Review. *Agronomy for Sustainable Development*, **36**, Article No. 36. https://doi.org/10.1007/s13593-016-0372-z

[12] Abel, S., Peters, A., Trinks, S., Schonsky, H., Facklam, M. and Wessolek, G. (2013) Impact of Biochar and Hydrochar Addition on Water Retention and Water Repellency of Sandy Soil. *Geoderma*, **202**, 183-191. https://doi.org/10.1016/j.geoderma.2013.03.003

[13] Brye, J. (2026) Conservation Agriculture Effects on Greenhouse Gas Emissions from Cotton, Soybean, and Corn in Southeast Arkansas. Master's Thesis, University of Arkansas.

[14] Major, J., Rondon, M., Molina, D., Riha, S.J. and Lehmann, J. (2012) Nutrient Leaching in a Colombian Savanna Oxisol Amended with Biochar. *Journal of Environmental Quality*, **41**, 1076-1086. https://doi.org/10.2134/jeq2011.0128

[15] Struhs, E., Sotoudehnia, F., Mirkouei, A., McDonald, A.G. and Ramirez-Corredores, M.M. (2022) Effect of Feedstocks and Free-Fall Pyrolysis on Bio-Oil and Biochar Attributes. *Journal of Analytical and Applied Pyrolysis*, **166**, Article 105616. https://doi.org/10.1016/j.jaap.2022.105616

[16] Mukherjee, A. and Lal, R. (2013) Biochar Impacts on Soil Physical Properties and Greenhouse Gas Emissions. *Agronomy*, **3**, 313-339. https://doi.org/10.3390/agronomy3020313

[17] Burke, J.M., Brye, K.R., Hamilton, M., Daniels, M.B., Riley, L., Cooper, B., *et al.* (2026) Biochar Rate Effects on Soil Water Content in Agricultural Production in the Lower Mississippi River Valley. *Journal of Environmental Protection*, **17**, 576-593. https://doi.org/10.4236/jep.2026.177029

[18] United States Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS) (2025) Land Resource Regions and Major Land Resource Areas of the United States, the Caribbean, and the Pacific Basin. https://www.nrcs.usda.gov/sites/default/files/2025-07/AgHandbook296-508-low-res.pdf

[19] National Oceanic & Atmospheric Administration (NOAA), National Centers for Environmental Information (NCEI) (2024) U.S. Climate Normals Quick Access. https://www.ncei.noaa.gov/access/us-climate-normals/#dataset=normals-monthly&timeframe=30&location=AR&station=USC00032148

[20] Gwaltney, L., Brye, K.R., Lunga, D.D., Roberts, T.L., Fernandes, S.B. and Daniels, M.B. (2025) Biochar Type and Rate Effects on Greenhouse Gas Emissions from Furrow-Irrigated Rice. *Agrosystems*, *Geosciences & Environment*, **8**, e70186. https://doi.org/10.1002/agg2.70186

[21] Sikora, F.J. and Kissel, D.E. (2014) Soil pH. In: Sikora, F.J. and Moore, K.P., Eds., *Soil Test Methods from the Southeastern United States*, University of Georgia, 48-53.

[22] Zhang, H., Hardy, D.H., Mylavarapu, R. and Wang, J. (2014) Mehlich-3. In: Sikora, F.J. and Moore, K.P., Eds., *Soil Test Methods from the Southeastern United States*, University of Georgia, 101-110.

[23] Zhang, H. and Wang, J.J. (2014) Loss on Ignition Method. In: Sikora, F.J. and Moore, K.P., Eds., *Soil Test Methods from the Southeastern United States*, University of Georgia, 155-157.

[24] Provin, T. (2014) Total Carbon and Nitrogen and Organic Carbon via Thermal Combustion Analyses. In: Sikora, F.J. and Moore, K.P., Eds., *Soil Test Methods from the Southeastern United States*, University of Georgia, 149-154.

[25] Nelson, D.W. and Sommers, L.E. (1996) Total Carbon, Organic Carbon, and Organic Matter. In: Sparks, D.L., *et al.*, Eds., *Methods of Soil Analysis*: *Part* 3 *Chemical Methods*, Vol. 34, SSSA and ASA, 961-1010.

[26] Brye, K.R. (2003) Long-Term Effects of Cultivation on Particle Size and Water-Retention Characteristics Determined Using Wetting Curves. *Soil Science*, **168**, 459-468. https://doi.org/10.1097/01.ss.0000080331.10341.36

[27] Brantley, K.E., Brye, K.R., Savin, M.C. and Longer, D.E. (2015) Biochar Source and Application Rate Effects on Soil Water Retention Determined Using Wetting Curves. *Open Journal of Soil Science*, **5**, 1-10. https://doi.org/10.4236/ojss.2015.51001

[28] Norman, R., Brye, K.R., Gbur, E.E., Chen, P. and Rupe, J. (2015) Long-Term Effects

of Alternative Residue Management Practices on Soil Water Retention in a Wheat-Soybean, Double-Crop System in Eastern Arkansas. *Open Journal of Soil Science*, **5**, 199-209. https://doi.org/10.4236/ojss.2015.59020

[29] Kalu, S., Simojoki, A., Karhu, K. and Tammeorg, P. (2021) Long-Term Effects of Softwood Biochar on Soil Physical Properties, Greenhouse Gas Emissions and Crop Nutrient Uptake in Two Contrasting Boreal Soils. *Agriculture, Ecosystems & Environment*, **316**, Article 107454. https://doi.org/10.1016/j.agee.2021.107454

[30] Wang, L., Xue, C., Nie, X., Liu, Y. and Chen, F. (2018) Effects of Biochar Application on Soil Potassium Dynamics and Crop Uptake. *Journal of Plant Nutrition and Soil Science*, **181**, 635-643. https://doi.org/10.1002/jpln.201700528

[31] Rawat, J., Sanwal, P. and Saxena, J. (2016) Potassium and Its Role in Sustainable Agriculture. In: Meena, V.S., Meena, R.S., Verma, J.P. and Maurya, B.R., Eds., *Potassium Solubilizing Microorganisms for Sustainable Agriculture*, Springer, 235-253. https://doi.org/10.1007/978-81-322-2776-2_17

[32] Allohverdi, T., Mohanty, A.K., Roy, P. and Misra, M. (2021) A Review on Current Status of Biochar Uses in Agriculture. *Molecules*, **26**, Article 5584. https://doi.org/10.3390/molecules26185584

[33] Khatoon, H., Solanki, P., Narayan, M., Tewari, L., Rai, J.P.N., and Hina Khatoon, C. (2017) Role of Microbes in Organic Carbon Decomposition and Maintenance of Soil Ecosystem. *International Journal of Chemical Studies*, **5**, 1648-1656.

[34] Wan, X., Huang, Z., He, Z., Yu, Z., Wang, M., Davis, M.R., *et al.* (2015) Soil C:N Ratio Is the Major Determinant of Soil Microbial Community Structure in Subtropical Coniferous and Broadleaf Forest Plantations. *Plant and Soil*, **387**, 103-116. https://doi.org/10.1007/s11104-014-2277-4

[35] Wei, X., Xie, B., Wan, C., Song, R., Zhong, W., Xin, S., *et al.* (2024) Enhancing Soil Health and Plant Growth through Microbial Fertilizers: Mechanisms, Benefits, and Sustainable Agricultural Practices. *Agronomy*, **14**, Article 609. https://doi.org/10.3390/agronomy14030609

[36] Gaskin, J.W., Speir, A., Morris, L.M., Ogden, L., Harris, K., Lee, D. and Das, K.C. (2007) Potential for Pyrolysis Char to Affect Soil Moisture and Nutrient Status of a Loamy Sand Soil. *Proceedings of the* 2007 *Georgia Water Resources Conference*, Athens, 27-29 March 2007, 1-3.

[37] Razzaghi, F., Obour, P.B. and Arthur, E. (2020) Does Biochar Improve Soil Water Retention? A Systematic Review and Meta-Analysis. *Geoderma*, **361**, Article 114055. https://doi.org/10.1016/j.geoderma.2019.114055

[38] Jeffery, S., Meinders, M.B.J., Stoof, C.R., Bezemer, T.M., van de Voorde, T.F.J., Mommer, L., *et al.* (2015) Biochar Application Does Not Improve the Soil Hydrological Function of a Sandy Soil. *Geoderma*, **251**, 47-54. https://doi.org/10.1016/j.geoderma.2015.03.022

[39] Aller, D.M. (2017) Scaling and Understanding of Biochar Aging Impacts on Soil Water and Crop Yields. Ph.D. Dissertation, Iowa State University.

[40] Liu, Z., Dugan, B., Masiello, C.A. and Gonnermann, H.M. (2017) Biochar Particle Size, Shape, and Porosity Act Together to Influence Soil Water Properties. *PLOS ONE*, **12**, e0179079. https://doi.org/10.1371/journal.pone.0179079

[41] Beryani, A., Flanagan, K., You, S., Forsberg, F., Viklander, M. and Blecken, G. (2025) Critical Field Evaluations of Biochar-Amended Stormwater Biofilters for PFAS and Other Organic Micropollutant Removals. *Water Research*, **281**, Article 123547. https://doi.org/10.1016/j.watres.2025.123547

[42] Wei, B., Peng, Y., Lin, L., Zhang, D., Ma, L., Jiang, L., *et al.* (2023) Drivers of Biochar-Mediated Improvement of Soil Water Retention Capacity Based on Soil Texture: A Meta-Analysis. *Geoderma*, **437**, Article 116591. https://doi.org/10.1016/j.geoderma.2023.116591

[43] Rabbi, S.M.F., Minasny, B., Salami, S.T., McBratney, A.B. and Young, I.M. (2021) Greater, but Not Necessarily Better: The Influence of Biochar on Soil Hydraulic Properties. *European Journal of Soil Science*, **72**, 2033-2048. https://doi.org/10.1111/ejss.13105

[44] Wang, D., Li, C., Parikh, S.J. and Scow, K.M. (2019) Impact of Biochar on Water Retention of Two Agricultural Soils—A Multi-Scale Analysis. *Geoderma*, **340**, 185-191. https://doi.org/10.1016/j.geoderma.2019.01.012