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Response of acidic silt loam soil properties to biochar application under soybean cultivation

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Biochar is widely recognized for its potential to stabilize soil acidity and enhance carbon sequestration, yet its functional effects in temperate acidic silt loam soils remain insufficiently quantified. A two-year field study was conducted in Kentucky to evaluate changes in soil physicochemical properties following annual application of 12 t ha⁻¹ of pine (*Pinus* spp.) sawdust biochar (pyrolyzed at 650 °C) under continuous soybean (*Glycine max*) cultivation. Composite soil samples (0–15 cm) were collected pre-planting (May) and post-harvest (October) to monitor acidity indices, organic reserves, fertility indices, and hydrological properties. Biochar acted primarily as a chemical and carbonaceous stabilizer rather than an immediate fertility enhancer. The amendment significantly maintained higher post-harvest pH levels compared to the control, effectively buffering against the seasonal acidification observed in unamended plots. Soil organic carbon (SOC) and buffer pH exhibited a distinct “lag effect,” with significant increases emerging only after two years of cumulative application; at the final October 2024 sampling, SOC in the biochar-treated plots had increased to 1.96% from a 1.74% baseline, whereas the control plots declined to 1.66%. Conversely, soil fertility and hydrological parameters showed no significant treatment effects, being driven instead by seasonal environmental factors and crop uptake. These findings suggest that an annual application of 12 t ha⁻¹ of pine biochar serves as an effective benchmark for mitigating acidification and building organic reserves in temperate silt loams, though further multi-rate studies are required to optimize application dosages for long-term agronomic use.

KEYWORDS

lag effect, nutrient dynamics, pine biochar, silt loam, soil acidity, soil amendment, soybean

1 Introduction

Globally, agricultural systems are challenged by soil degradation, primarily through accelerated acidification and the depletion of soil organic matter (SOM), which collectively challenge crop yields and long-term food security (Agegnehu et al., 2016; Huang et al., 2023; Lal, 2015; Shokri et al., 2025). In highly productive temperate regions like the U.S. Mid-South, intensive cultivation of soybean (*Glycine max*) often faces significant constraints on acidic silt loam soils (Bedassa et al., 2022; Xie et al., 2024). The prevalence of low pH (acidic) levels in these systems limits plant growth by increasing toxic aluminum (Al³⁺) solubility and reducing the bioavailability of essential nutrients (Agriculture Victoria, 2025;

Bakari et al., 2020; Ofoe et al., 2023). For this leguminous crop, acidity serves as a critical biological barrier; Al toxicity inhibits the early molecular signaling required for successful *Bradyrhizobium japonicum* infection and root nodule formation (Ferguson et al., 2010; Hungria and Stacey, 1997). These chemical challenges are often compounded in cropping systems in silty textures that lack robust SOM dynamics, exhibit poor water retention, the depletion of essential base cations (particularly Potassium, K) or have insufficient buffering capacity, leading to a deteriorating soil physical architecture and reduced moisture resilience and can exacerbate drought stress (Blanco-Canqui, 2017; Lal, 2015). Consequently, there is an urgent need for sustainable management strategies that can remediate these physicochemical constraints while maintaining the agronomic viability of sensitive crops like soybean.

Biochar, a carbon-rich material produced through the pyrolysis of organic feedstocks under oxygen-limited conditions, has emerged as a specialized soil amendment for stabilizing such acidic environments (Liu et al., 2025; Woolf, 2010). Unlike labile organic inputs, biochar's highly recalcitrant nature allows it to serve as a persistent soil conditioner, particularly in regions where rapid nutrient loss and structural instability are primary agronomic constraints (Kabir et al., 2023; Shackley et al., 2012). The functional value of biochar is derived from its complex physical-chemical architecture; its high porosity and expansive surface area can enhance moisture retention and porosity, which are critical factors for silty loam textures prone to compaction (Adekiya et al., 2025; Kabir et al., 2023; Nair et al., 2017). Chemically, biochar facilitates a 'liming effect' through its ash content and surface functional groups, which increases soil pH, raises Cation Exchange Capacity (CEC), and neutralizes exchangeable Al (Agegnehu et al., 2016; Haile et al., 2024; Liu et al., 2025). Furthermore, by sequestering stable carbon and reducing leaching losses, biochar offers a dual benefit of enhancing soil fertility and mitigating the environmental footprint of intensive systems (Khan et al., 2017; Malyan et al., 2021).

While numerous studies have evaluated biochar's potential to improve soil health, results often vary significantly based on soil type, amendment rate, and crop species. For instance, research in tropical Ferralsols has reported substantial improvements in nutrient availability and water retention (Agegnehu et al., 2016). However, such findings are not universally applicable to temperate silty loam soils, where the inherent chemical and physical properties differ drastically. In these temperate systems, many short-term studies have reported inconsistent results, particularly when conducted in neutral or alkaline environments (Mukherjee et al., 2014; Vijay et al., 2021). Despite the critical role of soybean in global agriculture, existing literature lacks sufficient field-based evidence on how biochar influences acidic silty loams under continuous soybean cultivation. Furthermore, most available research is limited to pots or single-season trials, which fail to capture the seasonal variability and long-term carbon stabilization essential for understanding soil recovery. In Kentucky's predominant silt loam soils, where native nutrient levels may appear adequate but are constrained by inherent acidity, the evaluation of biochar as a strategic ameliorant remains limited (Sistani et al., 2019). There is a distinct gap in understanding the temporal dynamics of these soil

parameters across multiple sampling periods in real-world agronomic setting.

To address these knowledge gaps, this longitudinal field study investigated the temporal impacts of pine (*Pinus* spp.) sawdust biochar on the physicochemical properties of an acidic silt loam under continuous soybean cultivation. Specifically, the objectives were to: (1) quantify the ameliorative effects of biochar on active and exchangeable acidity; (2) evaluate the buildup of soil organic reserves (total carbon [TC] and SOM) over multiple growing seasons; and (3) determine if biochar application ($12 \text{ t ha}^{-1}\text{yr}^{-1}$) significantly alter hydrological status and nutrient availability in this temperate climate. By monitoring these parameters across pre-planting and post-harvest intervals over a two-year cycle, this research aims to define the functional niche of pine biochar in temperate agriculture, specifically determining whether it acts as an immediate fertility enhancer or primarily as a strategic chemical stabilizer for neutralizing acidification and rebuilding soil carbon stocks.

2 Materials and methods

2.1 Study site and experimental design

The field experiment was conducted over two consecutive growing seasons (May–October 2023 and 2024) at the Harold R. Benson Research and Demonstration Farm at Kentucky State University, Frankfort, Kentucky, USA ($38^{\circ}07'09'' \text{ N } 84^{\circ}53'22'' \text{ W}$) (Supplementary Figure 1). The research site is situated at an elevation of approximately 250 meters above sea level. While the study was conducted within a temperate region, its local climate is specifically classified as humid subtropical (Cfa), defined by hot summers and year-round precipitation (Warf, 2010). Average air temperatures and cumulative annual precipitation were 13.9°C and 1047.24 mm in 2023 and 14.4°C and 1168.65 mm in 2024 respectively (Kentucky Mesonet, 2025).

The soil at the experimental site is McAfee silt loam with 6 to 12 percent slopes (USDA-NRCS, 2025). Before this trial, the area was managed as permanent cool-season grassland for hay production. While this management history preserved soil physical structure and organic matter (3.0%), long-term biomass removal likely contributed to the depletion of native K reserves. Consequently, baseline soil analysis (0–15 cm) confirmed a unique fertility profile: high Phosphorus (118.8 mg kg^{-1}) but limiting K (59.6 mg kg^{-1}) and active acidity (pH 5.07). Particle size analysis indicated a silty loam soil texture across the field, comprising approximately 9.9% sand, 71.5% silt, and 18.6% clay. Further physicochemical analysis revealed the soil contained 1.74% TC and 0.19% Total Nitrogen (TN). The soil's CEC was $16.08 \text{ cmol}(+) \text{ kg}^{-1}$, and additional extractable nutrient concentrations included $2337.0 \text{ mg kg}^{-1}$ for Calcium (Ca), 205.5 mg kg^{-1} for Magnesium (Mg), and 0.79 mg kg^{-1} for Zinc (Zn). While aluminum toxicity is a known constraint in such acidic soils, buffer pH was utilized as the standard agronomic proxy for titratable acidity rather than quantifying specific aluminum species.

The field experiment was arranged in a Randomized Complete Block Design (RCBD) with a split-plot in time structure. Biochar amendment served as the main plot factor, consisting of two explicit treatments: an unamended Control and a Biochar application (12 t ha^{-1}). These treatments were replicated four times across four spatial blocks, yielding a total of eight independent main plots. Soil sampling time (pre-planting and post-harvest) served as the subplot factor (repeated measure) collected from within these eight main plots.

2.2 Biochar characterization

The biochar used was a commercial product purchased from Wakefield Biochar (Valdosta, Georgia, USA). It was derived from southern yellow pine sawdust which was pyrolyzed at 650°C for 10-minute. This 650°C pyrolysis temperature was selected to maximize the aromaticity and inherent alkalinity of the material, which are necessary to effectively neutralize exchangeable acidity and provide a long-term carbon sink in the acidic silt loam soil profile (Antonangelo et al., 2019; Murtaza et al., 2024).

The physicochemical properties of the biochar were analyzed prior to application. The pine sawdust biochar exhibited an alkaline pH of 9.88 (measured in a 25% mixture) and had a packed density of 438.91 kg/m^3 . Proximate analysis revealed a highly recalcitrant structure dominated by 90.58% fixed carbon, with 6.11% volatile matter and a low ash content of 3.31%. Elemental analysis confirmed a carbon-rich composition consisting of 90.90% C, 4.76% Oxygen, 0.63% Hydrogen, 0.40% N, and minimal Sulfur at 0.006%. This elemental makeup yielded a highly condensed molar H:C (org) ratio of 0.08, characteristic of high-temperature pyrolysis.

2.3 Agronomic practices

One month prior to soybean planting, biochar was uniformly applied at a rate of 12 t ha^{-1} (approximately 0.6% w/w) using a manure spreader and incorporated to a depth of 15 cm through tillage. This rate was selected to balance agronomic feasibility and farmers affordability with the need to buffer the soil's active acidity (pH 5.07), based on previous field trials in temperate silt loams which suggest that application rates between 10 and 20 t ha^{-1} are sufficient to improve soil chemical stability without inducing nutrient immobilization (Laird et al., 2010; Rogovska et al., 2014).

The cropping sequence utilized two determinate soybean cultivars representing maturity groups (MG) common to regional production: MG2 (PB 2623 in 2023; PB 2922 in 2024) and MG4 (PB 423 in 2023; PB 4424 in 2024) (Mertz et al., 2025; Poudel et al., 2024). These groups were selected to ensure soil data were collected under a representative canopy across typical planting windows. While two maturity groups were included to enhance the robustness of the soil response data, cultivar-specific performance was not analyzed as an independent variable.

Soybeans were sown at a density of 35 seeds m^{-2} with a 38 cm row spacing (5 rows per plot). In 2023, planting was staggered (MG2: May 14 and MG4: May 21), while in 2024, both groups were sown on May 21. Weed management was conducted via precision drone application of a 5% glyphosate solution (42% active

ingredient). Following the October harvest, all crop residues were incorporated into the top 15 cm of the soil using a disk harrow to facilitate organic matter recycling. Plots remained fallow during the winter months to allow for residue stabilization. All experimental units were maintained under uniform agronomic conditions throughout the study period.

2.4 Soil sampling and laboratory analysis

Soil sampling was conducted at two critical physiological windows: pre-planting (May) and post-harvest (October). In 2023, baseline conditions were established by collecting one composite sample per block prior to planting ($n = 4$), followed by one composite sample per replication after harvest ($n = 8$). In 2024, the sampling intensity was increased to provide higher spatial resolution, with four samples collected per block (two per replication) for both the pre-planting and post-harvest intervals ($n = 16$). All collected soil samples were oven-dried at 38°C and ground to pass a 2-mm screen before analysis at the University of Kentucky Soil Testing Laboratory.

Soil pH (KCL) was measured in a 1:1 soil-to-liquid suspension using 10 mL of 1 M KCl and 10 cm^3 of soil, referred as Soil pH (KCL) (Soil and Plant Analysis Council, 2000). For regional consistency, soil-water pH was estimated using the established Kentucky calibration equation: Estimated Soil-water pH = $(0.91 \times \text{KCL pH}) + 1.34$ (Grove and Ritchey, 2023). Following pH measurement, 10 mL of Sikora II Buffer was added to the suspension and shaken for 10 minutes to determine the Buffer pH (Sikora, 2006). Exchangeable acidity was calculated using the Sikora Buffer Index (Sikora, 2006; Soil and Plant Analysis Council, 2000).

Plant-available macronutrients; P, K, Ca, Mg, and Zn were determined via Mehlich-3 extraction (Mehlich, 1984) followed by analysis via Inductively Coupled Plasma (ICP) spectroscopy (Soil and Plant Analysis Council, 2000). Analytical results initially reported in lb/acre were converted to mg/kg by applying a factor of 0.5 (University of Kentucky Division of Regulatory Services, 2023). TC and TN were quantified through the dry combustion method at 900°C using a LECO CN analyzer (Nelson and Sommers, 1996). Because the baseline soil is highly acidic (pH 5.07) and naturally non-calcareous, inorganic carbon was considered negligible. Therefore, measured TC served as a direct proxy for soil organic carbon (SOC), and SOM was estimated by multiplying the TC% with the Van Bemmelen factor of 1.72 (Nelson and Sommers, 1996).

Sand, silt, clay content and textural class was determined using the micropipette method (Burt et al., 1993; Miller and Miller, 1987). Hydraulic properties, including Field Capacity (FC) and Wilting Point (WP), were measured using a pressure plate apparatus (Dane and Hopmans, 2002). Plant Available Water (PAW) was calculated as: $\text{PAW} = \text{FC} - \text{WP}$. CEC was determined via ammonium saturation (Soil and Plant Analysis Council, 2000). The filtrate was analyzed via ICP to quantify exchangeable bases (Ca, Mg, and K) in units of meq 100g^{-1} (equivalent to cmol kg^{-1}). Total CEC was determined by leaching the ammonium-saturated soil with 10% NaCl and measuring ammonium with an ion-selective electrode. Base Saturation (BS) was computed as:

$$BS(\%) = \frac{(Exch. Ca + Exch. Mg + Exch. K)}{CEC} \times 100$$

2.5 Statistical analysis

All data were entered into Microsoft excel and statistical analyses were performed in R software (version 4.3.2). Data were initially visualized using boxplots to assess distribution pattern and assumptions of normality and homogeneity of variance were tested using the Shapiro–Wilk test and Levene’s test, respectively. For parameters meeting these assumptions, a linear mixed model (LMM) was employed using the lme4 package. The study was analyzed as a longitudinal repeated-measures design, utilizing a total of 44 observations across four sampling events to ensure robust statistical power. Biochar vs Control treatments across four sampling times (pre-planting vs. post-harvest) within two years were treated as fixed effects, resulting in denominator degrees of freedom (DenDF) ranging from 34 to 36 (estimated via the Satterthwaite approximation). To account for the experimental structure and temporal autocorrelation, plot nested within block was included as a random effect. If raw data violated normality assumptions, log, square-root, or inverse transformations were applied to improve adherence to model requirements. In cases where transformations failed to satisfy assumptions, a non-parametric Kruskal–Wallis test was utilized. A two-factor Analysis of variance (ANOVA) or its non-parametric equivalent was used to determine the main effects of biochar treatment, time, and their interaction on each soil parameter. If significant effects were detected ($p < 0.05$), pairwise comparisons of estimated marginal means were conducted with Tukey’s honest significant difference (HSD) test. For non-parametric, Kruskal–Wallis’s test was performed, followed by *post hoc* Dunn’s tests to separate means where significant differences occurred. The results are reported as

means $\pm$ standard error (SE) and group differences are reported in line graph with letters denoting significant differences and NS for non-significant.

3 Results

3.1 Temporal dynamics of soil active and potential acidity.

Baseline soil analysis in May 2023 confirmed no significant differences in acidity between experimental plots prior to biochar amendment ($p > 0.70$). Over the two-year study, soil pH values ranged from 5.0 to 5.4 (1 M KCl) and 5.9 to 6.3 (water). ANOVA indicated a significant main effect of sampling time for both soil pH (KCl) ($F_{(3, 34)} = 3.25$, $p = 0.034$) and estimated soil-water pH ($F_{(3, 34)} = 3.44$, $p = 0.028$). The main effect of treatment and the treatment $\times$ time interaction was not statistically significant for either soil pH (KCl) ($p = 0.165$; interaction $p = 0.199$) or estimated soil-water pH ($p = 0.129$; interaction $p = 0.233$). Despite the absence of a global interaction, pairwise comparisons were conducted at each sampling point to evaluate the temporal efficacy of biochar.

In October 2023, biochar-amended plots exhibited significantly higher soil pH (KCl) compared to the control ($p = 0.028$). This effect persisted into the second year, with biochar treatments maintaining significantly higher pH in October 2024 ($p = 0.046$) (Figure 1A). A similar pattern was observed for estimated soil-water pH, where biochar plots were significantly higher than the control in both October 2023 ($p = 0.024$) and October 2024 ($p = 0.035$) (Figure 1B). No significant differences between treatments were observed during May 2024.

Soil buffer pH data were analyzed using non-parametric methods due to non-normal distribution. The Kruskal–Wallis test

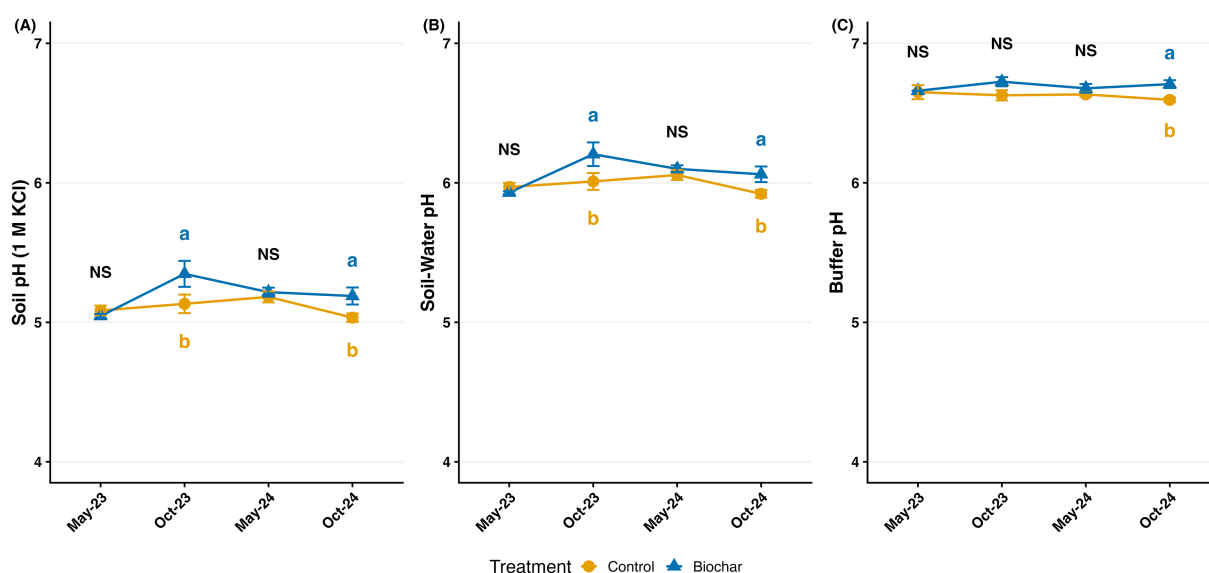


FIGURE 1

Temporal changes in (A) Soil pH (KCl), (B) Estimated soil-water pH, and (C) Buffer pH following biochar ($12 \text{ t ha}^{-1} \text{ yr}^{-1}$) application against control (no biochar). Values are means $\pm$ SE. Letters ('a', 'b') indicate significant differences ($p < 0.05$) between treatments at each sampling point; 'NS' indicates non-significant.

indicated significant differences in buffer pH distribution among groups ($\chi^2_{(7)} = 14.2$, $p = 0.047$). *Post-hoc* analysis revealed no significant changes in buffer pH during the first three sampling events (May 2023–May 2024). However, a significant treatment response was observed in October 2024 sampling ($p = 0.008$), where biochar-amended plots showed significantly higher buffer pH values compared to the control (Figure 1C).

3.2 Fluxes in plant-available macronutrients and exchange properties in soil

There were no significant differences in macronutrient pools between experimental plots prior to treatment application in 2023 ($p > 0.05$). Over the two-year study period, concentrations of P, K, Ca, and Mg exhibited significant temporal fluctuations driven by seasonal cropping cycles. However, the main effect of biochar amendment was not statistically significant (Figure 2). For K, analysis using the LMM revealed a highly significant main effect of sampling time ($F_{(3, 36)} = 8.12$, $p < 0.001$). However, neither the main effect of biochar treatment ($p = 0.70$) nor the treatment $\times$ time interaction ($p = 0.35$) was significant (Figure 2B). Due to non-normal distributions ($p < 0.01$), P, Ca, and Mg were analyzed using the non-parametric Kruskal-Wallis test. Results indicated no significant differences in rank means among treatment groups for P ($\chi^2_{(7)} = 10.4$, $p = 0.17$), Ca ($\chi^2_{(7)} = 7.9$, $p = 0.34$), or Mg ($\chi^2_{(7)} = 6.9$, $p = 0.44$) (Figures 2A, C, D). Pairwise comparisons at individual sampling points confirmed that while nutrient levels varied

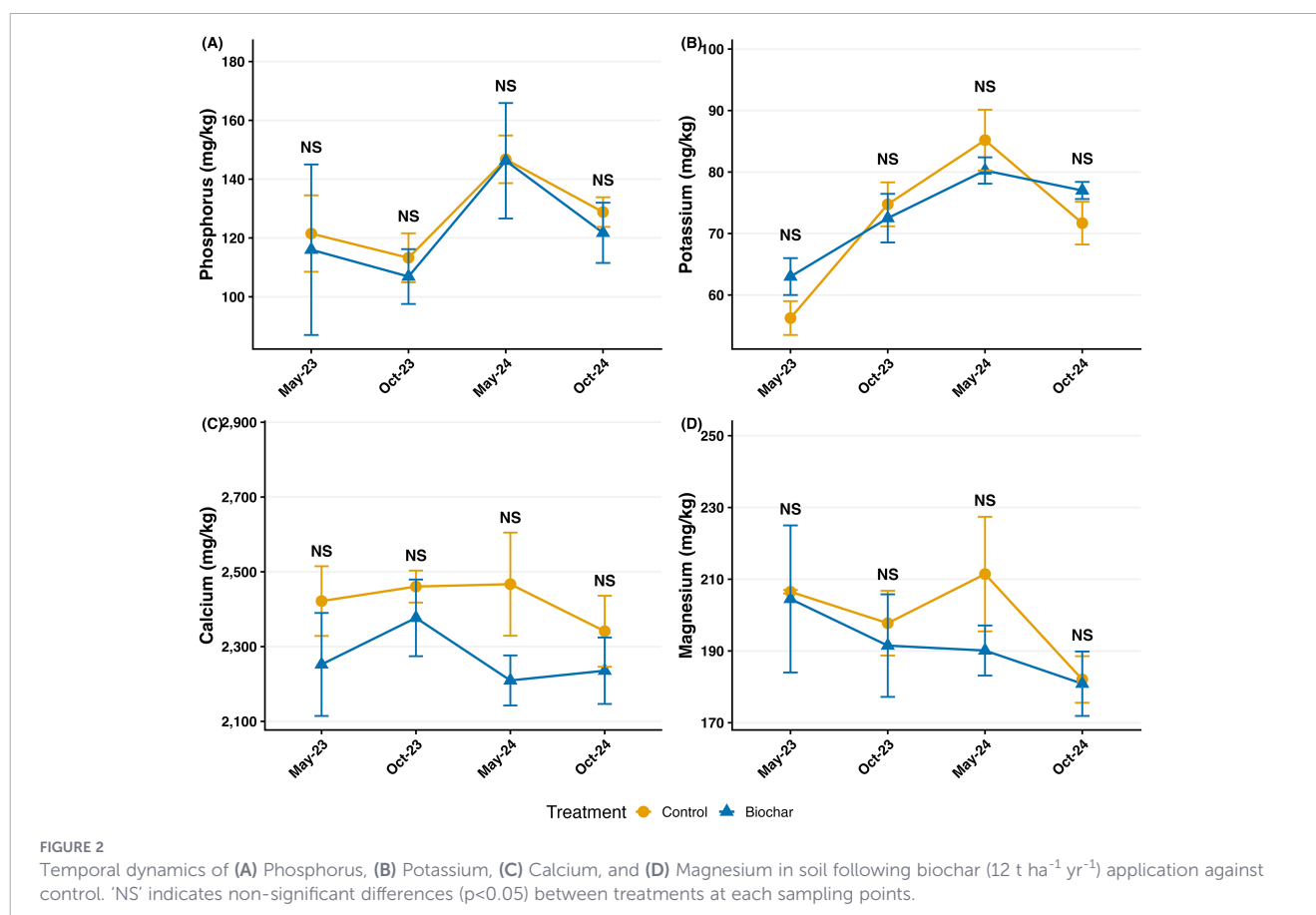
seasonally, biochar application did not significantly alter the status of these elements relative to the control within the timeframe of this study.

CEC exhibited no significant differences among experimental groups ($\chi^2_{(7)} = 4.58$, $p = 0.712$). Values remained statistically similar between treatments across all four sampling periods (Figure 3A). BS displayed a significant main effect of sampling time ($F_{(3, 36)} = 3.28$, $p = 0.032$), reflecting seasonal fluctuations in exchangeable bases (Ca, Mg, K) during the cropping cycle. However, neither the main effect of biochar treatment ($p = 0.45$) (Figure 3B) nor the treatment $\times$ time interaction ($p = 0.38$) was statistically significant.

3.3 Soil organic reserves, Zn, and hydrological properties

In this acidic, non-calcareous soil, measured TC served as a direct proxy for Soil Organic Carbon (SOC). SOC levels showed significant differences among experimental groups ($\chi^2_{(7)} = 20.55$, $p = 0.005$). While no treatment differences were observed during the first three sampling periods, a significant amendment effect emerged by October 2024. At this time point, biochar-amended plots maintained significantly higher levels of SOC (1.96% vs. 1.66%) compared to the control (Figure 4). This carbon increase corresponds to a proportional rise in Soil Organic Matter (SOM) from 2.86% in the control to 3.38% in the biochar plots.

TN met normality assumptions and was analyzed using LMM. The analysis revealed a significant main effect of sampling time ($F_{(3, 36)} = 8.12$, $p < 0.001$).



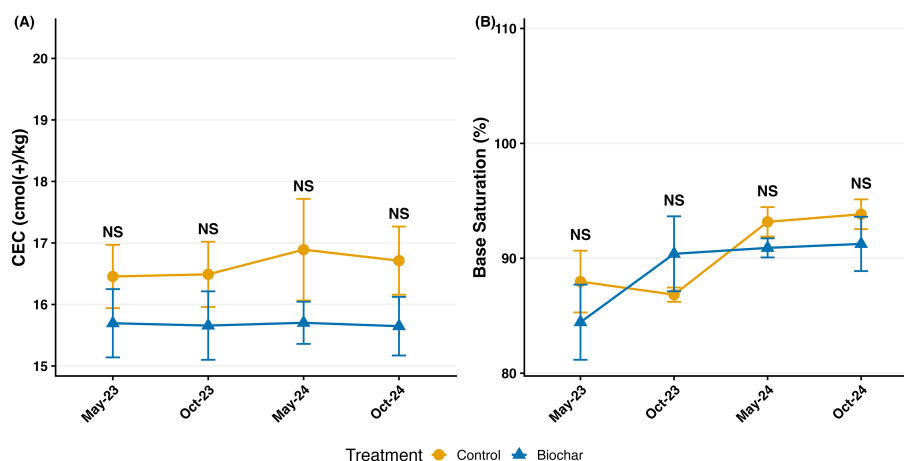


FIGURE 3

Temporal dynamics of (A) CEC and (B) Base saturation in soil following biochar ($12 \text{ t ha}^{-1} \text{ yr}^{-1}$) application against control. Values are means $\pm$ SE. 'NS' indicates non-significant ($p > 0.05$) between treatments at each sampling points. CEC is reported in $\text{cmol}(+) \text{ kg}^{-1}$ (equivalent to $\text{meq } 100 \text{ g}^{-1}$).

$_{36} = 35.42$, $p < 0.001$), with values decreasing noticeably from May 2023 (0.19%) to October 2024 (0.15%) across both groups. However, unlike C, N retention was not significantly affected by the amendment (Figure 5A). Neither the main effect of treatment ($p = 0.49$) nor the treatment $\times$ time interaction ($p = 0.57$) was statistically significant.

Similarly, Zn showed no significant differences among experimental groups ($\chi^2_{(7)} = 8.53$, $p = 0.288$). Pairwise comparisons confirmed that biochar application did not significantly alter Zn availability relative to the control at any sampling point (Figure 5B).

Soil hydrological indicators exhibited distinct temporal dynamics over the two-year study period. The global Kruskal-Wallis analysis revealed significant differences among the experimental groups for both PAW ($\chi^2_{(7)} = 34.50$, $p < 0.001$) and FC ($\chi^2_{(7)} = 33.50$, $p < 0.001$). Descriptive analysis indicated that both PAW and FC values decreased in the second year (2024) compared to the first year (2023) across all plots. *Post-hoc* pairwise comparisons using

Dunn's test indicated that there was no statistical difference among treatments ($p > 0.05$) at any specific sampling point (Figure 6).

4 Discussion

Our findings demonstrate that annual pine sawdust biochar application to an acidic silt loam soil functions primarily as a long-term chemical stabilizer rather than an immediate fertility enhancer. The most significant outcome of this two-year study was the dual temporal response: a consistent, seasonal buffering of active soil acidity following crop harvest, paired with a distinct "lag effect" where structural reserve acidity and organic carbon only increased significantly after two years of cumulative application. Unexpectedly, biochar did not alter macronutrient availability, Zn, CEC, BS, or soil hydrology, all of which were driven entirely by seasonal and environmental factors. These results directly answer our core research question, confirming that in high-production, temperate systems, biochar's agronomic value lies in mitigating long-term soil degradation and carbon depletion rather than substituting conventional fertilizers (Jeffery et al., 2017; Krapfl et al., 2014; Lévesque et al., 2022).

4.1 Ameliorative response: stabilization of soil pH and buffering capacity

The application of biochar acted as a targeted chemical conditioner, specifically mitigating the acidifying pressures of the soybean cropping cycle. While baseline acidity was uniform across the site (Figure 1), a clear seasonal pattern emerged in the active acidity pools. Biochar-amended soils successfully resisted the severe post-harvest pH decline observed in the control plots, maintaining a stable pH between May 2023 and May 2024. This stabilization was driven by the potent liming effect of the alkaline biochar (pH 9.88), where the dissolution of carbonates and release of base cations from the ash fraction actively consumed excess protons (Haile et al., 2024; Zubairu et al., 2022).

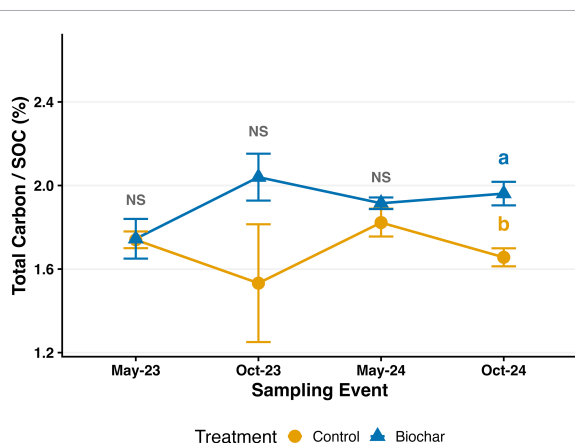


FIGURE 4

Temporal dynamics of total carbon (SOC) following biochar ($12 \text{ t ha}^{-1} \text{ yr}^{-1}$) application against control (no biochar). Values are means $\pm$ SE. Letters indicate significant differences ($p < 0.05$); 'NS' indicates non-significant. In this highly acidic (pH 5.07) and non-calcareous silt loam, inorganic carbon is negligible; therefore, TC is functionally equivalent SOC.

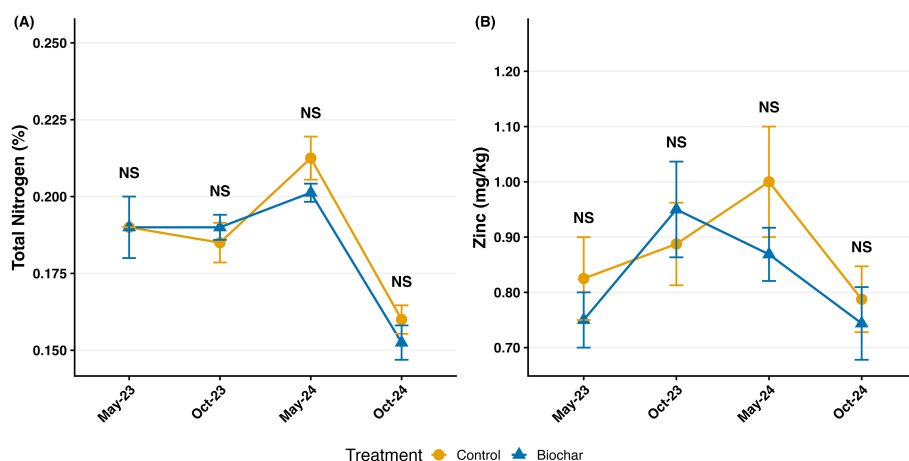


FIGURE 5

Temporal dynamics of (A) TN and (B) Zn in soil following biochar ($12 \text{ t ha}^{-1} \text{ yr}^{-1}$) application against control. Values are means $\pm$ SE. 'NS' indicates non-significant ($p > 0.05$) between treatments at each sampling points.

Notably, even with a second annual application of biochar in 2024 before planting, a slight decline in pH was observed by October 2024 compared to the previous post-harvest peak in October 2023. This trend illustrates the immense acidifying pressure inherent in intensive legume (Soybean) production. During the growing season, soybean roots extrude protons (H^+) into the rhizosphere to balance cation uptake, a process compounded by the nitrification of soil organic nitrogen and precipitation-induced leaching (Chen et al., 2013; Guo et al., 2010; Hinsinger et al., 2003; Rengel, 2003). The fact that pH levels remained significantly higher than the control despite these pressures confirms that the cumulative biochar amendment provided a vital alkaline buffer, even as the rhizosphere worked to neutralize it over two consecutive growing seasons. While the numerical shift from baseline (5.07) to final (5.19) is modest, the statistical and agronomic significance lies in the divergence from the control trajectory. By the final harvest, the biochar plots maintained a pH 0.16 units higher than the un-amended plots (5.03), which continued to acidify under continuous

cultivation. In a highly buffered silt loam, this arrest of seasonal acidification demonstrates a meaningful stabilization of the chemical environment.

Beyond active acidity, the response of the soil's buffer pH revealed a pronounced lag effect. Buffer pH, which measures the soil's intrinsic resistance to overall pH changes, remained completely unaffected during the first three sampling events spanning a year and a half. A measurable shift only materialized at the very end of this study in October 2024 (Figure 1C). This delayed response is biologically and chemically significant because it highlights the time-dependent nature of reserve acidity development. When fresh biochar is incorporated into the soil, it requires time to undergo the physical and biological oxidation necessary to develop oxygen-containing functional groups on its surface (Liu et al., 2025; Shi et al., 2017, 2018). As carboxylic and phenolic groups slowly form over multiple seasons, they enhance the soil's variable charge (Chen et al., 2013; Shi et al., 2018). Our results indicate that it took seventh months of field aging and aggregate integration for the

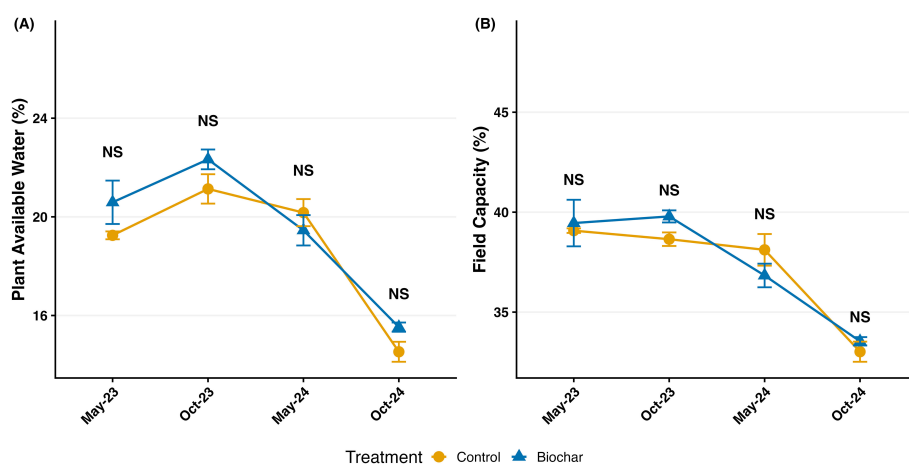


FIGURE 6

Temporal dynamics of (A) Plant available water and (B) Field capacity in soil following biochar ($12 \text{ t ha}^{-1} \text{ yr}^{-1}$) application against control. Values are means $\pm$ SE. 'NS' indicates no significant difference between treatments at each sampling point ($p > 0.05$).

biochar to fundamentally enhance the soil's underlying buffering capacity (Figure 1). For farmers and land managers working with high-production temperate soils, this confirms that biochar operates on a threshold-dependent timeline; its primary benefit is the gradual creation of a highly buffered rhizosphere that protects against the long-term degradation common to continuous cropping systems (Šimanský and Juriga, 2025).

4.2 Direct fertility evaluation: nutrient dynamics and soil exchange properties

The status of soil macronutrients in this study was governed primarily by seasonal biological cycles and inherent soil characteristics rather than biochar amendment. While concentrations of macronutrients exhibited significant temporal fluctuations over the four sampling events, the absence of consistent treatment effects indicates that nutrient cycling was mainly driven by plant uptake, residue incorporation, and seasonal weather patterns. This stability relative to the biochar treatment is consistent with acidic McAfee silt loam soil, which had been managed as permanent grassland for over a decade prior to the trial. In such nutrient-sufficient systems, the native nutrient supply often exceeds crop demand thresholds, masking any potential additive effects from the amendment (Jeffery et al., 2017; Lévesque et al., 2022).

The limited nutrient contribution from the amended biochar is directly attributable to its physicochemical properties. Although biochar is often cited as a source of soluble K, the pine sawdust material used here was characterized by a very low ash content (3.31%) and high fixed carbon (90.58%), indicating that it contained less amounts of immediately soluble salts compared to manure-based biochar (Enders et al., 2012; Lehmann and Joseph, 2015; Singh et al., 2010). As noted by Singh et al. (2010), wood-derived biochar typically possesses lower total N, P, K, and exchangeable cations than manure-based biochar's due to the inherently lower nutrient density of the woody biomass. Similarly, Ca and Mg levels remained statistically unchanged; although the biochar's alkaline pH (9.88) provided enough base cations to buffer active acidity, the total mass added was quantitatively insignificant compared to the soil's massive native reserves (Lévesque et al., 2022). The P availability also showed no response, likely because the amendment's low ash fraction provided insufficient phosphate to alter the soil's equilibrium, and the buffered soil pH conditions did not induce significant P-fixation or release (Penn and Camberato, 2019; Qin et al., 2025). Mechanistically, significant shifts in aggregate-associated nutrient pools often require multi-year stabilization and weathering periods to become fully exchangeable, particularly in soils with high native cation stocks (Bao et al., 2024; Xiu et al., 2025).

The stable soil exchange properties (CEC and BS) across treatments suggests that the functional groups on the fresh biochar surface were initially insufficient to alter the soil's total nutrient retention capacity within the two-year timeframe. This finding aligns with the specific properties of our pine feedstock; as noted by (Singh et al., 2010), wood-derived biochar's produced at higher temperatures typically possess significantly lower potential CEC than manure-based amendments due to the loss of volatile functional

groups. This is supported by the extremely low molar H:C ratio (0.08) of our biochar, which indicates a highly condensed, aromatic structure typical of high-temperature pyrolysis (>600 °C). Such materials are chemically recalcitrant and possess low initial CEC due to the loss of volatile functional groups during intense carbonization (Keiluweit et al., 2010; Spokas, 2010). BS also remained statistically unchanged, reflecting the massive buffering capacity of the native soil relative to the biochar input (Laird et al., 2010; Liu et al., 2025). While the biochar contributed sufficient alkalinity to neutralize active acidity and stabilize pH as explained above, the total mass of base cations added was quantitatively small compared to the soil's existing exchangeable reserves. Consequently, the amendment buffered the solution pH without causing a statistically detectable shift in the ratio of base cations to total exchange capacity (Shi et al., 2017; Zubairu et al., 2022).

The development of significant CEC in such stable biochar is fundamentally an oxidation-dependent process. Over time, field aging exposes the recalcitrant aromatic backbone to biotic and abiotic oxidation, progressively increasing the density of oxygen-containing functional groups (carboxyl and phenolic), which serve as new cationic adsorption sites (Chen et al., 2013; Liu et al., 2025; Shi et al., 2017, 2018). However, this surface functionalization is kinetically slow; it requires multi-year exposure to environmental weathering to manifest as a statistically measurable increase in bulk soil CEC. Furthermore, the lack of significant response in Zn indicates that the annual application rate of 12 t ha⁻¹ was safe and did not induce nutrient immobilization. While biochar can sometimes decrease Zn availability in acidic soils by raising pH or physically binding ions, in our case, the crop-driven processes and high native fertility outweighed the influence of the amendment (El-Naggar et al., 2024). Consequently, this “null result” confirms that this high-carbon, low-ash pine biochar can be integrated into existing temperate production systems without disrupting standard fertilization programs or risking yield penalties from nutrient tie-up.

4.3 Sequestration potential: soil organic reserves and carbon-nitrogen dynamics

The dynamics of SOC in this study highlight the temporal scale required for biochar integration and the eventual manifestation of measurable carbon accrual in temperate agricultural systems. The emergence of a significant amendment effect only at the final two-year sampling threshold, despite no observable differences during the first three samplings, confirms a distinct “Lag Effect” (Figure 4A). This delayed response suggests that meaningful biochar-induced improvements in soil organic reserves often require cumulative application and multi-year equilibration periods rather than immediate accrual (Chagas et al., 2022; Ernest et al., 2024; Yang et al., 2025). Our findings are consistent with long-term field observations. Ernest et al. (2024) reported that in temperate silt loams, substantial increases in SOC and SOM were only statistically separable after several years of continuous annual application. Similarly, a comprehensive meta-analysis of 169 studies by Chagas et al. (2022) confirmed that while carbon sequestration effects in the first 2–3 years are often statistically marginal, biochar

significantly expands stable carbon pools over longer durations as the amendment physically integrates into the soil matrix. Recent modelling approaches, such as the MIMICS-biochar model, support this trajectory, suggesting that the formation of protected carbon pools is a kinetically slow process that accelerates only after the biochar surface has been colonized and oxidized (Han et al., 2024).

In contrast to the carbon pools, the lack of response in TN mirrors findings in other short-term trials where N cycling is largely governed by microbial mineralization and immobilization processes that are not immediately altered by biochar unless paired with high-rate inorganic fertilization (Nguyen et al., 2017; Zhang et al., 2021). The significant temporal decline observed across all plots is consistent with standard seasonal drawdown patterns where nitrogen export in soybean grain typically exceeds the input from biological nitrogen fixation (Salvagiotti et al., 2008). This seasonal TN depletion (Figure 5A), rather than treatment-induced immobilization, likely governed the N dynamics. Crucially, the absence of a differential decline between treatments suggests that the pine biochar did not induce “N starvation” or competitive immobilization (Nguyen et al., 2017). This decoupling of C and N dynamics further emphasizes that while biochar is a potent tool for long-term C sequestration, its influence on the N cycle in high-fertility systems is less pronounced and heavily dependent on the stoichiometry of the specific feedstock (Wang et al., 2016).

Collectively, these results demonstrate that biochar’s measurable impact on soil organic reserves in temperate systems follows a threshold-dependent timeline. Consequently, short-term evaluations (under 2 years) may underestimate the sequestration potential of biochar by capturing only the initial priming phase while missing the subsequent stabilization phase that drives long-term soil health benefits.

4.4 Soil hydrological properties

The hydrological results in this study, characterized by significant temporal variation but a lack of significant treatment effects, align with theoretical expectations for fine-textured soils in temperate climates. The physical utility of biochar in silty loam systems is typically expressed through improvements in soil structure, specifically aggregation, porosity, and the resulting moisture dynamics (Blanco-Canqui, 2017).

The significant temporal fluctuations in FC and PAW underscore the dominance of seasonal moisture regimes over amendment-induced structural changes. Higher moisture values during 2023 in our experimental site coincided with cooler temperatures and greater precipitation, while the lower values observed in October 2024 (Supplementary Figure 2) reflected seasonal drawdown and warmer late-season conditions (Kentucky Mesonet, 2025). This confirms that in acidic silt loams, environmental variables remain the primary drivers of water availability. In such fine-textured soils, which already possess high native water-holding capacity, low-to-moderate biochar application rates ($12 \text{ t ha}^{-1}\text{yr}$) typically produce negligible hydrological shifts within a two-year window.

The inconsistent response of soil water properties to biochar is well-documented. While a meta-analysis of 169 studies reported that biochar application ($30\text{--}70 \text{ t ha}^{-1}$) could increase PAW content

by 28.5% and FC by 20.4%, these benefits are overwhelmingly concentrated in coarse-textured soils where biochar fills large macropores (Edeh et al., 2020). In contrast, silt-dominated landscapes often show negligible results in the short term (Blanco-Canqui, 2017). Specifically, research suggests that water retention improvements in fine soils typically manifest only above application thresholds of 15 t ha^{-1} (Paneque et al., 2016; Xiao et al., 2016). Our findings are further corroborated by Mukherjee et al. (2014), who found no significant changes in available water capacity when oak-derived biochar (produced at 650°C) was amended into a silty loam. This suggests that the immediate hydrological benefits of biochar in acidic, silt-rich landscapes are limited. Although biochar-amended plots maintained numerically slightly higher mean moisture values, the lack of statistical significance confirms that detecting measurable physical benefits likely requires longer observation periods to allow for the physical integration of biochar into soil macro-aggregates.

4.5 Synthesis of cumulative ameliorative impact

To clearly ascertain the changes in soil properties directly attributable to the biochar application, the final measurements from October 2024 were compared against the initial May 2023 baseline. The results indicate that the amendment’s primary influence was the maintenance of soil acidity levels and the accrual of organic reserves in a system otherwise prone to degradation. The baseline Soil pH (KCl) was recorded at 5.07; by the end of the 17-month study, the biochar-amended plots maintained a stabilized pH of 5.19. In contrast, the control plots showed a downward trajectory, reaching a more acidic 5.03 by the final sampling. A similar divergence was observed in the organic reserves. TC (SOC) increased from an initial baseline of 1.74% to 1.96% in the amended plots, a net accrual of 12.6%. Conversely, the control plots experienced a depletion of carbon reserves, declining to 1.66% by the final harvest. While the study tracked 11 different soil properties, including macronutrients (P, K, Ca, Mg), Zn, ion exchange capacity (CEC, BS), and hydrological indicators (FC, PAW), most of these parameters simply fluctuated with the seasons and crop needs. However, the clear divergence in pH and SOC trajectories confirms that the biochar worked exactly where it was needed most, stabilizing acidity and building carbon without disrupting the rest of the soil’s nutrient or water balance in acidic McAfee silt loam soil.

5 Conclusion

Pine sawdust biochar functions as a long-term chemical and carbonaceous stabilizer in acidic silt loams, rather than an immediate source of crop nutrients. The primary value of the amendment observed over 17 months was its ability to act as a buffer; it successfully arrested the natural acidification trend caused by intensive soybean cultivation and initiated a measurable increase in organic carbon reserves. However, the lack of significant shifts in soil hydrology, CEC, or macronutrient availability suggests that

these properties are governed by the soil's intrinsic mineralogy and seasonal environmental drivers, which were not fundamentally altered by short-term application.

While the 12-t ha⁻¹ application rate demonstrated clear benefits for pH and SOC maintenance, it should be viewed as an observed performance benchmark rather than an optimized agronomic recommendation. Because only a single application level was evaluated, future research is necessary to conduct multi-rate trials that can identify the “tipping point” where biochar might begin to influence the soil's physical architecture. Ultimately, this study provides a baseline for utilizing woody biochars to protect against the degradation of temperate cropping systems, though long-term monitoring (>3 years) remains essential to determine the cumulative effects on soil structure and productivity.

Data availability statement

The original contributions presented in the study are included in the article/[Supplementary Material](#). Further inquiries can be directed to the corresponding author.

Author contributions

BB: Writing – review & editing, Data curation, Formal analysis, Investigation, Methodology, Software, Writing – original draft. DK: Investigation, Methodology, Writing – review & editing. SP: Writing – review & editing, Investigation, Methodology. LM: Investigation, Methodology, Writing – review & editing. AM: Writing – review & editing. AC: Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Validation, Writing – review & editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fagro.2026.1719143/full#supplementary-material>

SUPPLEMENTARY FIGURE 1

Map of study area (A) Franklin County, Kentucky (B) Harold R. Benson Research and Demonstration Farm.

SUPPLEMENTARY FIGURE 2

Monthly weather patterns during the experimental years 2023 (A) and 2024 (B) at Franklin County, KY, USA. Bars represent total monthly precipitation (mm) and lines represent average high (red), mean (blue), and low (green) temperatures (°C). Shaded regions in bars indicate soil sampling periods in May (pre-planting) and October (post-harvest) (Kentucky Mesonet, 2025).

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