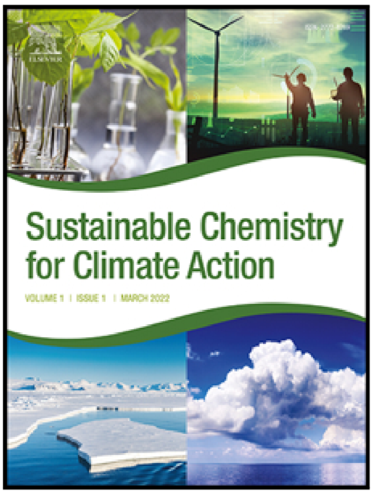

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Effects of biochar and fertilizer application on greenhouse gas emissions and soil carbon sequestration potential under field conditions

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Abstract

Integrated assessments of soil management interventions on greenhouse gas (GHG) emissions and carbon sequestration are crucial for developing innovative and sustainable agricultural systems. However, the potential application of biochar with fertilizer to maximize environmental benefits in reducing soil GHG emissions remains unclear. In this study, a field experiment was conducted to assess the effects of biochar application, with and without fertilizer, on GHG reductions and carbon sequestration potential in a sorghum field at Prairie View A&M University's research farm in the southern Great Plains of Texas, USA. The findings indicated that biochar application with fertilizer increased soil organic carbon and surface-level soil moisture, while reducing both surface and subsurface nitrogen levels. Furthermore, biochar application with full and reduced fertilizer application rates was found to reduce CH_4, CO_2, and N_2O fluxes from 5.5% to 12.4%. Biochar application with full-rate fertilizer was found to increase sorghum yields up to (+35%), while a 2.5 t/acre application of biochar with reduced fertilizer found decreased sorghum yields. Besides, biochar application significantly increased net ecosystem carbon balance, with maximum sequestration under B5 treatments (up to 19.6 Mg C ha^{-1}), followed by B2.5, highlighting its potential to enhance carbon sequestration for climate mitigation and sustainable soil management. N_2O was found to be the most potent gas in terms of its cumulative global warming potential (GWP). CH_4 and CO_2 contributions were generally low across treatments, accounting for 5–10% or less of the total GWP, and showed relatively little variation among treatments. These results indicate that fertilizer management has a strong influence on N_2O emissions, whereas biochar alone has a minor effect on reducing daily GWP. The findings indicate that biochar, with and without fertilizer application, in sorghum fields improves soil physicochemical properties and reduces soil GHG emissions and increased carbon sequestration.

Keywords: Biochar; Global Warming Potential; Greenhouse Gas emissions; Sustainable agriculture; Carbon Sequestration; net ecosystem carbon balance

1. Introduction

Integrated assessments of soil management interventions on greenhouse gas (GHG) emissions and carbon sequestration are crucial for developing smart and sustainable agricultural systems [1–3]. Despite this growing relevance, comparative studies examining conventional fertilizer-based systems and biochar-amended soils with respect to their carbon sequestration potential and GHG mitigation under field conditions remain limited. Most previous research has primarily focused on soil fertility, nutrient use efficiency, crop yield, plant growth, soil biological activities, and microbial communities [4–7]. Historically, field-based fertilizer studies have focused on maximizing crop yield and improving nutrient use efficiency [8], while also maintaining soil health and minimizing environmental impact [9–12].

Similarly, studies conducted in the USA have primarily focused on assessing the potential of biochar application in enhancing agriculture, as reviewed, which identifies biochar's multifunctional benefits: enhancing soil fertility and crop productivity, sequestering carbon, reducing greenhouse gas emissions, and improving water quality [13–15]. For instance, [16] evaluated different application rates combined with organic and inorganic fertilizers on plant growth, nutrient uptake, yield, and ear quality of sweet corn, while [17] examined the effects of biochar on crop growth and nitrogen (N), a greenhouse study was conducted with carrot, lettuce, and soybean. [18] examined biochar has been investigated for its potential to enhance the nutrient supply efficiency of organic fertilizers, maintain soil quality, and promote sustainable crop production. Additionally, [19] investigated long-term biochar application, which promotes rice productivity by regulating root dynamic development and reducing nitrogen leaching.

Field research indicates that biochar-fertilizer blends enhance nitrogen use efficiency (NUE) and plant nitrogen uptake, while reducing nitrogen losses through leaching compared to conventional fertilizer treatments [20], nitrogen transformation dynamics [21], and increase soil cation exchange and soil pH modulation [22], organic matter conversion and nitrogen cycling [21, 23]. On the other hand, excessive use of inorganic fertilizers gradually caused water pollution and eutrophication [24, 25], emission of GHGs due to soil microbes converting excess applied nitrogen into nitrous oxide (N_2O) [26, 27], soil quality degradation through microbial imbalance and acidification [25], while certain biochars can release toxic substances [28, 29], microbial community shifts, and ecological imbalance, increasing soil risks [30, 31], heavy metals or organic pollutants [32].

The integrated impacts of biochar with fertilizer are increasingly gaining acceptance. However, yield gains reported in the existing literature from co-application of fertilizer with biochar are conflicting [33]. The effects were influenced by biochar properties (production temperature, C: N ratio) and soil conditions, mostly very acidic soil where pH <5 [33], improved soil properties [34], yield increase [35], and increased soil microbes [36]. Few investigations have explicitly integrated these perspectives, comparing conventional fertilizer and biochar treatments under field conditions with respect to both carbon sequestration potential and greenhouse gas emissions [37]. This separation limits the identification of management strategies that can simultaneously support productivity and long-term climate mitigation.

Fertilizer and biochar amendments can exert contrasting effects on soil carbon and greenhouse gas dynamics. Conventional fertilizers may enhance biomass production and residue inputs, which can contribute to soil organic carbon (SOC) accrual, yet they can also accelerate organic matter decomposition, potentially increasing CO_2 and N_2O emissions [19]. In contrast, biochar introduces recalcitrant carbon directly into the soil and can alter microbial activity and nutrient cycling, often resulting in enhanced carbon stabilization and reduced greenhouse gas emissions [3]. Understanding these trade-offs is crucial for evaluating whether biochar can serve as a viable alternative or complement to conventional fertilizers in climate-smart agriculture [38].

Globally, integrated assessments comparing fertilizer- and biochar-based management systems for carbon sequestration and GHG mitigation remain scarce. This knowledge gap is particularly acute in regions with degraded soils and low organic carbon stocks, such as the southern Great Plains, Texas, where interventions that simultaneously enhance productivity and climate resilience are urgently needed [39]. Systematic field-scale evaluations quantifying the effects of biochar and fertilizer on both soil carbon and GHG fluxes under realistic agricultural conditions remain limited.

Unlike many previous studies that focus on either greenhouse gas emissions or soil carbon sequestration in isolation, our study provides an integrated assessment of net ecosystem carbon balance (NECB) by simultaneously accounting for carbon inputs (biomass production) and outputs (CO_2, N_2O, and CH_4 emissions) under field conditions. This allows for a more comprehensive evaluation of the climate mitigation potential of biochar–fertilizer interactions.

In addition, while meta-analyses often synthesize data across diverse environments, they lack a site-specific understanding of processes. The specific objectives of the study are: (i) quantifying treatment-specific trade-offs between productivity and emissions under controlled field conditions, (ii) evaluating combined biochar and fertilizer treatments across multiple application rates, and (iii) linking soil carbon dynamics with trace gas fluxes to assess overall system-level sustainability.

2. Materials and methods

2.1. Experiment design

This study was conducted from May 2025 to August 2025 in the research farm of the College of Agriculture, Food, and Natural Resources at Prairie View A&M University, USA. The study area was situated at an altitude of 89 m above sea level, spanning a latitude range of 30° 5' 33.70" N to 30° 5' 51.94" N, and a longitude range of -95° 58' 25.84" W to -95° 58' 3.69" W. The site has a total annual rainfall of 1,455 mm, based on 2 years of flux tower data. The minimum temperature, recorded in January, is around -5 °C, while the maximum temperature, recorded in June, is around 33 °C. The dominant crops in the states and the study areas are cotton, sorghum, and other crops. The crops are primarily cultivated using either rainfed or irrigation-based farming practices.

The soil at the experimental site was a Wockley fine sandy loam with relatively uniform fertility. The main physical and chemical properties of the soil were: soil bulk density of 1.65 g/cm³ and pH of 6.5. The field trial was conducted in a randomized block design with 9 treatments (including a control) and 3 replicates per treatment. The experiment was conducted across three different plots; therefore, each plot varied in size. Hence, each plot-1 occupied 5.84 acres (plot 1), 6.97 acres (plot 2), and 3.48 acres (plot 3). Each plot is then subdivided into 30 subplots, yielding a total of 90. Plot-1 subdivided by 99 ft by 73 ft, 89 ft by 59 ft for plot 2, and 66 ft by 63 ft for plot 3, with 8 ft row spacing between each replicate subplots. Furthermore, 3 subplots were kept as buffer zones in each plot. The details of each treatment and experimental are shown in Table 1.

Table 1. The description of treatments and their abbreviations.

Codes	Treatments	Abbreviations	Replicates
T1	Biochar rate 1 (2.5 tons/acre) with recommended fertilizer full rate	B2.5+FNPK	9
T2	Biochar rate 1 (2.5 tons/acre) with recommended fertilizer 0.25 rate	B2.5+QNPK	9
T3	Biochar rate 2 (5 tons/acre) with recommended fertilizer full rate	B5+FNPK	9
T4	Biochar rate 2 (5 tons/acre) with recommended fertilizer 0.25 rate	B5+QNPK	9
T5	Biochar rate 1 (2.5 tons/acre)	B2.5	9
T6	Biochar rate 1 (5 tons/acre)	B5	9
T7	Recommended fertilizer full rate	FNPK	9
T8	Recommended fertilizer 0.25 rate	QNPK	9
T9	Control	Control	9
Buffer	-		9
Total	-		90

The elemental composition of inorganic fertilizer is Urea (78 kg/ha), Diammonium Phosphate (45 kg/ha), and Muriate of Potash (48 kg/ha). The biochar used was produced from pine woods through pyrolysis at 500 °C under limited oxygen and was supplied by International Biochar Production plc, USA. The mesh size of the elemental biochar is 0.13 mm, while its composition is as follows: carbon % (64.88±4.48), Hydrogen %(8.40±0.56), Nitrogen %(0.28±0.07), Sulfur (0.10±0.03), Phosphate (0.45 ± 0.07), Chloride (1.65±1.42), Nitrite (5.62±2.92), Nitrate (5.03±0.45), and Sulfate (4.40±0.58).

In early May 2025, biochar was evenly spread on the soil surface and immediately tilled into the soil for ridging. A furrow depth of 10-15 cm was opened between the ridges for fertilizer application prior to sowing. Sorghum was sown by placing two seeds per hole at the middle of the ridges with 10 cm plant spacing and 10 cm row spacing, and was harvested on August 15, 2025. Sorghum is a summer crop that matures within three months. Biochar and NPK were applied manually using a broadcasting approach, following sorghum germination and growth, with applications made approximately 16 cm above the ground. After planting, Roundup herbicide was applied to control weeds. All treatments received the same field management, and the other management measures were identical to the routine field management.

2.2. Plant sampling and analysis

Samples of sorghum grain, stem, and root from nine 9-foot by 9-foot quadrants in each plot and replicate were collected using a random sampling method. The dry and wet biomass of each plant component (grain, stem, and root) was then measured and analyzed.

2.3. Soil sample collection

In this study, soil samples were collected from two depth intervals (0–15 cm and 15–45 cm) and analyzed for bulk density using both disturbed and intact core samples. The selection of soil depths at these two was based on their ecological and agronomic relevance [40]. The 0–15 cm layer represents the topsoil, which is the most biologically active zone, strongly influenced by management practices, organic matter inputs, and root activity. In contrast, the 15–45 cm layer represents the subsoil, which is less directly affected by surface management but plays a critical role in nutrient storage, root penetration, and long-term carbon stabilization.

After collection, the samples were transported to the laboratory for analysis. Bulk density was determined using intact core samples by oven-drying them at 105 °C until a constant mass was achieved. The dry mass of the soil within the known core volume was then used to calculate bulk density. In contrast, disturbed soil samples intended for carbon, hydrogen, nitrogen, and sulfur (CHNS) analysis were dried at 65 °C, then gently ground using a mortar and pestle until they passed through a 60-mesh sieve to ensure homogeneity prior to elemental analysis.Then, soil chemical (carbon) analysis conducted using the Walkley-Black method. The sample's total SOC content was analyzed by dry combustion (elemental analysis, ISO 10694, 1995) [41, 42].

The direct assessment of SOC entails collecting soil samples directly in the field and analyzing them in the laboratory using combustion techniques. The IPCC (2006) recommends sampling the top 30 cm of soil depth for SOC stock estimation, as changes in SOC stock due to management are primarily confined to the top 30 cm in most soils. In other words, this is the depth at which changes in the soil carbon pool are typically likely to be detected during the project period.

2.4. Greenhouse gas flux measurements

Greenhouse gas (GHG) fluxes in the soil, including carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4), were measured using nine field-established experimental treatments, including the control. The static chamber method in conjunction with an automated gas sampling system was used to quantify greenhouse gas fluxes. To reduce soil disturbance during the measurement period, 5 cm-tall permanent chamber collars were placed in each sub-plot.

Each multiplexer was linked to two trace gas analyzers, with one analyzer measuring N_2O and H_2O and the other measuring CH_4 and CO_2. Gas was sequentially sampled from each chamber by the multiplexer. In the gas sampling, each multiplexer was connected to 6–7 chambers. For each chamber, a 4-minute observation period was set, with an additional 45-second pre-purge and 45-second post-purge period. The full sampling cycle across all chambers was completed every 2 hours. Area-based gas samples were taken while the chamber was closed for 120 seconds. To allow for chamber air mixing and system stabilization, a 30-second sampling delay was implemented before data acquisition. The linear rate of change in gas concentration during the chamber closure period was used to calculate gas fluxes.

2.5. Estimation of greenhouse gas emissions and global warming potential

Using chamber-based flux measurements, greenhouse gas (GHG) emissions of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) were measured directly from soil. Gas fluxes were measured for each treatment and plot between June 30 and July 29, 2025, using static chambers connected to automated gas analyzers. Fluxes measured on each sampling day were assumed to represent mean daily fluxes for the corresponding measurement interval.

Measured gas fluxes were initially expressed in molar units (nmol m^{-2} s^{-1}) and converted to mass-based units by applying gas-specific molecular weights and appropriate temporal and spatial scaling factors, including conversions from nanomoles to moles, seconds to days, and square meters to hectares. Cumulative emissions over the measurement period were calculated by integrating daily fluxes using the trapezoidal rule and expressed in kilograms per hectare.

To enable comparison of the climate impacts of different greenhouse gases, cumulative emissions of CO_2, CH_4, and N_2O were converted to carbon dioxide equivalents (CO_2-eq) using a 100-year time horizon. Global warming potential (GWP_{100}) coefficients of 1 for CO_2, 27 for CH_4, and 273 for N_2O were applied, following the recommendations of the Intergovernmental Panel on Climate Change Sixth Assessment Report [43–45]. The total GWP for each treatment was calculated as the sum of the CO_2-equivalent emissions from all three gases. To more accurately assess the influence of biochar on soil greenhouse gas dynamics, cumulative emissions of CO_2, CH_4, and N_2O were incorporated into the GWP calculation using the following equation (1):

$$GWP = M_{\mathrm{CH_4}} * 27 + M_{\mathrm{CO2}} + M_{\mathrm{N2O}} \ * 273 \qquad (1)$$

where *M* represents the cumulative emissions of each gas, with CO_2 expressed in kg ha^{-1} yr^{-1} and CH_4 and N_2O in g ha^{-1} yr^{-1}. The net ecosystem carbon balance (NECB) was assessed by integrating key components of ecosystem carbon dynamics under different treatments. These included changes in SOC, above- and below-ground biomass carbon pools, net greenhouse gas fluxes (CO_2, N_2O, and CH_4, expressed in CO_2 Equivalents), and carbon input from biochar amendments incorporated into the soil. The combined accounting of these components provided a comprehensive estimate of net carbon gain or loss, enabling evaluation of the overall climate impact and carbon sequestration potential of the experimental treatments. The NECB was calculated using the following general mass balance approach (Equation 2):

$$NECB = \Delta\mathrm{SOC} + C_{AGB} + C_{BGB} - \ (\mathrm{CO}^2 + \mathrm{N}^2\mathrm{O} + \mathrm{CH}^4) + C_{biochar} \qquad (2)$$

Where

ΔSOC is the change in SOCstock over time, C_{AGB} is carbon in above-ground biomass, C_{BGB} is carbon in below-ground biomass, $C_{biochar}$ is carbon input from biochar amendment incorporated into soil.

2.6. Statistical analysis

All statistical analyses were conducted using SPSS software (version 20.0.0). Data were first checked for normality and homogeneity of variances, and transformations were applied when necessary to meet the assumptions of analysis of variance. A two-way factorial analysis of variance (ANOVA) was performed to evaluate the main effects of biochar application rate (None, B2.5, and B5), NPK fertilization (None, FNPK, and QNPK), and their interaction on crop yield, soil properties, and greenhouse gas fluxes.

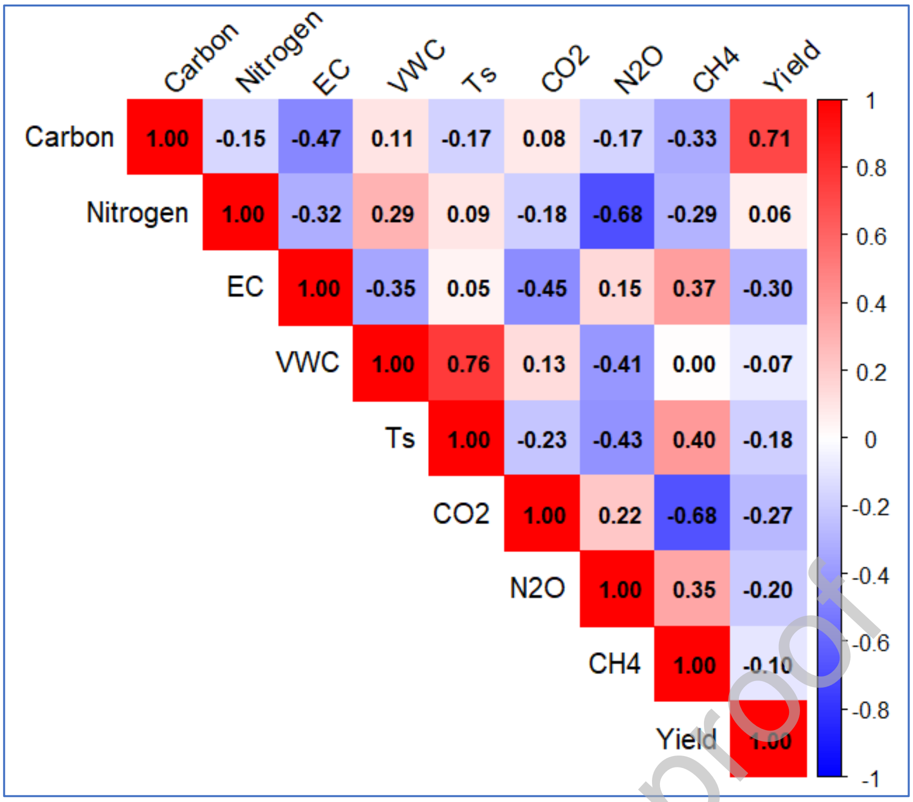
3. Results

3.1.Pearson correlation coefficient

The Pearson correlation coefficient shows the relationships among soil physicochemical properties, greenhouse gases, and crop yields. Volumetric water content (VWC) demonstrated a strong positive correlation with soil temperature (r = 0.76), indicating tight coupling between moisture and thermal regimes across treatments. In contrast, electrical conductivity (EC) was negatively correlated with carbon (r = −0.47), nitrogen (r = −0.32), and VWC (r = −0.35), suggesting that higher nutrient and moisture conditions were associated with lower salinity levels. Carbon and nitrogen showed generally weak relationships with other soil variables, indicating relatively independent variation within the soil system (Fig.1).

The correlation between greenhouse gas emissions and soil properties was both distinct and variable. CO_2 emissions were negatively correlated with EC (r = −0.45) and soil temperature (r = −0.23), but showed only moderate relationships with carbon (r = 0.08) and other soil properties. This indicates that soil environmental conditions more influenced CO_2 fluxes than carbon availability alone. Nitrogen transformations and moisture jointly regulated the dynamics of N_2O–temperature conditions, as evidenced by the strong negative relationship between N_2O emissions and nitrogen ($r = -0.68$) and moderate negative associations with VWC ($r = -0.41$) and temperature ($r = -0.43$). Conversely, CH_4 emissions exhibited a robust negative correlation with CO_2 ($r = -0.68$) and positive relationships with EC ($r = 0.37$) and temperature ($r = 0.40$), underscoring the divergent microbial controls that regulate carbon pathways (Fig. 1).

Soil carbon was the most strongly and positively associated with crop yield ($r = 0.71$), while EC, CO_2, N_2O, and CH_4 exhibited mild to moderate negative relationships. This implies that SOCwas instrumental in maintaining productivity, whereas yields were typically reduced under elevated greenhouse gas emissions and unfavorable soil chemical conditions. In general, the findings suggest that soil environmental factors (moisture, temperature, and salinity) have a more significant impact on GHG emissions. In contrast, soil carbon is the primary factor driving crop productivity. This underscores the existence of distinct regulatory mechanisms that regulate emissions and yield in the system (Fig. 1).



	Carbon	Nitrogen	EC	VWC	Ts	CO2	N2O	CH4	Yield
Carbon	1.00	-0.15	-0.47	0.11	-0.17	0.08	-0.17	-0.33	0.71
Nitrogen		1.00	-0.32	0.29	0.09	-0.18	-0.68	-0.29	0.06
EC			1.00	-0.35	0.05	-0.45	0.15	0.37	-0.30
VWC				1.00	0.76	0.13	-0.41	0.00	-0.07
Ts					1.00	-0.23	-0.43	0.40	-0.18
CO2						1.00	0.22	-0.68	-0.27
N2O							1.00	0.35	-0.20
CH4								1.00	-0.10
Yield									1.00

Fig. 1. Pearson correlation matrix of soil physicochemical properties, greenhouse gas emissions, and crop yield

3.2. Soil physiochemical properties

3.2.1. Soil carbon and nitrogen

Fig.2 shows the baseline carbon and nitrogen content of the research farm plot. As shown in Fig.2, the SOC content at the surface layer (0.30) is slightly higher than in the subsurface layer (0.28). The median values show a similar pattern (0.29 vs 0.2967), indicating a relatively consistent distribution across samples. However, variability was greater in the Subsurface (SD = 0.071) than in the Surface (SD = 0.042), suggesting more heterogeneous carbon distribution at depth, likely due to uneven carbon stabilization and downward transport processes.

The nitrogen content distribution at the surface and subsurface showed very small differences, with slightly higher mean values in the subsurface (0.035) compared to the surface (0.033).

Median values also reflect this slight increase with depth. The Surface layer exhibited lower variability (SD = 0.0045) than the Subsurface (SD = 0.0092), indicating a more stable nitrogen distribution in the topsoil. In contrast, subsurface nitrogen was more variable, possibly due to leaching or redistribution (Fig. 2). Soil carbon showed slightly higher mean values in the surface layer than in the subsurface. In contrast, nitrogen exhibited marginally higher concentrations in the subsurface. Variability was greater in the subsurface for both carbon and nitrogen, indicating increased heterogeneity in deeper soil layers.

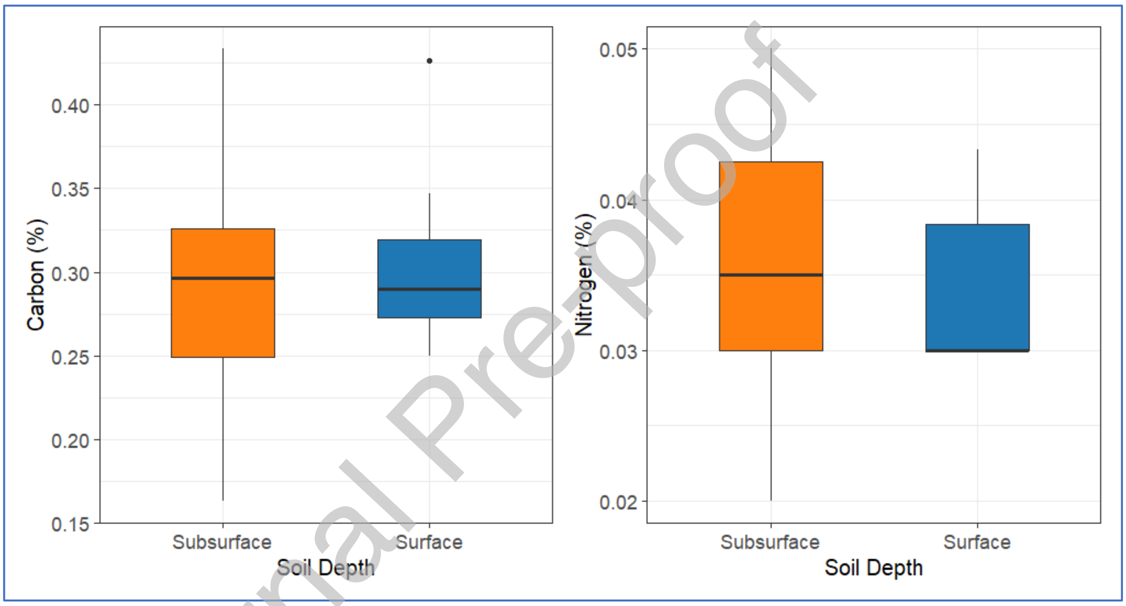


Fig. 2. Baseline Carbon and nitrogen percentage based on CHNS analysis at two different depths: depth-1, i.e., surface, and depth-2, subsurface.

Fig. 3 shows the box plot of SOC for baseline and post-treatment samples compared with the control in the Prairie View A&M University research farm plots. At the surface level, SOC was highest under treatment B5+QNPK (0.48 ± 0.14%) and lowest under FNPK treatment (0.34 ± 0.08%). On the other hand, at the subsurface level, SOC was highest under the B5+QNPK treatment (0.31 ± 0.09) and lowest under the B2.5+FNPK treatment (0.25 ± 0.07).

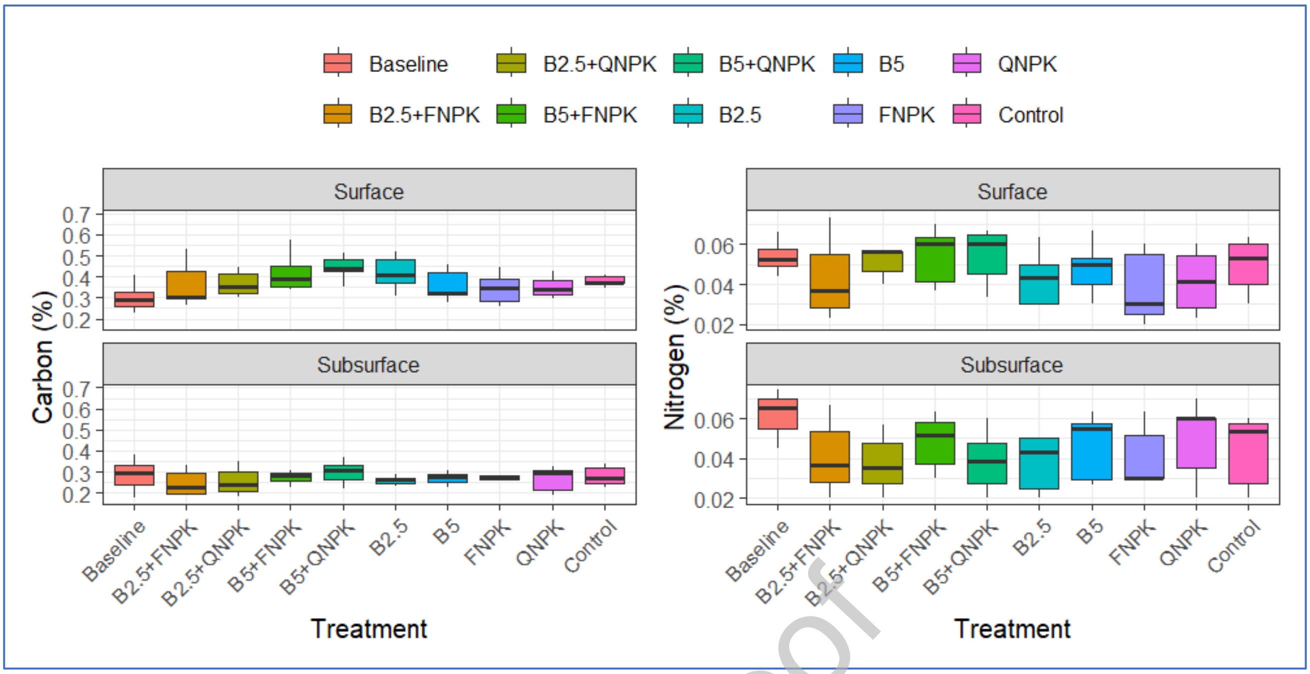


Fig. 3. SOC from CHNS at 9 different treatments, three plots with two depths 1 i.e., surface and depth-2 subsurface.

Table 2. A two-way ANOVA for the effects of biochar and fertilizers on SOC and total nitrogen.

Factor	DF	Carbon %			Nitrogen %		
		SS	F	P	SS	F	P
Biochar	2	0.17	14.72	0.000	0.010	7.305	0.001
NPK	2	0.02	1.60	0.203	0.004	2.686	0.070
Depth	1	0.38	65.52	0.000	0.000	0.149	0.700
Biochar: NPK	4	0.04	1.57	0.183	0.005	1.746	0.140
Biochar: Depth	2	0.20	17.04	0.000	0.002	1.139	0.322
NPK: Depth	2	0.03	2.18	0.115	0.000	0.127	0.881
Biochar:NPK: Depth	4	0.03	1.17	0.324	0.000	0.166	0.956
Residuals	306	1.7661			0.2136		

Fig. 3 and Table 3 present box plots of total nitrogen concentrations at baseline and after treatments in the field at the Prairie View A&M University research farm. At the surface layer, the nitrogen concentration was highest under biochar amendments alone and under biochar with fertilizer (0.05 ± 0.02%), and lowest under full and reduced fertilizer application rates (0.04 ± 0.02%). In contrast, at the subsurface layer, the highest nitrogen concentration was observed under biochar amendments at 5 t/acre with fertilizer application rates (0.05 ± 0.02%), whereas the lowest concentration was observed under the B2.5 treatment (0.04 ± 0.005%).

At the surface layer, nitrogen concentration was highest under the baseline conditions (0.07 ± 0.07%) and lowest under B2.5+FNPK treatment (0.03 ± 0.0073%) in Plot 2. In contrast, at the subsurface layer, the highest nitrogen concentration was observed under baseline conditions (0.07 ± 0.009%), whereas the lowest concentration occurred under QNPK treatment (0.02 ± 0.008%) in Plot 2. At the surface layer, nitrogen concentration was highest under the B5+QNPK Treatment (0.07 ± 0.07%) and lowest under the FNPK treatment (0.04 ± 0.002) in Plot 2. In contrast, at the subsurface layer, the highest nitrogen concentration was observed under control conditions (0.06 ± 0.002%), whereas the lowest concentration was observed under FNPK treatment (0.03 ± 0.005%).

Table 2 presents information on SOCand total nitrogen at the end of the field experiment, along with the impacts of various nitrogen and biochar application rates, treatments, and their interactions. Treatments with and without fertilizer showed an increase in SOC at the surface levels as a result of biochar amendments, with the relative changes corresponding to the application rates (Table 2). Biochar amendments at rates of 2.5 t/acre and 5 t/acre, in conjunction with full-rate fertilizer, increase SOC by 21.6% and 40.6%, respectively, at the surface level compared to the control. Biochar amendments alone, at a rate of 5 t/acre with reduced fertilization, increased SOC by 57% at the surface level. In contrast to the surface level, biochar amendments with or without fertilization at the subsurface decreased SOC by 2.5% to 12% compared to the control (Table 3). A significant biochar 15cm depth interaction ($p<0.001$) indicates that the effect of biochar on SOC differed between surface and subsurface soils (Table 2). However, SOC was found to increase with biochar amendments of 5 t/acre and reduced fertilization rates.

It was discovered that applying biochar with and without fertilizer reduced total nitrogen, by 7% to 30% at the surface level and 19.5% to 37.8% at the subsurface level, in contrast to biochar additions with and without fertilizer at the surface level. Despite a reduction in total nitrogen, biochar had a substantial impact on soil total nitrogen ($p < 0.001$), whereas fertilizer and soil depth had no significant main effects ($p > 0.05$) (Tables 2 and 3).

Table 3. Soil organic carbon (SOC) and total nitrogen (mean±S.D.), and the percent of change over the sorghum field at different depths by biochar and NPK amendment.

Depth	Treatments	SOC (%)		N (%)	
		mean±S.D	% change	mean±S.D	% change
Surface	Control	0.31±0.07	0.0	0.06±0.04	0.0
	FNPK	0.34±0.08	12.5	0.04±0.02	-30.1
	QNPK	0.36±0.07	17.9	0.04±0.02	-23.9
	B2.5	0.42±0.11	36.5	0.05±0.01	-23.2
	B2.5+FNPK	0.37±0.12	21.6	0.05±0.02	-20.7
	B2.5+QNPK	0.38±0.09	23.5	0.05±0.01	-13.8
	B5	0.38±0.12	23.3	0.05±0.02	-20.1
	B5+FNPK	0.43±0.11	40.6	0.05±0.02	-6.9
	B5+QNPK	0.48±0.14	57.4	0.05±0.02	-8.8
Subsurface	Control	0.28±0.06	0	0.06±0.01	0.0
	FNPK	0.26±0.05	-7.17	0.04±0.02	-31.7

	QNPK	0.26±0.07	-7.56	0.05±0.02	-22.0
	B2.5	0.26±0.03	-9.13	0.04±0.02	-37.8
	B2.5+FNPK	0.25±0.07	-12.00	0.04±0.02	-31.7
	B2.5+QNPK	0.26±0.08	-8.21	0.04±0.02	-33.6
	B5	0.28±0.06	-2.72	0.05±0.02	-19.5
	B5+FNPK	0.28±0.04	-2.46	0.05±0.02	-25.6
	B5+QNPK	0.31±0.09	8.52	0.04±0.02	-33.0

Soil carbon and nitrogen concentrations responded differently to biochar application and NPK fertilizer type, with surface soils generally showing greater changes than subsurface soils. Surface carbon increased under combined biochar and fertilizer treatments, with the largest increase observed under 5 t ha^{-1} biochar combined with QNPK fertilizer, reaching up to 57.4% relative to the unfertilized control. Moderate increases in surface carbon (20–40%) were also recorded under 2.5 t ha^{-1} biochar with QNPK and 5 t ha^{-1} biochar with FNPK.

In contrast, subsurface carbon remained relatively stable or showed slight decreases of less than 13%, indicating that the effects of amendments were more pronounced in the topsoil. Nitrogen exhibited a different pattern, generally decreasing under most treatments compared with the control, particularly in subsurface soils where reductions reached 25–37% under 2.5 and 5 t ha^{-1} biochar combined with FNPK or QNPK. Surface nitrogen decreased more moderately, ranging from 6.9% to 30%, while biochar alone tended to reduce subsurface nitrogen more than surface nitrogen. Fertilizer addition without biochar also resulted in slight decreases in nitrogen, with QNPK causing larger reductions than FNPK. Overall, biochar enhanced surface carbon sequestration, while both biochar and fertilizer reduced nitrogen availability in subsurface soils, highlighting the depth- and nutrient-specific effects of soil amendments and the importance of considering these factors in managing soil fertility and mitigating greenhouse gases.

3.2.2. Physical characteristics

Two-way ANOVA and the percentage change under biochar treatments with and without fertilization are shown in Tables 4 and 5, respectively. Electrical conductivity was significantly affected by biochar, with or without fertilization, at both the surface and subsurface levels. For instance, significant two-way interactions were observed for biochar × NPK ($P < 0.001$), biochar × depth ($P < 0.001$), and NPK × depth ($P < 0.001$). Additionally, the three-way interaction between biochar, NPK, and depth was highly significant ($P < 0.001$), indicating that the effect of treatments on EC depended on both the combination of Biochar and NPK and the soil depth.

Table 4. Soil physical characteristics using two-way analysis of ANOVA under treatment on biochar, NPK, as well as the interaction of biochar with NPK.

Factor	DF	Electrical Conductivity (mS/cm)			Soil moisture (m^3/m^3)			Soil temperature (ºC)		
		SS	F	P	SS	F	P	SS	F	P
Biochar	2	0.93	58.7	0.00	0.15	29.5	0.00	1134.2	37.5	0.00
NPK	2	4.73	297.2	0.00	0.00	0.7	0.49	191.1	6.3	0.00
Depth	1	3.79	477.1	0.00	0.68	275.8	0.00	1119.9	74.0	0.00

Biochar: NPK	4	0.51	16.1	0.00	0.22	22.1	0.00	1767.7	29.2	0.00
Biochar: Depth	2	0.26	16.2	0.00	0.05	9.6	0.00	494.6	16.3	0.00
NPK: Depth	2	0.27	16.7	0.00	0.02	3.7	0.02	189.8	6.3	0.00
Biochar:NPK: Depth	4	1.97	62.0	0.00	0.12	11.7	0.00	999.6	16.5	0.00
Residuals	4644	36.9			12.3			74935.1		

Full-rate NPK applications (B2.5+FNPK and B2.5+QNPK), were found to increase electrical conductivity by 60.6% and 34.8%, respectively, compared to the control. In contrast, B5+FNPK, B5+QNPK, and B5 were decreased by 20%, 25%, and 12.6%, respectively, compared to the control. EC values were generally higher in subsurface soils compared with surface soils. Compared to the control, FNPK treatments increased EC by 28–61%, whereas QNPK effects were smaller and sometimes negative, especially at the surface. Biochar alone slightly decreased EC in some depths (−5 to −24%), but combinations of biochar and FNPK led to the largest increases in EC, particularly with B5 + FNPK at the subsurface (up to +49%) (Table 5 and Fig. 4).

Table 5. Mean±S.D. and percentage of change on soil physical characteristics under treatment with biochar, NPK, as well as the interaction of biochar with NPK at the surface and subsurface.

	Treatments	Electrical Conductivity (mS/cm)		Volumetric Water Content (m^3/m^3)		Soil temperature (°C)	
		mean±S.D	%change	mean±S.D	%change	mean±S.D	%change
Surface	Control	0.16±0.07	0.0	0.17±0.00	0.00	23.88±4.75	0.00
	FNPK	0.25±0.18	60.6	0.18±1,71	1.71	24.87±3.44	4.16
	QNPK	0.11±0.06	-25.9	0.19±7.76	7.76	26.15±2.32	9.52
	B2.5	0.12±0.05	-21.1	0.16±6.71	-6.71	23.55±5.99	-1.40
	B2.5+FNPK	0.21±0.09	34.8	0.17±1.33	1.33	24.21±5.01	1.37
	B2.5+QNPK	0.17±0.06	11.2	0.16±8.17	-8.17	22.32±4.84	-6.52
	B5	0.14±0.07	-12.6	0.19±9.23	9.23	24.56±3.91	2.86
	B5+FNPK	0.12±0.09	-20.0	0.18±4.92	4.92	25.45±3.31	6.59
	B5+QNPK	0.12±0.08	-25.1	0.18±3.65	3.65	23.57±5.83	-1.29
Subsurface	Control	0.19±0.06	0.0	0.21±0.00	0.00	26.3±2.2	0.0
	FNPK	0.25±0.15	28.3	0.18±12.8	-12.81	25.0±3.4	-5.0
	QNPK	0.21±0.06	8.3	0.22±5.84	5.84	26.1±1.8	-0.6
	B2.5	0.18±0.08	-5.9	0.20±5.36	-5.36	25.8±2.8	-1.7
	B2.5+FNPK	0.25±0.12	31.7	0.20±6.28	-6.28	25.8±2.2	-2.0
	B2.5+QNPK	0.22±0.05	14.9	0.19±9.97	-9.97	23.8±4.2	-9.3
	B5	0.15±0.08	-24.2	0.19±8.46	-8.46	23.8±4.3	-9.5
	B5+FNPK	0.29±0.07	48.5	0.21±0.82	-0.82	25.0±3.1	-4.7
	B5+QNPK	0.17±0.07	-10.6	0.20±6.65	-6.65	25.5±3.2	-2.9

Two-way ANOVA and the percentage change in soil moisture under biochar treatments with and without fertilization are shown in Tables 4 and 5, respectively. Soil moisture was significantly affected by biochar, as well as biochar with or without fertilization, at both surface and subsurface levels. For instance, soil moisture was significantly influenced by biochar, depth, and biochar: NPK interactions, whereas the main effect of NPK alone was not significant ($p = 0.489$). Subsurface soils consistently had higher SM than surface soils. Biochar-only treatments tended to slightly reduce SM (−5 to −8%), whereas QNPK and FNPK treatments caused minor positive or negative changes depending on the combination. The largest positive effect on soil moisture (+7%) was observed with QNPK at the surface in the absence of Biochar. All treatments at the subsurface scale result in a reduction in soil moisture of 1% to 13% compared to the control (Table 5 and Fig. 5).

Similar to electrical conductivity, biochar, NPK, and the integrated application of biochar with or without NPK were found to have statistically significant effects on soil temperature at both surface and subsurface depths ($p < 0.000$). Compared to the control, B2.5 and B2.5+QNPK at the surface level decreased soil temperature by 1.4% and 6.5%, respectively, while other treatments increased soil temperature by up to 9.5% (QNPK). On the other hand, all treatments at the subsurface resulted in decreases in soil temperature ranging from 0.5% to 9.5% under treatments QNPK and B5, respectively, compared to the control (Tables 4 and 5, and Fig. 6).

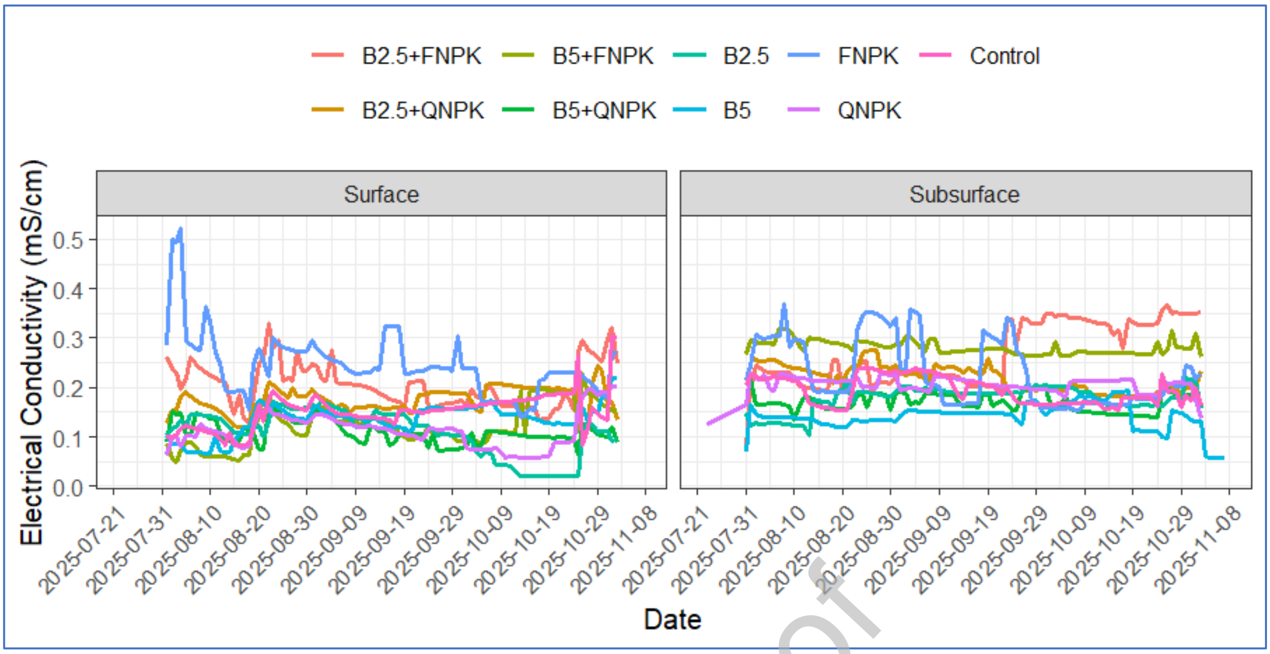


Fig. 4.. Soil electrical conductivity under biochar with and without NPK treatment at the surface and subsurface levels.

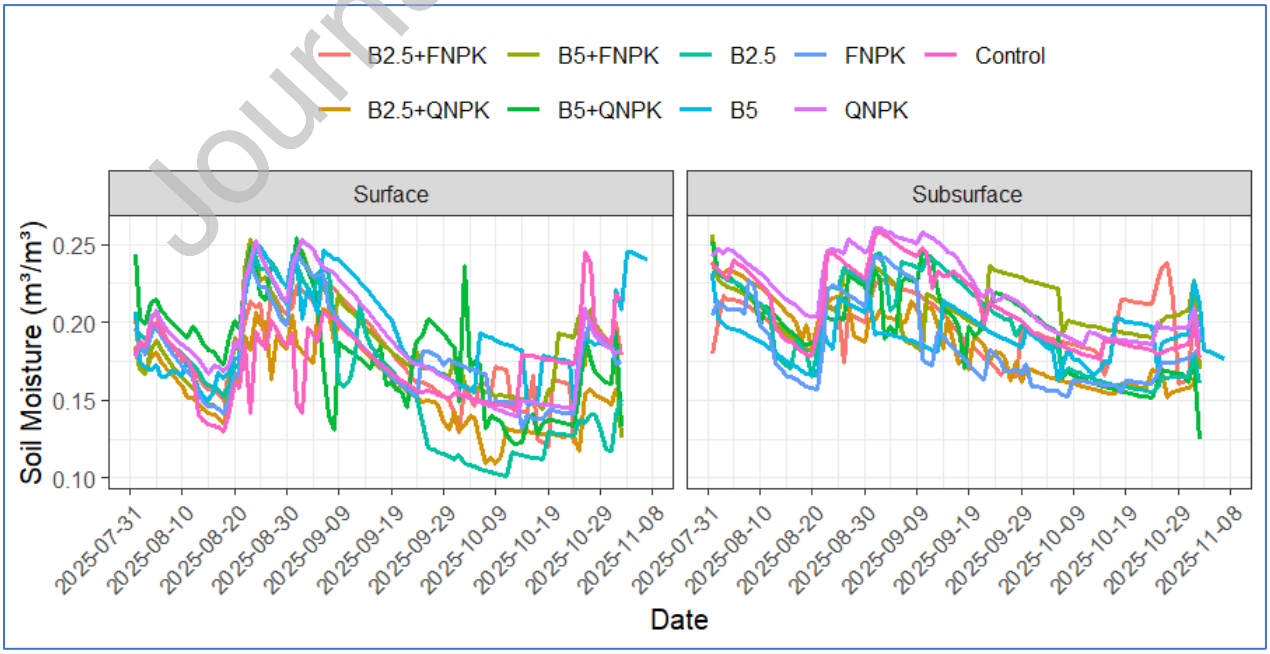


Fig. 5. Soil moisture under biochar with and without NPK treatment at the surface and subsurface levels.

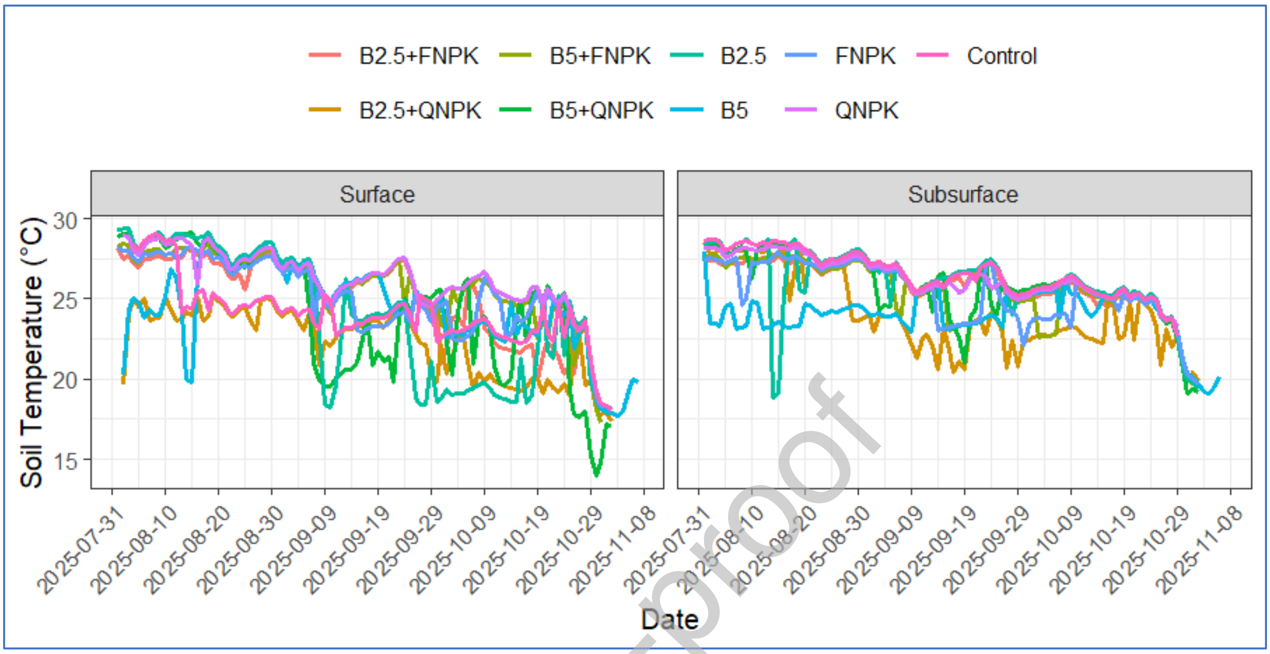


Fig. 6. Soil temperature under biochar with and without NPK treatment at the surface and subsurface levels.

3.3. Greenhouse gas fluxes

3.3.1. CH_4 fluxes

Table 6 presents information on CH_4, CO_2, N_2O, and yield at the end of the field experiment, as well as the impacts of various NPK and biochar application rates, treatments, and their interactions. Treatments with and without fertilizer showed increased CH_4 emissions resulting from biochar amendments, with the relative changes corresponding to the application rates (Table 6). Biochar amendments rates of B2.5+FNPK, B2.5+QNPK, and B5+QNPK decreased CH_4 by 9%, 12.4%, and 5.5%, respectively compared to the control. On the other hand, the highest CH_4 emissions recorded at FNPK application rates without biochar amendments were 30% higher than those without biochar amendments (Table 7).

Table 6. A two-way ANOVA for the effects of biochar and fertilizers on CH_4, CO_2, and N_2O.

Factor	DF	CH_4			CO_2			N_2O			Yield t ha^{-1}			
		SS	F	P	SS	F	P	SS	F	P	DF	SS	F	P
Biochar	2	0.21	9.07	0.000	21.15	14.23	0.00	0.03	8.04	0.001	2	45.9	3.91	0.024
NPK	2	0.12	5.17	0.006	81.03	54.52	0.00	0.01	3.99	0.000	2	9.4	0.8	0.45
Biochar: NPK	4	0.33	7.39	0.000	60.47	20.34	0.00	0.15	21.47	0.000	4	8.8	0.38	0.83
Residuals	525	5.94			390.12			0.93			72	423		

Table 7. CH_4, CO_2, N_2O, and sorghum yield (mean±S.D.) and percent of change over the sorghum field as amended by biochar and NPK fertilization.

Treatments	CH_4		CO_2		N_2O		Yield t ha^{-1}	
	mean±S.D	%change	mean±S.D	%change	mean±S.D	%change	mean±S.D	%change
Control	0.39±0.12	0.0	4.04±1.06	0.0	0.17±0.05	0.0	4.68±2.13	0.0
FNPK	0.51±0.12	30.0	3.53±0.97	-12.5	0.23±0.00	30.0	4.87±1.89	4.2
QNPK	0.41±0.12	5.4	5.46±0.28	30.0	0.21±0.04	28.6	3.73±1.89	-20.3
B2.5	0.41±0.12	5.4	4.64±1.03	15.0	0.21±0.03	29.0	5.83±1.61	24.7
B2.5+FNPK	0.35±0.09	-9.0	5.00±0.98	23.8	0.19±0.05	15.8	5.21±0.65	11.5
B2.5+QNPK	0.34±0.08	-12.4	5.42±0.42	30.0	0.23±0.02	30.0	4.21±1.84	-8.1
B5	0.39±0.11	1.0	4.91±0.77	21.5	0.22±0.04	30.0	6.35±3.26	35.7
B5+FNPK	0.40±0.10	2.5	3.95±0.94	-2.1	0.19±0.05	13.4	6.02±1.44	28.8
B5+QNPK	0.36±0.10	-5.5	4.77±0.95	18.1	0.19±0.05	15.1	6.39±0.58	36.6

A two-way factorial ANOVA revealed that the effects of biochar and NPK fertilization on GHG emissions differed among gases (Table 7). Biochar application had a significant effect on CH_4 emissions ($P < 0.001$), as did NPK fertilization ($P = 0.006$). A strong Biochar × NPK interaction was observed ($P < 0.001$), indicating that the effect of biochar on CH_4 emissions varied depending on the type of NPK fertilizer applied (Table 6). For instance, the mean ± S.D. emissions of CH4 vary from 0.51±0.12 under treatment FNPK to 0.34±0.08 under treatment B2.5+QNPK. CH_4 emissions increased under fertilizer-only treatments, with FNPK causing the largest increase (up to 30%) relative to the control. Biochar application, particularly at B2.5, mitigated fertilizer-induced CH_4 emissions, resulting in reductions of up to 12% under fertilized conditions. At the higher biochar rate (B5), CH_4 emissions were generally comparable to those of the control, suggesting a stabilizing effect (Fig. 7).

3.3.2. CO_2 fluxes

Biochar amendments, both alone and in combination with fertilization, were found to increase CO_2 emissions by 15% to 30% compared to the control. On the other hand, the full-rate FNPK application and B5+FNPK decreased CO_2 emissions by 12.5% and 2.1%, respectively, with respect to the control (Table 7). The mean concentration of CO_2 varies by treatment, as shown in Table 5. For instance, treatment of QNPK and B2.5+F NPK as emitters for CO_2 5.46± 0.28 and 5.42± 0.42, respectively. Furthermore, B5 and FNPK were GHG emitters, with values of 4.91 ± 0.77 and 0.353 ± 0.97, respectively, indicating new CO2 emissions compared to the control. Biochar applications increased CO_2 emissions across treatments, although under FNPK, the application of (B5) biochar resulted in CO_2 emissions similar to those of the control, indicating that higher biochar rates may partially offset the effects of fertilizer (Fig. 8).

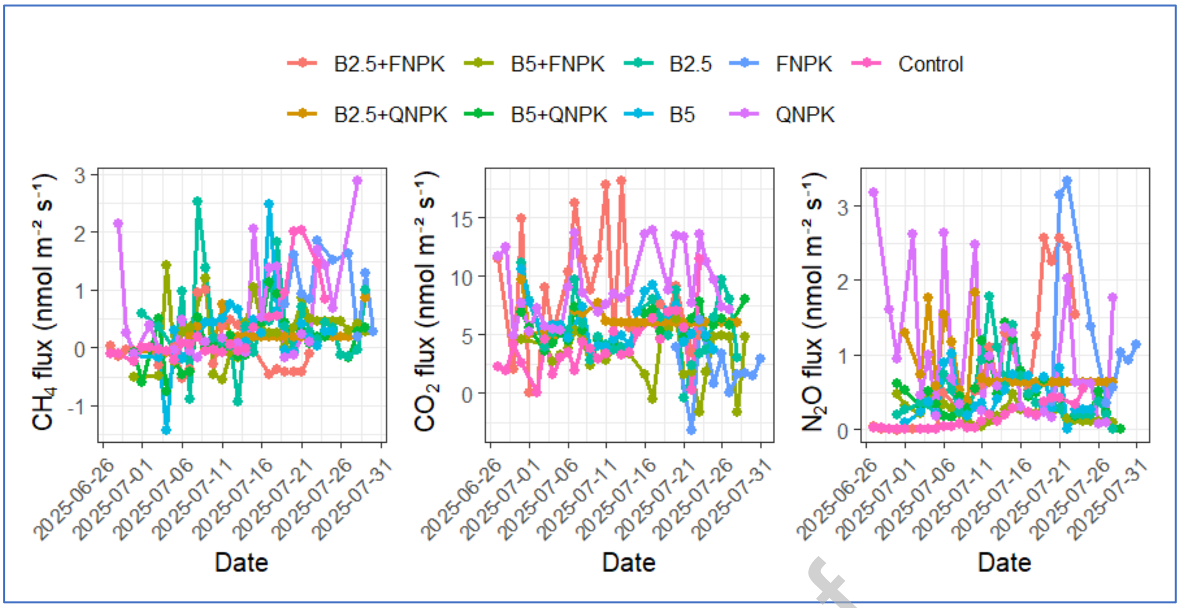


Fig. 7. CH_4, CO_2, and N_2O flux under biochar with and without NPK treatment at the sorghum field.

3.3.3. N_2O fluxes

Similar to CH_4 and CO_2, N_2O fluxes showed a pronounced Biochar × NPK interaction ($P < 0.001$), indicating that the direction and magnitude of biochar effects on N_2O emissions depended strongly on fertilizer type. For instance, N_2O emissions were increased from 13% to 30% under treatment B5+FNPK and FNPK, B5, and B2.5+QNPK, respectively, compared to the control. For instance, treatment of FNPK and B2.5+F NPK and B5+FNPK, B5+QNPK as emitters for N_2O 0.23± 0.02 and 0.19± 0.05, respectively. N_2O emissions were highly sensitive to fertilization, with both FNPK and QNPK increasing emissions by up to 30% relative to the control. Biochar applied alone also increased N_2O emissions; however, when combined with fertilizer, biochar reduced N_2O emissions compared with fertilizer-only treatments, particularly under FNPK, where reductions of approximately 13–16% were observed. Across CH_4, CO_2, and N_2O, significant Biochar × NPK interactions indicate that greenhouse gas emissions were jointly regulated by biochar rate and fertilizer management rather than by single factors alone (Tables 6, 7, and Fig.7).

In general, biochar application reduced fertilizer-induced increases in CH_4 and N_2O emissions; however, it tended to increase CO_2 emissions, particularly with QNPK fertilization. These findings underscore the importance of integrated soil amendment strategies for mitigating agricultural greenhouse gas emissions, demonstrating that biochar's effects on greenhouse gas emissions are gas-specific and heavily dependent on fertilizer management.

3.4. Global warming potentials and net ecosystem carbon balance

Daily greenhouse gas emissions, expressed as kg CO_2-equivalents per hectare per day (kg CO_2-eq ha^{-1} day^{-1}), varied considerably across treatments and gases (Table 8). Across all treatments, N_2O was the dominant contributor to total global warming potential (GWP), accounting for more than 85% of daily GWP in most cases. Biochar treatments alone (B2.5 and B5) resulted in moderate N_2O emissions (5504 ± 6367 and 4478 ± 3369 kg CO_2-eq ha^{-1} day^{-1}, respectively) with minor contributions from CO_2 and CH_4. The addition of NPK fertilizers substantially increased N_2O emissions. For example, B2.5+FNPK emitted 9135 ± 11874 kg CO_2-eq ha^{-1} day^{-1} and FNPK alone produced 18231 ± 23294 kg CO_2-eq ha^{-1} day^{-1}.

Table 8. Daily CH_4, CO_2, and N_2O emissions (mean ± S.D.), total global warming potential (GWP), and percent change relative to control under biochar and NPK fertilization treatments in the sorghum field.

Treatments	CH_4 (kg CO_2-eq ha^{-1})	CO_2 (kg CO_2-eq ha^{-1})	N_2O (kg CO_2-eq ha^{-1})		% change

	mean±S.D.	mean±S.D.	mean±S.D.	Total GWP kg CO_2-eq ha^{-1}	
Control	165± 398	163± 127	1856± 2537	2183	0
FNPK	452± 381	84± 152	18231± 23294	18768	760
QNPK	258± 416	352± 127	10421± 13342	11031	405
B2.5	157± 367	208± 126	5504± 6367	5868	169
B2.5+FNPK	-8.5± 193	318± 215	9135± 11874	9445	333
B2.5+QNPK	76± 95	239± 60	8417± 4873	8731	300
B5	64.± 456	224± 94	4478± 3369	4766	118
B5+FNPK	106± 217	123± 155	2316± 1352	2545	17
B5+QNPK	57± 436	377 ± 208	13221± 13106	6827	213

CH_4 and CO_2 contributions were generally low across treatments (<5–10% of total GWP) and showed relatively small variation among treatments. The variability among replicates, indicated by high standard deviations, suggests spatial heterogeneity or temporal fluctuations in N_2O emissions. These results indicate that fertilizer management has a strong influence on N_2O emissions, whereas biochar alone has a minor effect on reducing daily GWP (Table 8).

The NECB varied substantially across treatments, ranging from 4.42 to 19.60 Mg C ha^{-1}, indicating clear effects of management practices on ecosystem-scale carbon dynamics. The control (4.53 Mg C ha^{-1}) and mineral fertilizer treatments (FNPK: 4.43 Mg C ha^{-1}; QNPK: 4.71 Mg C ha^{-1}) showed relatively low and comparable NECB values, suggesting limited influence of inorganic fertilization alone on net carbon gain (Fig.8).

In contrast, biochar application markedly increased NECB across all treatments. The highest carbon sequestration was observed under B5-based treatments (up to 19.60 Mg C ha^{-1}), followed by B2.5 treatments, indicating a strong positive response to increasing biochar rates. Combined biochar and fertilizer applications also maintained high NECB values, demonstrating that biochar was the primary driver of enhanced ecosystem carbon retention, while mineral fertilizers had a secondary or minimal modifying effect.

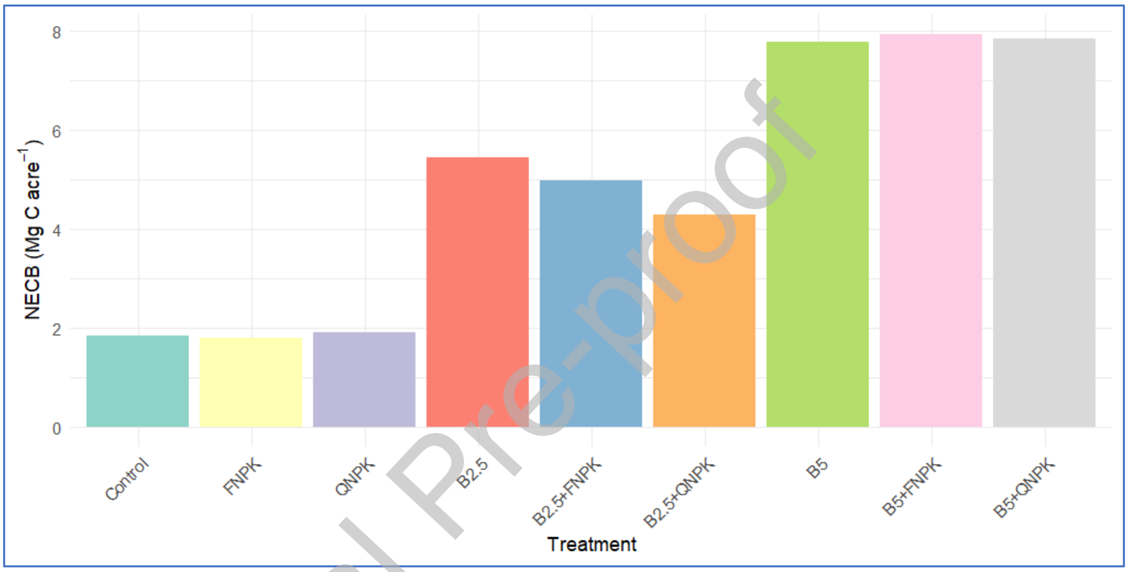


Fig. 8. Net ecosystem carbon balance by treatment.

3.5. Sorghum yield

Biochar applicatioon significantly increased sorghum yield ($P < 0.05$), with plots amended with B2.5 and B5 showing higher biomass than the control. Conversely, NPK fertilization by itself did not significantly affect biomass ($P = 0.45$), and the interaction between NPK and biochar was likewise non-significant ($P = 0.83$), suggesting that the beneficial impact of biochar on yield was constant regardless of NPK application. These findings suggest that biochar amendment is an effective method for increasing sorghum yield, whereas NPK fertilization may not have a significant effect in this particular experiment. Compared with fertilizer application, biochar slightly increased sorghum yield (Tables 6 and 7).

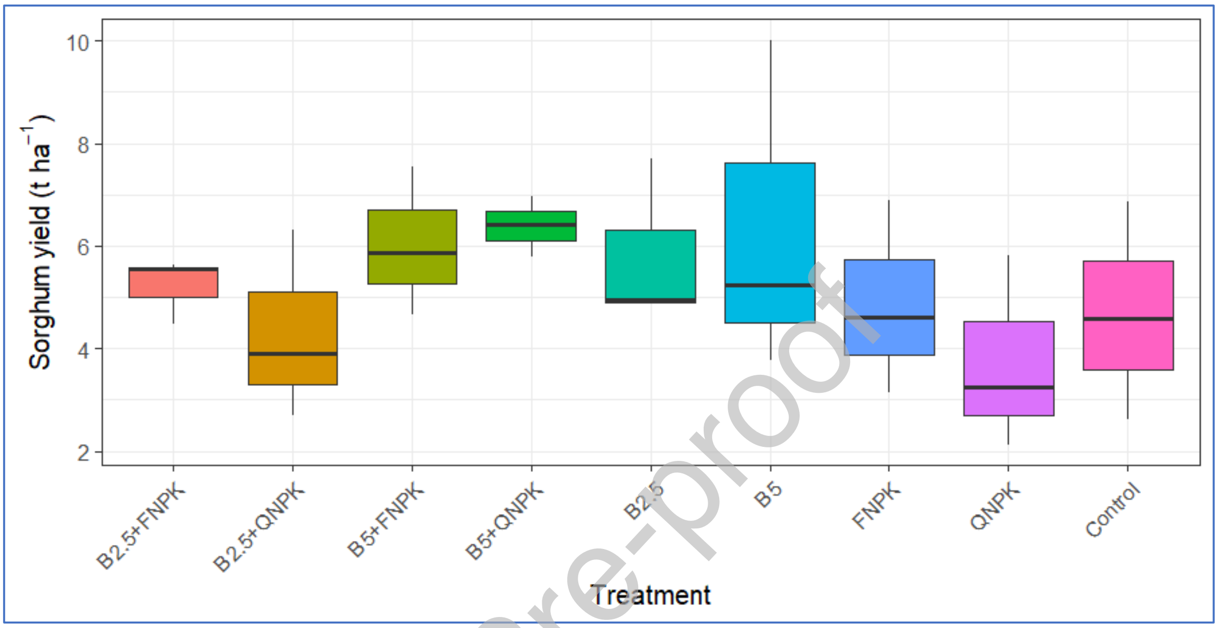


Fig. 9. Sorghum yield under biochar with and without NPK treatment in the sorghum field.

For instance, B2.5 and B5 biochar application increased sorghum biomass by 24.7% and 35.7%, with a mean and standard deviation of 5.083 ± 1.61 t ha^{-1} and 6.35 ± 3.26 t ha^{-1}, respectively, compared to the control, while QNPK resulted in a decrease of sorghum yield by 20.3% with a mean of 3.71 ± 1.89 t ha^{-1}. On the other hand, B2.5 biochar application with reduced fertilizer rates resulted in an 8.1% decrease in sorghum yield compared to the control. Similarly, B5+QNPK produced 6.4 ± 0.58 t ha^{-1}, corresponding to a 36.6% increase, while B5+FNPK resulted in 6.01 ± 1.44 t ha^{-1}, a 28.8% increase relative to the control(Table 7 and

Fig. 9). Overall, biochar application had a greater impact on sorghum yield than fertilizer alone, and higher biochar rates typically led to larger increases in yield. However, the type of fertilizer used in conjunction with the biochar determined the magnitude of the response, suggesting that the rate of biochar and nutrient management interact.

4. Discussion

4.1. Impacts of biochar and inorganic amendment on soil chemical and physical properties

The positive effects of biochar and fertilizer application on the surface soil's chemical properties of carbon and nitrogen, as found in this investigation, are in line with results reported in the USA [46] and other parts of the world [47–50]. For instance, [46] as documented in Efaw USA, reported that total nitrogen and SOC improved by 3% and 21%, respectively, under biochar and nitrogen treatment combinations. The findings of this study confirmed that SOCconcentration at the surface was significantly higher ($p < 0.001$) than at the subsurface, due to the rapid decomposition of SOC at the surface.

Furthermore, a meta-analysis by [51] reported that biochar application increased soil cation exchange capacity, pH, and organic carbon, with a greater effect in coarse- and fine-textured soils. Additionally, [48] reported that 6 years of 1.5 t ha^{-1} biochar application in paddy soil improved the pore structure and increased rice productivity in China. [34] indicated that soil pH, electrical conductivity, and dissolved organic carbon increased with the optimal fertilizer application rates of 1.5 g biochar + 80% chemical fertilizer. Furthermore, Yang et al. (2023) reported that SOCand nitrogen levels were significantly improved under higher biochar and fertilizer application rates; however, this improvement negatively affected the C/N ratio in

China. A review paper conducted by [49, 50, 52] also reported that biochar application can reduce GHGs and improve SOC, serving as a tool for wastewater treatment too.

However, contrasting findings were reported by [53] on biochar economics, which are often marginally viable and tightly tied to the assumed duration of agronomic benefits. According to [54] there is no one-size-fits-all solution for biochar in soils. The potential of biochar addition to increase soil nutrients, carbon, and plant productivity has also been observed to alter microbial populations and negatively impact plant growth [55]. Thus, to obtain the benefits of biochar application, it is essential to understand the physical and chemical properties that are affected by the choice of feedstock and pyrolysis conditions. Thus , [56] recommended that the O: C ratio could provide a more robust indicator of biochar stability than production parameters. In general, the application of biochar can increase SOC, soil nutrients, soil structure, bulk density, pH, water retention, and others, but also the other side of biochar has altered microbial populations and negatively impacts plant growth, and its application depends on understanding the physical and chemical properties of biochar as well as soil initial properties.

4.2. Effects of biochar application on greenhouse gases and carbon sequestration

A comprehensive review by [57] documented that the carbon sequestration potential of biochar in soil systems ranges from 0.7 to 1.8 GtCO_2-C(eq)/year. A biochar with a high C/N ratio, with a high porosity, and alkaline soil is favorable for effective carbon sequestration. Besides, [58] reported that biochar application successfully reduced emission of CH_4 from poultry manure composting piles. The importance of biochar application for reducing GHG emissions is not guaranteed by biochar itself. Hence, [59] documented from a meta-analysis reported that applying biochar under low N fertilization input could obviously reduce soil N_2O emissions,

CO_2 emissions, and CH_4 emissions by 18.7 %, 17.9 %, and 16.9 %, respectively, but under high N fertilization could increase both trace gases emissions.

In contrast, a study conducted in the Texas Highlands, USA, reported that the combined application of biochar and fertilizers produced differential effects on CH_4, CO_2, and N_2O emissions, indicating that these gases respond uniquely to the interactions between biochar and fertilizers[57]. These findings collectively suggest that the carbon sequestration potential and reduction of trace greenhouse gas emissions are not uniform across ecosystems, but instead vary significantly with biochar characteristics, soil conditions, and environmental context.

In line with this study, various findings have also reported the importance of biochar and fertilizer application in improving SOC and reducing GHG emissions [60–62]. For instance, a review by (Zhong et al., 2025) reported that biochar application regulates N cycles and N_2O emissions through denitrification, with effects dependent on biochar application rates, which require knowing the threshold amounts. [60] also reported that biochar N_2O emissions were reduced under specific moisture and temperature conditions in both laboratory and field cropping systems. Similarly [61] indicated that biochar application at an appropriate rate reduces N_2O emissions. Besides, [63] indicated that biochar application with or without fertilizer significantly reduced GHG emissions compared to the control treatment. Moreover, [64] also reported that biochar application significantly increased rice yields and decreased N_2O emissions, but increased total CH_4 emissions. [65] reported that economic loss of a higher amount of biochar application, higher biochar application rates of 24 and 28 t ha^{-1} resulted in negative net present worth and internal rate of return values and benefit-cost ratio values below 1, indicating economic infeasibility at these levels.

A review of research compiled and synthesized by Li et al. (2024) indicates that biochar may not always reduce soil GHG emissions. It reduced CO_2, N_2O, and CH_4 under low nitrogen fertilizer input, but significantly increased emissions when nitrogen application was high (>300 kg N ha^{-1}). Hence, in support of this study, biochar's mitigation potential is context-dependent, and high fertilizer rates [59] and repeated applications may exacerbate certain emissions [66], potentially reversing the benefits. This study revealed that biochar application with minimal fertilizer contributed to a reduction in GHG emissions [67], improved surface SOC, increased sorghum yields, and enhanced soil pH and electrical conductivity, in line with findings from other regions globally [67–70] and in the USA [71]. Research conducted in the Southern Great Plains, Texas, by Shembo et al. (2025) reported that a 5% application rate of commercial biochar provides an effective balance between plant performance and soil quality improvement in Sandy loam soil.

For instance, Yang et al. (2023) reported that a combination of biochar application and a nitrogen dose of 255kg ha^{-1} was the most effective strategy for irrigated wheat fields in China, enhancing SOC content while reducing carbon emissions. A review by Wang et al. (2023) also documented that soil applications of biochar, whether as a controlled-release fertilizer or an immobilization agent, improve soil health while simultaneously suppressing CH_4 and N_2O emissions. In contrast to these findings, [72] reported that biochar addition increased CH_4 uptake by 96% but not significantly for CO_2 and N_2O, which is in line with our findings. SOC

Our study found that biochar application with fertilizer increased sorghum yield at the Prairie View Research farm, which aligns with both global and regional studies. For instance, a review and meta-analysis by (Bai et al., 2022) documented that biochar and inorganic fertilizer increased crop yield by 25.3% ± 3.2% and 21.9% ± 4.4%, respectively. The co-application of biochar with both inorganic and organic fertilizers increased crop yield by 179.6% ± 18.7. Similarly, [73] also indicated that biochar application in agro-ecosystems significantly improved water productivity and crop yield by 14.8% and 11.2%, respectively, based on a global synthesis of field experiments. [74] reported that the Biochar application had a negligible effect on corn yields in the US Midwest. Moreover, field experiments by [75] have indicated that biochar application improves soil biochemical properties, as well as the root and shoot biomass of wheat. Moreover, Uzoma et al. (2011) documented that the application of biochar at mixing rates of 15 and 20 t ha^{-1} significantly increased maize grain yield by 150% and 98%, respectively, compared with the control. In contrast to these findings, [76] reported that neither biochar nor manure amendments significantly affected maize yield under limited irrigation in Northern Colorado, USA.

This research investigated the effects of biochar application with fertilizer on reduced CO2 and CH4 emissions and increased sorghum yield when B2.5 and B5 are applied together with reduced and full NPK fertilizer. Although biochar application in agroecosystems has shown positive environmental effects, continuous biochar application and excessive fertilizer use may pose irreversible environmental risks [32]. For instance, previous studies based on literature reviews have synthesized that biochar's potential could have adverse effects on animals, microorganisms, humans, and plants [28, 32, 77]. The results indicate the short-term responses of SOC, NECB, and greenhouse gas fluxes (CO_2, N_2O, CH_4) to the application of biochar and fertilizer during a single growing season. Although the observed trends indicate potential advantages in reducing emissions and enhancing carbon storage, these effects are preliminary and may evolve over time as biochar matures and soil biogeochemical processes develop.

4.3. Limitations and contributions of the research

The results of this study were obtained during a single growing season (May–August) in sorghum cultivation. Consequently, they represent short-term responses and cannot be directly applied to long-term carbon sequestration or sustained greenhouse gas mitigation. Furthermore, the results' broader applicability may be restricted by the use of commercially produced biochar and the absence of an assessment of environmental hazards, including nutrient leaching and soil microbial responses. Long-term and multi-crop studies are required to document system-level impacts and cumulative effects.Despite these limitations, this study provides valuable field-based evidence on the effects of biochar and fertilizer application on GHG emissions and soil carbon sequestration. The findings enhance our understanding of biochar as a nature-based solution for mitigating climate change, improving SOC, and enhancing crop yields. Moreover, this research serves as a baseline study for sorghum production in the Southern Great Plains of the United States, where sorghum is widely used for biofuel production and animal feed. The results may be transferable to regions with similar environmental conditions globally.

5. Conclusion

This study was designed to assess the effects of biochar and NPK fertilizer application on GHG emissions and the potential for soil carbon sequestration in a field experiment conducted at Prairie View A&M University's research farm. The analysis focuses on the application of biochar in combination with inorganic fertilizers to enhance SOC sequestration, reduce GHG emissions, and improve sorghum yield. The results reveal that biochar application, together with inorganic fertilizer, improved surface SOC (0-15 cm) compared with subsurface SOC (15 to 45 cm). On the other hand, the nitrogen concentration between the surface and the subsurface remained unchanged after treatments compared to the control.

This study shows that biochar application significantly increased NECB, with the highest sequestration under B5 treatments (up to 19.6 Mg C ha^{-1}), followed by B2.5, indicating a positive response to increasing biochar rates. These results suggest that biochar can enhance short-term carbon sequestration and contribute to climate change mitigation. The application of B2.5, combined with quarterly fertilizer application rates, reduced CH_4 emissions. Additionally, B5+QNPK also led to a decrease in CO_2 flux compared to the control. The study also confirmed that the effects of biochar application alone and with fertilizer on SOC improvements, GHG emissions reductions, and sorghum yield improvements are not uniform across plots. Hence, the effects of biochar application in combination with fertilizer depend on the baseline soil physicochemical properties and management practices. Likewise, the impacts of the studied management interventions on SOC, GHGs, and yields were not uniform, increasing to negligible levels. Additionally, certain management interventions, such as the use of biochar with reduced fertilizer, have demonstrated positive effects on SOC improvements and GHG emission reductions. Hence, this finding confirms that one size does not fit all, underscoring the importance of understanding soil properties before implementing or applying biochar to maintain environmental sustainability and mitigate climate change through nature-based solutions. Overall, the findings provide field-based evidence of the short-term impacts of biochar and fertilizer management on carbon dynamics and greenhouse gas emissions. However, long-term studies are required to confirm the persistence and scalability of these effects for climate mitigation and sustainable agricultural management

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Author contributions

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Ram L. Ray: Writing – review & editing, Supervision, Resources, Project administration, Methodology, Data curation, Conceptualization. Srijana Chaudhary: Writing – review & editing, Visualization, Data curation, Conceptualization. Olukayode Kuloyo: Writing – review & editing, Visualization, Resources, Data curation, Conceptualization. Christian Davies: Writing – review & editing, Validation, Data curation, Conceptualization.

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Availability of data and materials

Data will be made available on request.

Statements and Declarations

Ethics approval and consent to participate

This study did not involve any human participants, animals, or sensitive data requiring ethical approval. Therefore, no ethics approval or consent to participate was necessary.

Consent for publication

All authors have read and agreed to the published version of the manuscript.

Competing interests

The authors declare that they have no competing financial or non-financial interests to disclose.

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Declaration of interests

☒The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: