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Improving soil health through manure and biochar amendments under climate-smart agriculture

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Abstract

Enhancing crop productivity and soil sustainability under climate-smart agriculture involves strategically using soil amendments to improve soil health and resilience. A field experiment at Prairie View A&M University, Texas, studied the effects of soil amendments (chicken and dairy manures and biochar) on some soil health indicators. The experiment used two biochar rates (2268 and 4536 kg ha^{-1}) and two types of manure (chicken and dairy) at three rates (0, 224, and 448 kg total N ha^{-1} for sweet corn [*Zea mays* (L.)] and 0, 180, and 360 kg N ha^{-1} for sorghum [*Sorghum bicolor* (L.) Moench]) in a factorial design with three replications. Soil macronutrients and micronutrients were measured as chemical soil health indicators, and bulk density, porosity, and saturated hydraulic conductivity were measured as physical soil health indicators. Dairy manure significantly increased soil calcium (Ca) and potassium (K) concentrations. Higher manure application rates improved soil nutrient concentration, with the highest phosphorus (P), Ca, magnesium (Mg), and manganese (Mn) concentration levels at the double recommended rate. Biochar did not affect nutrient concentration but improved soil physical properties by increasing porosity, hydraulic conductivity, and reducing bulk density, especially at higher rates in sweet corn. Correlation analysis showed bulk density was negatively correlated with key nutrients like potassium (K), Ca, and Mg, while porosity and hydraulic conductivity positively influenced nutrient availability. The principal component analysis highlighted that sweet corn and sorghum respond positively to selected soil amendments, while their specific impacts vary based on crop type. The findings emphasize balancing manure and biochar application rates to optimize soil fertility and minimize environmental risks, supporting sustainable soil management strategies.

Plain Language Summary

As weather patterns become more unpredictable, farming is becoming more difficult, making it essential to find ways to increase food production while maintaining healthy soil. In this study, we tested how chicken and dairy manures and biochar affect soil health and crop growth in corn and sorghum fields in Texas. We found that dairy manure increased key nutrients like calcium and potassium in the soil. Applying more manure led to even higher levels of phosphorus, calcium, magnesium, and manganese. Biochar did not increase nutrient levels but helped improve soil structure by making it more porous and allowing water to move more easily, especially in corn fields. We also found that corn and sorghum responded differently to these treatments. These findings show that using the right mix of manure and biochar can improve soil health and crop yield. This approach supports long-term, sustainable farming in a changing climate.

1 | INTRODUCTION

The global population is expected to surpass 9 billion in the coming decades (D. Gu et al., 2021; United Nations, Department of Economic and Social Affairs, Population Division, 2019). This significant growth will increase global food demand by 70% by 2050, necessitating enhanced agricultural productivity to ensure global food security (Baroudy et al., 2020). Agricultural soils, crucial for producing food and fiber, are limited and largely nonrenewable. Therefore, enhancing soil functions and ecosystem services is crucial to achieve agricultural sustainability and productivity. Enhancing soil physical, chemical, or biological properties can impact sustainability directly and indirectly (Bünemann et al., 2018).

In general, soil quality/health refers “to the ability of a specific type of soil to function within the limits of natural or managed ecosystems to support plant and animal productivity, improve water and air quality, and contribute to human health and habitation” (Karlen et al., 1997). Proper soil management can also contribute to improving water and air quality, human health, and habitation (Awal, Fares, et al., 2021; Fares et al., 2008; Veettil et al., 2024). Therefore, understanding soil health is essential for addressing land degradation, improving soil management, increasing crop production, and ensuring food security (Kalambukattu et al., 2018; Okon et al., 2019). Deprived soil quality can impair vital soil functions and reduce crop yields, directly impacting food security. Therefore, assessing soil health is crucial to identify areas with varying soil health levels and determine their suitability for agriculture, including specific crop cultivation (Thapa et al., 2024).

Soil health is determined by its physical, chemical, and biological characteristics. Physical indicators include bulk density, porosity, aggregate stability, texture, and compaction, while chemical indicators encompass pH, salinity, organic matter content, cation exchange capacity, and macro- and micronutrient levels (AbdelRahman et al., 2019). Physical indicators influence germination, root growth, and water infiltration, while chemical indicators affect microbial activity and nutrient availability (Martinez-Salgado et al., 2010). Physical properties also control nutrient storage, leaching, erosion, water movement, and soil organic carbon (SOC) stabilization (Carrizo et al., 2015; Jat et al., 2018). Understanding these aspects is essential for effective soil management practices that support sustainable agriculture (Moore et al., 2016; Veettil et al., 2024).

Climate-smart-based soil amendments, such as organic manure and biochar, are crucial for enhancing agricultural resilience and sustainability amid climate change (Thapa et al., 2024). These amendments focus on improving soil health, increasing carbon (C) sequestration, and reducing greenhouse gas emissions (Adil et al., 2022; Brenzinger et al., 2021; Joona et al., 2024; Kottegoda et al., 2023; Veettil et al., 2024; Verhagen et al., 2014). Chicken and dairy manures, known for their high concentrations of macro- and micronutrients, have been used as natural fertilizers for centuries (Celik et al., 2010; Chambers et al., 2001; Pain, 1999). The rise in temperature leads to a faster breakdown of soil organic matter due to increasing microbial activity (Li et al., 2020). Ghimire et al. (2019) reported an increase in SOC mineralization by 72%–177% at 30°C compared to 20°C. Hence, in areas like Texas, where the temperature is high, biochar provides a long-term soil management solution because it stays in the soil for many years after application due to its recalcitrant nature (Lehmann et al., 2008; Whitman, 2011). Studies have shown that biochar application improved soil physical, chemical, and biological properties, thereby improving water and nutrient holding capacity, cation exchange capacity, infiltration capacity, aggregate stability, and porosity, and reducing soil erosion, runoff, and bulk density (Asai et al., 2009; Harvey et al., 2012; S. D. Joseph et al., 2010; Kimetu & Lehmann, 2010; Liang et al., 2006).

Numerous studies have shown the benefits of chicken and dairy manures and biochar on the soil’s chemical and physical properties. For instance, Dungan et al. (2022) reported that dairy manure enhanced microbial biomass and nutrient availability in semiarid soils. Dairy manure also increased both macro- and micronutrient levels (Rayne & Aula, 2020). Organic manure improved soil aggregate stability and reduced nitrate leaching (Tanha et al., 2024). Biochar reduces bulk density and enhances water retention (Gu 2024; Pandian et al., 2024). However, most studies focus on individual amendments, with limited research on their combined effects under varying soil types and climatic conditions (Sant'Anna et al., 2024; Tarkalson et al., 2024). Therefore, more integrative studies are needed across diverse agroecosystems. Moreover, the potential of combining different soil amendments to optimize soil health and agricultural productivity has not been fully explored. Bridging these gaps will be crucial for developing more effective soil management strategies in the face of growing global challenges.

This study examined the impacts of organic amendments on soil health under a sweet corn [*Zea mays* (L.)]–sorghum [*Sorghum bicolor* (L.) Moench] rotation system, with sweet corn planted in the first year followed by sorghum in the second year. Corn is a nutrient-intensive crop that demands a consistent supply of fertilizers, particularly nitrogen (N), throughout its growth cycle to achieve optimal development (Jat et al., 2013), while sorghum is often cultivated in areas with reduced soil fertility and limited water availability (Rani et al., 2019). Sorghum is an appealing alternative to corn due to its superior resilience to drought and poor soil fertility (Borba et al., 2012) and lower N requirement (Olanite et al., 2010). Soil health changes with the crop type and management practices. The overarching goal of this study was to compare and evaluate the combined effects of three organic amendments (biochar and chicken and dairy manures) at different rates (two for biochar and three for the manures) in the soil health indicators under southeast Texas conditions. The specific objective of this study was to explore the combined effect of these amendments on the chemical and physical soil health indicators in a sweet corn–sorghum rotation system with sweet corn planted in the first year, followed by sorghum in the second year.

2 | MATERIALS AND METHODS

2.1 | Site description and experimental design

The field experiment was conducted at the College of Agriculture, Food, and Natural Resources research farm, Prairie View A&M University, Texas (Latitude: 30˚5′33.9″ N, Longitude: 95˚58′43.14″ W) during the 2022 and 2023 growing seasons. The site received an average annual rainfall of 1183 mm, based on monthly data from 1980 to 2020 (PRISM data: http://www.prism.oregonstate.edu/) and mean temperatures ranging from 14.9˚C to 25.6˚C. The soil type was Wockley fine sandy loam, classified as fine-loamy, siliceous, semiactive, hyperthermic Plinthaquic Paleudalfs (Awal, Hassan, et al., 2021).

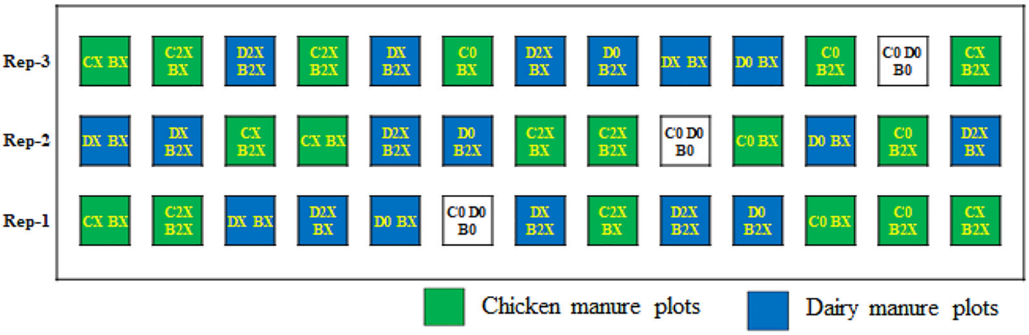
Core Ideas

- Dairy manure significantly increased soil calcium and potassium concentrations compared to chicken manure.
- Higher manure rate significantly enhanced phosphorus, magnesium, and manganese levels compared to lower and control.
- Biochar increased soil porosity, saturated hydraulic conductivity, and reduced bulk density.

The experiment used a 2 × 2 × 3 factorial design with two biochar rates (2268 and 4536 kg ha^{-1} as Level I and Level II), two types of manure (chicken and dairy), and three manure application rates (0, 224, and 448 kg N ha^{-1} as control, recommended, and double recommended rates, respectively, for sweet corn, and 0, 180, and 360 kg N ha^{-1} as control, recommended, and double recommended rates, respectively, for sorghum in a factorial randomized design with three replications (Figure 1). The application rates were based on the recommended N rate per hectare. Each plot measured 3 m × 2.5 m, with 2 m paths between plots and 3.5 m gaps between blocks. Manure and biochar were mixed into the top 15 cm of soil. Sweet corn and sorghum seeds were planted 30 cm apart within rows and 60 cm between rows. The crops were irrigated using the drip irrigation system. IrrigWise, a web-based irrigation scheduling tool, was utilized to determine irrigation requirements by incorporating near-real-time site-specific data on rainfall, reference evapotranspiration, soil water content, and plant growth stages (Awal, Fares, et al., 2021). Manual weedings were performed throughout the growing season. The nutrient concentration of organic amendments used in the experiment is summarized in Table 1 (Thapa et al., 2024).

2.2 | Analyzing the chemical soil health indicators

Five soil samples were collected from each plot at 0- to 15-cm depth after the harvest of each crop. To ensure these samples accurately reflected the experimental conditions and minimized edge effects, soil samples were collected exclusively from the middle two rows of sweet corn and sorghum growth season. A systematic zigzag pattern was employed within the middle portion of these two central rows to collect each of the five subsamples. These subsamples were thoroughly mixed in a clean bucket to form a single composite



Rep-3	CX BX	C2X BX	D2X B2X	C2X B2X	DX B2X	C0 BX	D2X BX	D0 B2X	DX BX	D0 BX	C0 B2X	C0 D0 B0	CX B2X
Rep-2	DX BX	DX B2X	CX B2X	CX BX	D2X B2X	D0 B2X	C2X BX	C2X B2X	C0 D0 B0	C0 BX	D0 BX	C0 B2X	D2X BX
Rep-1	CX BX	C2X B2X	DX BX	D2X BX	D0 BX	C0 D0 B0	DX B2X	C2X BX	D2X B2X	D0 B2X	C0 BX	C0 B2X	CX B2X

🟩 Chicken manure plots 🟦 Dairy manure plots

FIGURE 1 The plots at Prairie View A&M University, Waller County, Texas. Plot design includes representations of the treatment types and the treatment rates in three replications. Green plots represent the organic amendment with chicken manure, and blue plots represent dairy (B = biochar; C = chicken manure; D = dairy manure; C0, B0, and D0 = without manure or biochar. For sweet corn, X = 224 kg total N ha^{-1} and 2X = 448 kg total N ha^{-1}. For Sorghum, X = 180 kg total N ha^{-1} and 2X = 360 kg total N ha^{-1}. BX = 2268 kg ha^{-1} and B2X = 4536 kg ha^{-1} for sweet corn and sorghum.)

TABLE 1 The concentration of plant-available nutrients, pH, and electrical conductivity in manure and biochar.

Nutrient concentration	Chicken manure	Dairy manure	Biochar
Carbon (%)	27.32	14.62	58.71
Nitrogen (%)	3.05	0.5	1.46
Phosphorus (g kg^{-1})	9.60	5.75	1.08
Potassium (g kg^{-1})	27.16	12.60	5.45
Calcium (g kg^{-1})	16.24	72.28	29.95
Magnesium (g kg^{-1})	5.64	4.79	6.68
Boron (mg kg^{-1})	50.1	18.98	10.96
Cupper (mg kg^{-1})	817.99	25.23	8.9
Iron (mg kg^{-1})	2494	6025	1203
Zinc (mg kg^{-1})	465	129	22
Manganese (mg kg^{-1})	500	335	90
Sulfur (%)	1.37	0.64	3.15
pH	7.02	8.40	5.67
Electrical conductivity (mS cm$^{-1)}$	17.73	8.73	18.96

sample for that specific plot. The soil samples were dried at 60˚C for 48 h, ground, and sieved through a 0.15 mm mesh. Soil carbon (C), N, and sulfur (S) were analyzed using a Carbon Hydrogen Nitrogen Sulfur (CHNS) Elemental Analyzer (Elementar Americas, Inc.), while the concentrations of phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), copper (Cu), iron (Fe), zinc (Zn), and Mn were determined using an inductively coupled plasma optical emission spectroscopy (ICP-OES instrument, Agilent Company).

2.3 | Analyzing the physical soil health indicators

Undisturbed soil core samples (2.5 cm radius, 5 cm height) were randomly collected from the top 10 cm of soil using a sledgehammer soil sampler from all plots to analyze the effects of soil amendments on soil physical properties. Fine nylon mesh was used to secure soil in the cores, which were saturated in water for 24 h and then oven-dried at 105˚C for 72 h. Soil bulk density (ρ) and porosity (β) were calculated using standard equations developed by Grossman and Reinsch (2002) and Flint and Flint (2002):

$$\rho = W_{\mathrm{d}}/V \qquad (1)$$

$$\beta = \left(W_{\mathrm{s}} - W_{\mathrm{d}}\right)/V \qquad (2)$$

where W_{s} is the saturated soil sample weight (g), W_{d} is the oven-dried sample weight (g), and V is the volume of the core samples (cm^3).

Soil infiltration was measured using a tension infiltrometer (Soil Measurement System) to determine saturated hydraulic conductivity (K_{sat}) under field conditions. The instrument consists of a 20 cm diameter perforated disc, a water reservoir (5.1 cm diameter, 81 cm length), and a bubbling tower (2.54 cm diameter, 30 cm length). The disc was soaked to remove air bubbles and placed on a sand layer for optimal soil contact. Infiltration tests were conducted at tensions of −10, −5, and −2.5 cm, with steady-state water flux recorded to calculate K_{sat} using the equation developed by Wooding (1968).

$$K_{sat} = \frac{Q}{\pi r^2 \exp(\alpha\psi)\left[1 + \frac{4}{\pi r \alpha}\right]} \quad (3)$$

where Q (LT^{-1}) is steady state water flux, r (m) is circular source radius, α (T^{-1}) is inverse macro porosity capillary length, ψ (L) is the tension of which α is used to calculate K_{sat} (LT^{-1}). We conducted infiltration tests at two tensions, Lower tension (ψ_1) and larger tension (ψ_2), the Hussen and Warrick (1993) equation is used to calculate α.

$$\alpha = \frac{\ln\left[Q(\psi_2)/Q(\psi_1)\right]}{\left|\psi_2 - \psi_1\right|} \quad (4)$$

2.4 | Statistical analysis

The collected data were statistically analyzed using Statistix 10 software (Analytical Software). A one-way analysis of variance was performed to assess the impact of different amendment treatments on soil health indicators. Tukey's test at $p < 0.05$ was applied to identify significant differences among treatments. A correlation matrix, expressed as a heatmap, was prepared using the corrplot package in R software (Holatko, Bielska et al., 2022) to examine the relationships between soil chemical and physical health indicators. In addition, principal component analysis (PCA) was performed with the PCA package in R (Holatko, Bielska et al., 2022; Team, 2020). The original data were standardized before analysis. In this study, only the factors with eigenvalue > 1 were considered for further analysis. PCA was applied to evaluate the relationship between soil health indicators and applied amendment rates.

3 | RESULTS AND DISCUSSION

3.1 | Soil chemical health indicators

Details on how manure type, rate, and biochar rate influence soil fertility are provided below (Figures 2 and 3). The type of manure had no significant impact on the soil nutrient concentration for most nutrients in sweet corn, except for K and Ca. However, manure type significantly influenced the P, K, Ca, Mg, and aluminum (Al) levels for sorghum. Soil treated with dairy manure showed 32% higher K and Ca content than chicken manure in sweet corn and 45.4% and 67.5% higher K and Ca levels, respectively, in sorghum. Conversely, P and Al content in soils treated with dairy manure were 33.4% and 26.3% lower, respectively, than in soils treated with chicken manure for sorghum. Research has shown that poultry manure improves soil C, N, P, K, Ca, and Mg (Adekiya et al., 2016, 2020). Poultry manure is a valuable agricultural fertilizer, especially for N and P (Hoover et al., 2019; Toor, 2009). Bernal et al. (2009) reported that dairy manure serves as a source of N, P, and K. Similarly, other studies indicate that applying organic amendments increases soil nutrient concentration, such as C and N (Holatko, Hammerschmiedt et al., 2022; Mustafa et al., 2021). However, manure type did not affect C and N content in this experiment. Chicken and dairy manures were calculated and applied based on N content to ensure equivalent nitrogen inputs across treatments. Also, the experimental soil was sandy loam, which might have led to easy loss of nutrients from this soil due to low cation exchange capacity, high leaching rates, and low organic matter content. Similarly, a decrease in soil C and N content was observed by P. O. Joseph et al. (2025) after 12 weeks of poultry manure inoculation in coarse-textured soil. This suggests that C and N from the manure might be mineralized, and these nutrients were not sustained in the later growth stage (Soremi et al., 2017).

The impact of manure application rate was significant for most nutrients except for C, N, and Fe for sweet corn and sorghum. Increasing the manure application rate from the control to the double recommended rate led to a marked increase in nutrient levels. For instance, the double recommended rate led to the highest P, Ca, Mg, and Mn concentrations, significantly surpassing the levels in the control group. Other studies also enhanced P, K, Ca, and Mg with the increased rate of manure (Adekiya et al., 2019; Mpanga et al., 2021). This pattern suggests that higher manure rates are more effective at enriching the soil with organic matter and nutrients, potentially leading to better soil health and crop productivity. Awal, Hassan, et al. (2021) also observed that chicken manure enhanced total N (TN), P, K, and several other micronutrients more effectively than dairy manure, especially at higher application rates. Additional research has indicated that higher manure application rates increase Cu, Mn, and Zn concentrations (Oguntade et al., 2018, 2022). Conversely, Al concentrations were significantly higher in control treatments than the double recommended rate, possibly reflecting changes in soil acidity or soil chemical properties. Thus, it is essential to consider the potential contamination risks associated with excessive manure use, particularly concerning environmental safety.

Biochar is widely recognized for enhancing soil C and sequestration of other nutrients (Mechler et al., 2018; Toor,

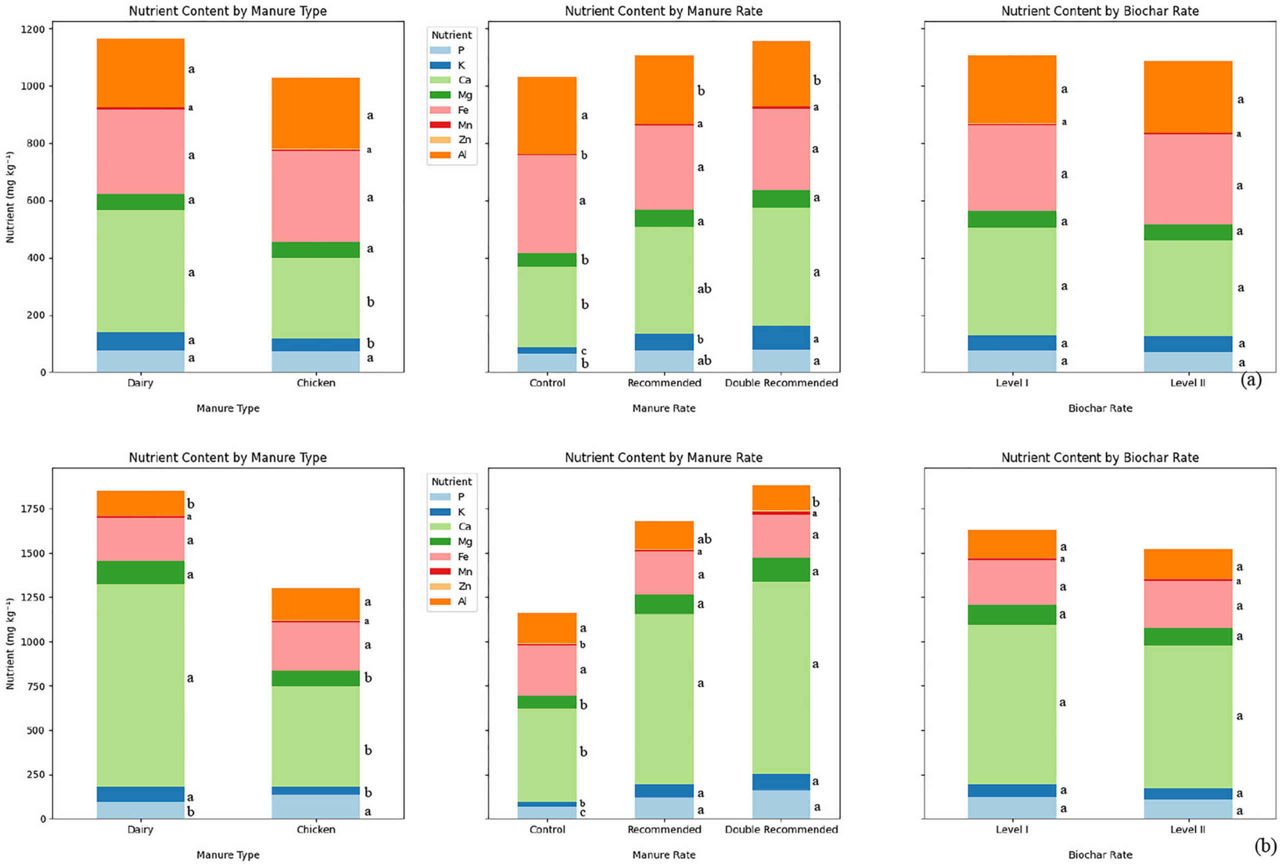


FIGURE 2 Effect of manure types and rates, and biochar rates on soil macronutrients and micronutrients at 0- to 15-cm depth after (a) sweet corn and (b) sorghum harvests. The same letter indicates no significant difference among means by least significant difference (LSD) comparison of means at $\alpha = 0.05$. Letters are within manure type, manure rate, and biochar rate.

2009). Biochar alters soil chemical properties, with its effects largely dependent on the application rate (Zhang et al., 2016). Studies by Oladele et al. (2019) and Choudhary et al. (2021) reported that higher biochar application rates increase nutrient levels. Wang et al. (2014) observed elevated levels of C, N, P, K, Ca, and Mg following biochar application. Additionally, biochar has been shown to increase Mn, Cu, Fe, and Zn concentrations (Badamasi et al., 2023; Choudhury & Mandal 2021). However, in our experiment, the biochar application rate did not significantly affect soil nutrient concentration.

Sweet corn was planted in the first year, and sorghum in the second year on the same plots. Differences were observed in plant-available nutrient concentrations after harvesting sweet corn and sorghum. So, the comparison reflects that most plant-available nutrients were higher after sorghum harvest compared to sweet corn season, despite a higher manure application rate for sweet corn. The architecture of the plant root system plays a crucial role in plant nutrient availability by facilitating the efficient absorption of water and nutrients from the soil (Ali et al., 2015). The lower nutrient concentrations in the soil after sweet corn harvest are likely due to its fibrous, shallow, and dense root system (Hochholdinger, 2009; Mi et al., 2016), which primarily accesses readily available nutrients from the topsoil. In contrast, sorghum's deep and extensive root system (X. Chen et al., 2020; V. Singh et al., 2010) allows it to extract nutrients from deeper soil layers.

3.2 | Soil physical health indicator

Figure 4 presents detailed data on how manure type and rate, as well as biochar rate, influence soil physical properties. The data obtained from Veettil et al. (2024) for sweet corn were used to compare soil physical properties with those of sorghum. In this experiment, the type of manure applied had no significant effect on K_{sat}, bulk density, or soil porosity for sweet corn. While other researchers observed a decrease in bulk density with the use of poultry manure (Agbede et al., 2008; Brye et al., 2004; Fares et al., 2008; Mandal et al., 2013). Chicken manure application also increased K_{sat} and porosity (Agbede et al., 2020; Cayci et al., 2017). However, manure type significantly influenced K_{sat} in the case of sorghum (Figure 4). For sorghum, K_{sat} in soils treated with dairy manure was 31.2% lower than in soils treated

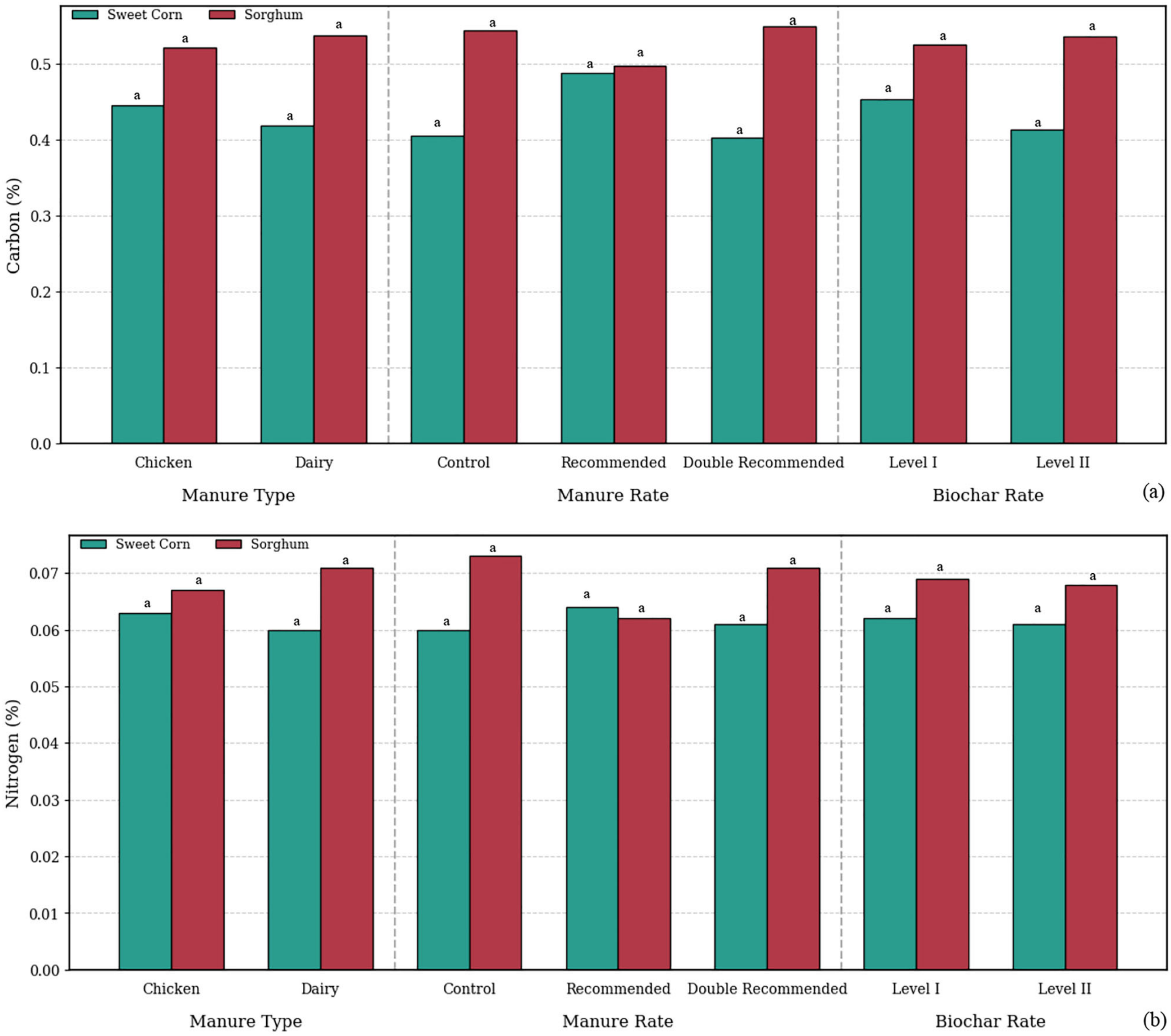


FIGURE 3 Effect of manure types and rates, and biochar rates on (a) carbon and (b) nitrogen concentration at 0- to 15-cm depth after sweet corn and sorghum harvests. The same letter indicates no significant difference among means by least significant difference (LSD) comparison of means at $\alpha = 0.05$. Letters are within manure type, manure rate, biochar rate, and crop.

with chicken manure. Other researchers also found that dairy manure increased porosity, K_{sat}, and decreased bulk density (Dadashi et al., 2019; El-Nagar and Mohamed, 2019; Fares et al., 2008; Iqbal et al., 2012).

In contrast, the manure application rate significantly affected these physical indicators for sweet corn. Higher manure application rates generally led to increased K_{sat} and porosity and decreased bulk density, similar to Fares et al. (2004) and Fares et al. (2008). A similar trend was observed for sorghum in these parameters; however, no significant differences were detected across the different manure rates. The double recommended rate resulted in K_{sat} and porosity being 25% and 29.27% greater, respectively, compared to control treatments for sweet corn.

The improvement in physical soil health indicators from manure application can be attributed to increased soil organic matter. El-Samnoudi et al. (2019) found that chicken manure significantly impacted bulk density and K_{sat}, with higher applications increasing soil porosity and creating more soil pores. Similar findings were reported by Semida et al. (2013). Ojeniyi et al. (2013) observed that applying poultry manure at 5 t ha^{-1} reduced soil bulk density by 13.9% compared to the control. In another study, Abdullahi et al. (2015) found that a chicken manure application rate of 12 t ha^{-1} reduced bulk density and increased porosity. Organic matter of manure generally enhances soil porosity and K_{sat} while reducing bulk density. Also, in this experiment, crop types affected the soil physical health indicator, probably due to differences in root architecture of sweet corn and sorghum.

The biochar application rate significantly influenced the soil physical properties in sweet corn. Higher biochar rates increased K_{sat} and porosity while reducing bulk

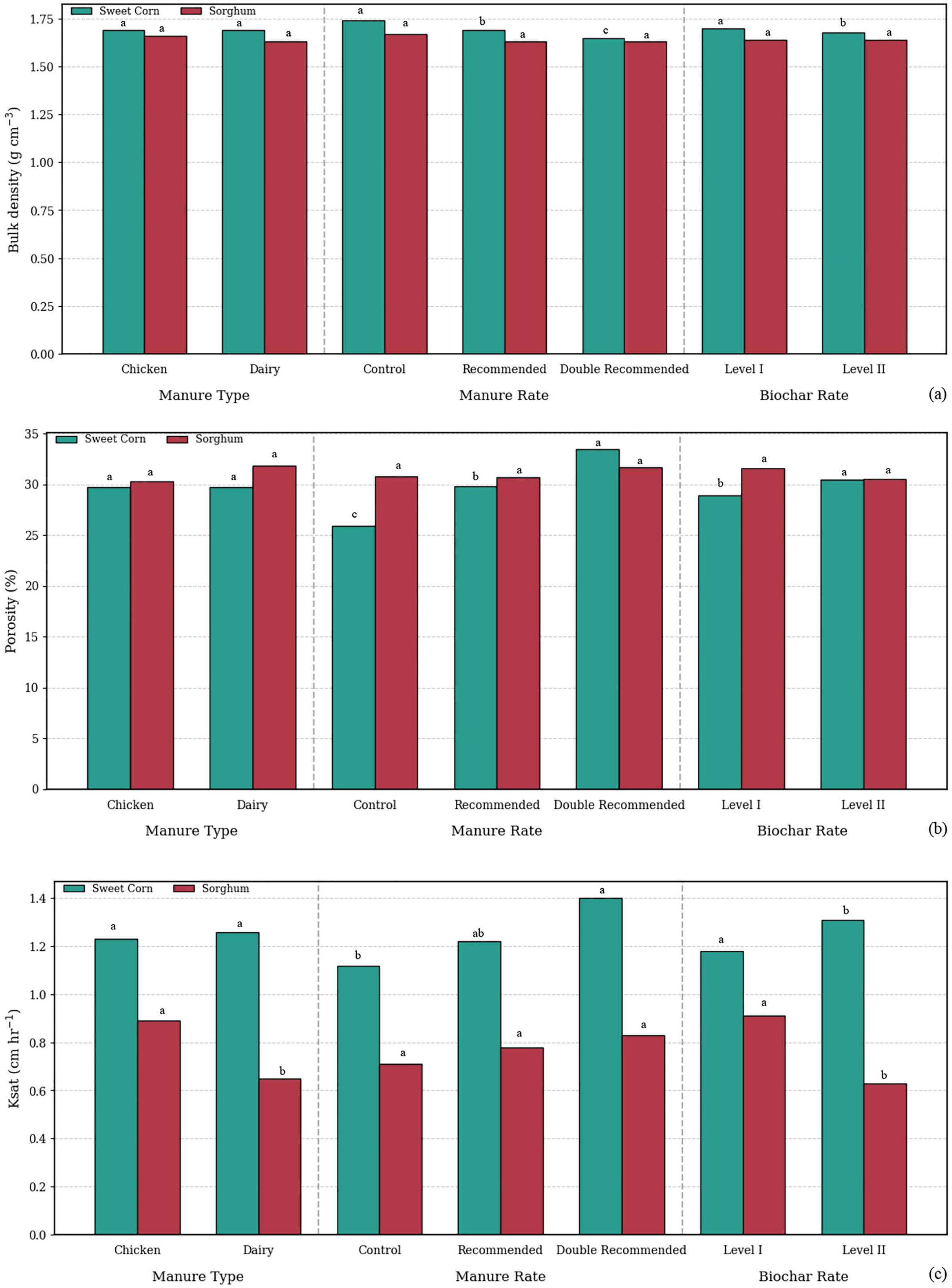


FIGURE 4 Effect of manure types and rates, and biochar rates on soil physical properties (a) bulk density, (b) porosity, and (c) saturated hydraulic conductivity (K_{sat}) at 0- to 10-cm depth after sweet corn and sorghum harvests. The same letter indicates no significant difference among means by least significant difference (LSD) comparison of means at $\alpha = 0.05$. Letters are within manure type, manure rate, biochar rate, and crop.

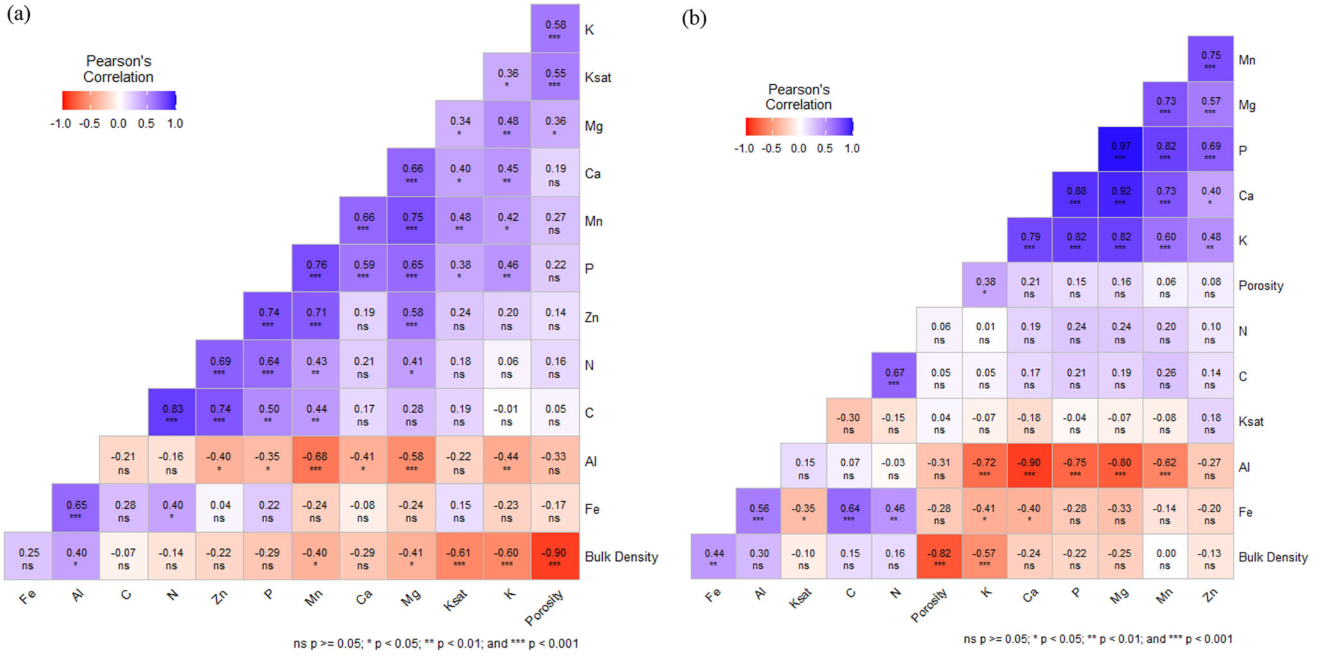


FIGURE 5 The correlation heatmap shows the Pearson correlation between all the physical and chemical health indicators for (a) sweet corn and (b) sorghum. K_{sat}, saturated hydraulic conductivity.

density. Similar to our study, other studies found a higher K_{sat} biochar application in response to the improvement in the porosity and structure in biochar-amended soil (Herath et al., 2013; Major et al., 2010). Like our findings, Adekiya et al. (2020) observed reduced bulk density and increased porosity with higher biochar rates. The porous structure enhances soil porosity and decreases the bulk density of biochar (Adekiya et al., 2019; Ndor et al., 2015; Nyambo et al., 2018). Adekiya et al. (2020) also found increased K_{sat} with higher biochar levels, a trend that aligns with Prober et al. (2014). This effect occurs because the high porosity of biochar creates additional soil pores upon application (Prober et al., 2014).

3.3 | Correlation between chemical and physical soil health indicators

The correlation matrix describes the interactions between soil physical properties, bulk density, porosity, K_{sat}, and soil chemical properties (Figure 5). Bulk density, a measure of soil compaction, affects nutrient availability and movement within the soil. In this study, bulk density was positively correlated with Fe in sorghum, indicating that higher bulk density is associated with increased concentrations of these elements. Conversely, it showed significant negative correlations with K, Mg, and Mn for sweet corn and with K only for sorghum. Consistent with our findings, P. D. Singh et al. (2020) reported that increased bulk density significantly reduced the availability of N, P, K, Zn, and Fe. Also, Mar et al. (2021) observed that K content was negatively correlated with bulk density. The strong inverse relationship between bulk density and porosity indicates that denser soils are less porous, limiting nutrient movement and retention. No correlation was observed between bulk density and K_{sat} for sorghum, while it was negatively correlated with corn in this study. Udom and Ehilegbu (2018) also reported a negative correlation between bulk density and K_{sat}, suggesting that compacted soils may have lower water permeability, which could hinder nutrient transport and availability and could lead to nutrient deficiencies in plants.

Porosity showed positive correlations with Mg and K, suggesting that soils with higher porosity retain and provide better availability of these nutrients. More porous soils allow for increased air and water movement, enhancing the accumulation and accessibility of essential nutrients. Saturated hydraulic conductivity (K_{sat}) is widely recognized as an indicator of soil physical quality (Andrews et al., 2001) and K_{sat} also exhibited moderate positive correlations with P, Ca, Mg, and Mn for corn, indicating that higher K_{sat} may create favorable conditions for nutrient uptake, as water movement is essential for transporting dissolved nutrients to plant roots. Researchers have observed that the soil K content was positively correlated with soil moisture content (Mar et al., 2021; B. Singh & Singh, 2004). SOC was moderately correlated with K_{sat}, and TN, P, K, Ca, and Mg were negatively correlated with K_{sat} (Egbuchua, 2014).

Soil Organic Carbon (SOC) impacts soil properties and overall soil quality significantly. Vasu et al. (2016) state that SOC influences soil properties across various soil and crop management strategies. Several correlations among soil nutrients were observed in this study. For instance, Ca showed

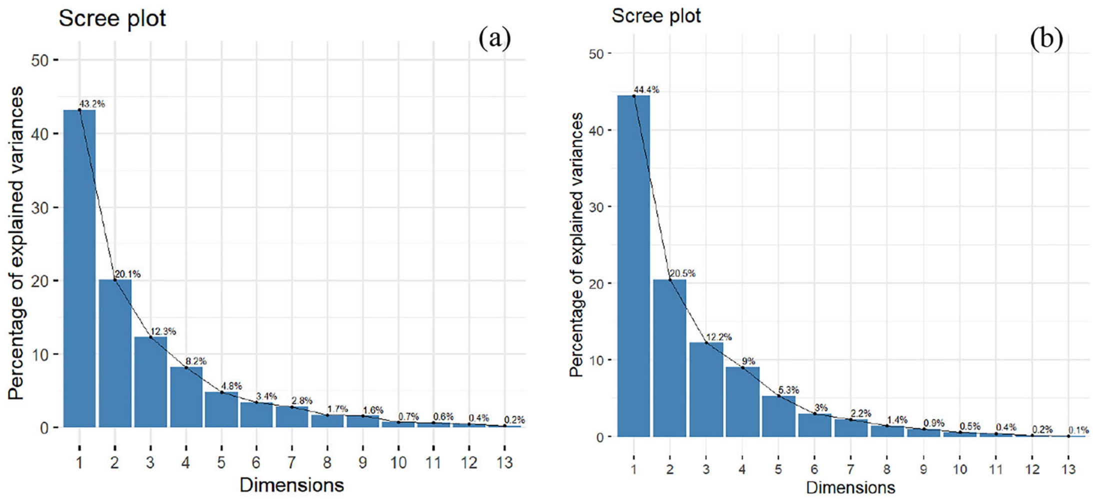


FIGURE 6 Scree plots for the different components considered for principal component analysis with variability for (a) sweet corn and (b) sorghum.

strong positive correlations with P, Mg, and K. Manganese also showed positive correlations with Ca and N. Phosphorus was positively correlated with Zn and Mn. Ghode et al. (2020) found that SOC had positive relationships with N, K, Ca, Mg, S, Fe, Zn, and Cu, as well as a significant positive correlation with B. However, it exhibited a negative relationship with available P and Mn. Our results also showed a strong positive correlation between C and N, attributed to N mineralization from SOC (Vanilarasu & Balakrishnamurthy, 2014). Cao et al. (2012) and Somasundaram et al. (2013) observed similar strong positive correlations between C and N. Several researchers have reported correlations between C and macronutrients (N, P, and K) as well as micronutrients (Hamarashid et al., 2010; Kumar et al., 2009; Plante et al., 2006; Pandey et al., 2019; Rajeswar et al., 2009). Nath (2014) has observed a negative correlation between bulk density and soil carbon and macronutrients. Chaudhari et al. (2013) observed an increase in soil primary and secondary macronutrients with a decrease in bulk density. Also, the available micronutrients (Fe, Mn, Zn, and Cu) were increased with the reduction in bulk density (Chaudhari et al., 2013). A positive correlation between C, Zn, and Mn was observed, while Mar et al. (2021) observed a negative correlation between soil P and K.

3.4 | Principal component analysis

The scree plot illustrates the percentage of variance explained by each principal component in the analysis (Figure 6). For sweet corn, Dim 1 accounts for the most significant variance at approximately 43.2%, followed by Dim 2 at 20.1% and Dim 3 at 12.3%. Dim 1 explains 44.4% of the variance for sorghum, followed by Dim 2 at 20.5% and Dim 3 at 12.2%. A noticeable "elbow" appears after Dim 3, indicating a sharp decline in explained variance for subsequent dimensions. Dim 4 through 10 each contribute less than 10%, with individual contributions ranging from 8.2% to 0.5%, while Dim 9 through 13 contribute minimally, each explaining less than 1% of the variance. This pattern suggests that the first four dimensions capture the most significant variance, above 80% (Table 2), in the data, and retaining them would likely be sufficient for a robust analysis.

The factor contribution graph (Figure 7) illustrates the contributions of various soil properties to the principal components (Dim 1 to Dim 13) for sweet corn and sorghum. For sweet corn, nutrients such as C, N, P, Ca, Mg, and Zn are consistently influential across multiple dimensions, highlighting their critical roles in sweet corn growth. In contrast, sorghum shows higher contributions from C, N, Mn, Fe, and Zn across several dimensions. In sweet corn, Mn has a high contribution, with P and K showing moderate contributions, whereas in sorghum, P, Ca, and Mg contribute most strongly, followed by K, Mn, and Al for Dim 1. This color-coded analysis suggests that sorghum is more influenced by the soil physical properties, bulk density, porosity, and K_{sat}, than sweet corn. These findings underscore the importance of crop-specific management strategies tailored to each crop's unique interactions between nutrients and soil properties.

The PCA biplot analysis (Figure 8) reveals significant differences in how sweet corn and sorghum respond to manure amendments, particularly regarding nutrient enrichment and soil physical properties. For sweet corn, the first two principal components (Dim1 and Dim2) explain 63.3% of the variance (43.2% by Dim1 and 20.1% by Dim2). For sorghum, Dim1 and Dim2 together explain a slightly higher total of 64.9% (44.4% by Dim1 and 20.5% by Dim2), indicating that the PCA model for sorghum captures slightly more of the overall variance in selected soil chemical and physical properties

TABLE 2 Eigenvalue, variance, and cumulative variance of principal components 1 to 4 (PC1 to PC4) for sweet corn and sorghum.

Crop	PCs	PC1	PC2	PC3	PC4
Sweet corn	Eigenvalue	5.62	2.61	1.6	1.07
	Variance (%)	43.21	20.06	12.28	8.2
	Cumulative variance (%)	43.21	63.27	75.55	83.75
Sorghum	Eigenvalue	5.78	2.66	1.59	1.18
	Variance (%)	44.43	20.46	12.21	9.01
	Cumulative variance (%)	44.43	64.9	77.11	86.12

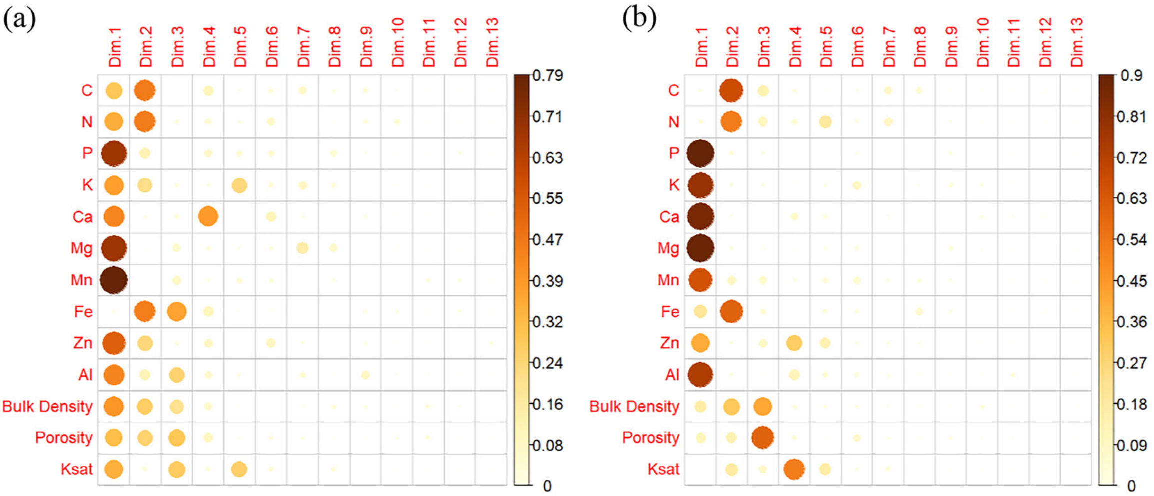


FIGURE 7 Principal component analysis for the contribution of all soil health indicators according to 13 principal components (Dims) for (a) sweet corn and (b) sorghum

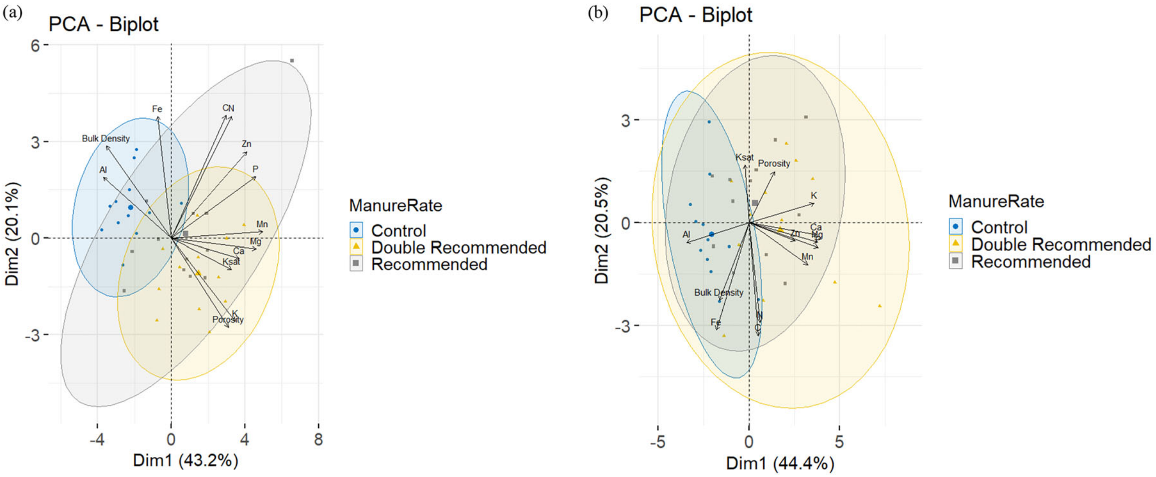


FIGURE 8 Principal component analysis (PCA) biplot of soil health indicators and manure application rates for (a) sweet corn and (b) sorghum.

within the first two dimensions. The treatments (control, recommended, and double recommended manure rates) show some separation, particularly along Dim 1 in sweet corn and sorghum biplots. The control group (blue) tends to cluster to the left, suggesting distinct soil characteristics possibly influenced by lower nutrient levels than manure-treated plots. For both crops, bulk density and Al are positively correlated with Dim1, indicating that these properties were more pronounced in the control plots. Key nutrients such as K and Ca exhibit positive correlations along Dim1 for both crops, suggesting that manure amendments, especially at higher rates, enhance the availability of these essential nutrients in the soil. However, specific soil nutrient responses differed between sweet corn and sorghum. Carbon and Fe showed positive correlations with Dim 2 in the sweet corn biplot, suggesting that these properties exhibit considerable variability based on manure treatments in sweet corn fields. In contrast, sorghum, porosity, and K_{sat} contributed more significantly along Dim 2, indicating that soil physical properties, such as water movement and soil pore structure, are more sensitive to manure treatments in sorghum fields.

In soil quality assessment, PCA is recognized as a highly effective tool for reducing the number of variables by identifying the most significant ones at the field scale (Fathizad et al., 2020). Takoutsing et al. (2016) identified soil nutrient concentrations as primary factors contributing to most of the variability in soil health in maize systems. Similarly, Liu et al. (2014) found that soil properties such as electrical conductivity, pH, SOC, and soil texture are effective descriptors of soil quality. Principal components selected through PCA, such as nutrient concentration, are crucial in evaluating soil quality (Maghami Moghim et al., 2024). These properties have been extensively used in soil quality assessments. For instance, Y.-D. Chen et al. (2013), Fathizad et al. (2020), and Choudhury and Mandal (2021) used similar soil quality indicators in their studies. Kardoni (2023) emphasized the importance of Ca and N as primary indicators of soil health using PCA, particularly concerning various cropping systems and fertilization practices. While sweet corn and sorghum respond positively to soil amendments, their specific impacts vary based on crop type. Sweet corn shows a more pronounced response regarding nutrient availability, whereas sorghum demonstrates a stronger association with soil physical properties. This difference can be attributed to the inherent crop characteristics; sweet corn has a relatively shallow root system and rapid early growth, making it more responsive to readily available nutrients. In contrast, sorghum develops a more profound and extensive root system, allowing it to interact more effectively with soil structure and moisture dynamics. This comparison highlights how organic amendments affect soil properties differently based on crop type, offering insights that can inform management decisions tailored to the response of each crop to soil amendments.

4 | CONCLUSION

The study highlights the intricate relationship between manure types, application rates, and biochar levels on soil health, demonstrating their substantial impact on the soil chemical and physical properties. Dairy manure significantly increased soil K and Ca concentration, while higher manure application rates enhanced nutrient levels and improved physical properties such as soil hydraulic conductivity and porosity. However, caution is necessary to mitigate potential contamination risks associated with excessive manure use. Biochar, although not significantly affecting nutrient concentration, contributed to improved soil physical health by increasing porosity and reducing bulk density. Despite the higher manure application rate for sweet corn, soil nutrient concentrations were greater after growing sorghum. This finding underscores the critical role of plant type in nutrient uptake and the efficient absorption of water and nutrients from the soil. Selecting the appropriate plant type is essential for promoting sustainable soil health. Correlation analysis and PCA further illuminated the interactions between these amendments, highlighting nutrient availability, soil compaction, and porosity as key determinants of soil health. The findings emphasize the importance of balancing organic amendment rates to optimize soil fertility while minimizing environmental risks. This comparison reveals how organic amendments affect soil properties differently depending on crop type, underscoring the need for tailored application strategies to support sustainable soil management. Future research should investigate the long-term effects of manure and biochar on soil health and microbial activity and optimize application rates to balance nutrient availability and environmental sustainability. Additionally, studies should evaluate economic feasibility and broader environmental impacts to promote sustainable soil management practices.

AUTHOR CONTRIBUTIONS

Binita Thapa: Conceptualization; data curation; formal analysis; investigation; methodology; software; visualization; writing—original draft; writing—review and editing. **Ripendra Awal**: Conceptualization; funding acquisition; investigation; methodology; project administration; resources; supervision; writing—review and editing. **Ali Fares**: Conceptualization; funding acquisition; investigation; methodology; project administration; resources; supervision; writing—review and editing. **Atikur Rahman**: Investigation; writing—review and editing. **Anoop Veettil**: Investigation; methodology; writing—review and editing. **Almoutaz Elhassan**: Investigation. **Niraj KC**: Software; visualization.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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