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Transforming Soil: Climate-Smart Amendments Boost Soil Physical and Hydrological Properties

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Abstract: A field study was conducted to investigate the effects of selected climate-smart agriculture practices on soil bulk density (ρ), porosity (β), hydraulic conductivity (K_{sat}), and nutrient dynamics in southeast Texas. Treatment combinations of two types of organic manure (chicken and dairy) with three rates (0, 224, and 448 kg N ha^{-1}) and two levels of biochar (2500 and 5000 kg ha^{-1}) were used in a factorial randomized block design. Bulk density and porosity measurements were conducted on undisturbed soil core samples collected from the topsoil (0–10 cm) of a field cultivated with sweet corn. K_{sat} was calculated from the steady-state infiltration measured using the Tension Infiltrometer (TI). The ANOVA results indicated that the manure application rates, and biochar levels significantly affected the soil properties. Compared to the control, β increased by 15% and 29% for the recommended and double recommended manure rates. Similarly, hydraulic conductivity increased by 25% in the double-recommended rate plots compared to the control. Also, we applied the concept of non-parametric elasticity to understand the sensitivity of soil physical and chemical properties to K_{sat}. ρ and β are critical physical properties that are highly sensitive to K_{sat}. Among soil nutrients, Boron showed the highest sensitivity to K_{sat}. Hydraulic conductivity can be enhanced by employing selected climate-smart practices and improving water management. Future directions for this study focus on scaling these findings to diverse cropping systems and soil types while integrating long-term assessments to evaluate the cumulative effects of climate-smart practices on soil health, crop productivity, and ecosystem sustainability.

Keywords: climate-smart agriculture; hydraulic conductivity; elasticity; soil nutrients; soil properties

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1. Introduction

Soil is essential for operating all land-based ecosystems and food production [1,2]. However, intense agricultural practices, such as monoculture, over-application of fertilizers, and irrigation mismanagement, combined with the climate change impact, lead to degradation in the physical, chemical, and biological properties of soil and a reduction in its ability to support plant growth and other ecosystem functions [3–6]. Sustainable agricultural practices, such as Climate-Smart Agriculture (CSA), can increase crop yield and ensure that the soil remains productive for future generations [7,8]. CSA refers to farming methods that address the challenges of climate change and food security through sustainable agricultural production and the reduction of greenhouse gas (GHG) emissions. CSA mainly focuses on two aims: (i) alleviate climate change from a farm to a national scale by developing GHG emissions reduction strategies, and (ii) increase agricultural productivity to support income and food security [1,9]. Organic amendments (e.g., dairy manure, chicken manure) and biochar application are often recommended for achieving CSA goals. However, the overapplication of organic fertilizers can lead to changes in properties and heavy metal accumulation in soils [10,11].

CSA affects soil health by promoting practices that enhance soil fertility, structure, and biodiversity while reducing soil erosion and degradation [12,13]. One of the critical climate-smart practices is the application of organic amendments. These amendments help build resilient soils capable of withstanding extreme weather events, sequestering carbon, and sustaining productivity in a changing climate [14]. The physical and hydrologic properties of soil, which are affected by organic amendment applications, are hydraulic conductivity, bulk density, and porosity. Hydraulic conductivity is a soil health indicator, which refers to the ability of the soil to transfer water [15] and solute. Specifically, hydraulic conductivity significantly determines precipitation's partition to surface and groundwater flow [16]. Therefore, hydraulic conductivity is essential in runoff and erosion modeling [17]. It is also one of the most uncertain parameters of the soil [18]. The saturation state of the soil influences hydraulic conductivity. In this study, we quantified the saturated hydraulic conductivity, K_{sat}. K_{sat} is quantified when all the pore spaces are filled with water, and K_{sat} primarily depends on the interconnectedness of pore spaces [11].

In general, soil properties, including K_{sat}, bulk density (ρ), and porosity (β), may change with agricultural management practices [11]. Organic amendment application increases β and decreases ρ concerning the soil organic matter, which may increase soil infiltration and hydraulic conductivity [19,20]. Many studies have reported the effect of organic amendments on soil physical properties. For example, Fares et al. [11] reported that K_{sat} increased significantly ($p < 0.01$) with the increase in chicken and dairy manure amendment rates and levels in a study conducted on highly weathered tropical soil. This study also indicated that the increased manure amendment rates and levels significantly decreased ρ and increased β. Bhattacharya et al. [21] also reported the same results in their research using farmyard manure-amended soils. Shi et al. [22] reported the long-term effect of organic fertilizer on soil hydraulic properties. The study found that, compared with the control, field capacity and total porosity significantly ($p < 0.05$) increased, whereas soil bulk density significantly ($p < 0.05$) decreased with organic manure applications. Soil amendment with biochar can alter soil hydrologic properties by changing soil physical and chemical characteristics. For instance, Gholami et al. [23] reported decreased K_{sat} due to adding fine biochar in the soil. Hussain et al. [24] also mentioned that the K_{sat} may vary with biochar particle size and reported an increased K_{sat} for larger biochar particle size.

The relationship between structural characteristics, such as ρ and β, and hydrologic properties is complex and highly non-linear. Modeling the relationship among them is challenging using physically based models and conventional statistical approaches [25]. Similarly, understanding the relationship between K_{sat} and soil nutrients is essential to recognize how nutrients move through the soil profile, impacting plant growth and environmental processes. K_{sat} influences the rate of nutrient transport [26]. Soils with high hydraulic conductivity tend to allow rapid movement of water and nutrients, potentially leading to more significant leaching losses if not managed properly. Similarly, managing soil nutrients is critical for maintaining optimal hydraulic conductivity. For example, soil organic matter and cations, such as calcium (Ca) and magnesium (Mg), lead to better structure and aggregation, improving hydraulic conductivity and indicating a positive correlation [27,28]. Conversely, cations like sodium (Na) can cause the dispersion of soil particles, thereby reducing hydraulic conductivity [29]. However, the influence of organic amendments on K_{sat} is complex and less transparent, suggesting that the influence of organic amendments on soil hydraulic conductivity is multifaceted and requires further investigation.

The specific objectives of this study were to (i) evaluate the effect of organic amendment types (biochar, chicken, and dairy manure) and rates (biochar Level I & II; manure Recommended and Double-recommended) on bulk density, porosity, and hydraulic conductivity, and (ii) investigate the sensitivity of soil physical properties and soil nutrients on hydraulic conductivity. To achieve these objectives, we used ANOVA and elasticity analysis. The paper is organized as follows. Section 1 provides a brief introduction to the importance of the investigation. Section 2 describes experimental design, field data

collection, and lab analysis. Section 3 describes the findings and related discussions. The practical implications of this study highlight its potential benefits for farmers and its alignment with the broader goals of climate-smart agriculture (CSA). Organic amendments, such as biochar, chicken manure, and dairy manure, can significantly improve soil hydraulic conductivity (K_{sat}), bulk density, and porosity across various soil types. Improved K_{sat} enhances water infiltration and reduces surface runoff, making soils more resilient to heavy rainfall events in clayey soils prone to waterlogging while increasing water retention in sandy soils prone to drought. These benefits are critical for farmers managing soils under diverse climatic and geographic conditions. Furthermore, the study supports CSA objectives by demonstrating how organic amendments build resilient soil systems, enhance water use efficiency, and mitigate the impacts of extreme weather events. By improving soil structure, water movement, and nutrient retention, these amendments promote sustainable agricultural productivity while contributing to carbon sequestration and reducing greenhouse gas emissions [30]. This aligns directly with CSA's dual goals of enhancing food security and addressing climate change, ensuring long-term soil health and productivity for future generations.

2. Materials and Methods

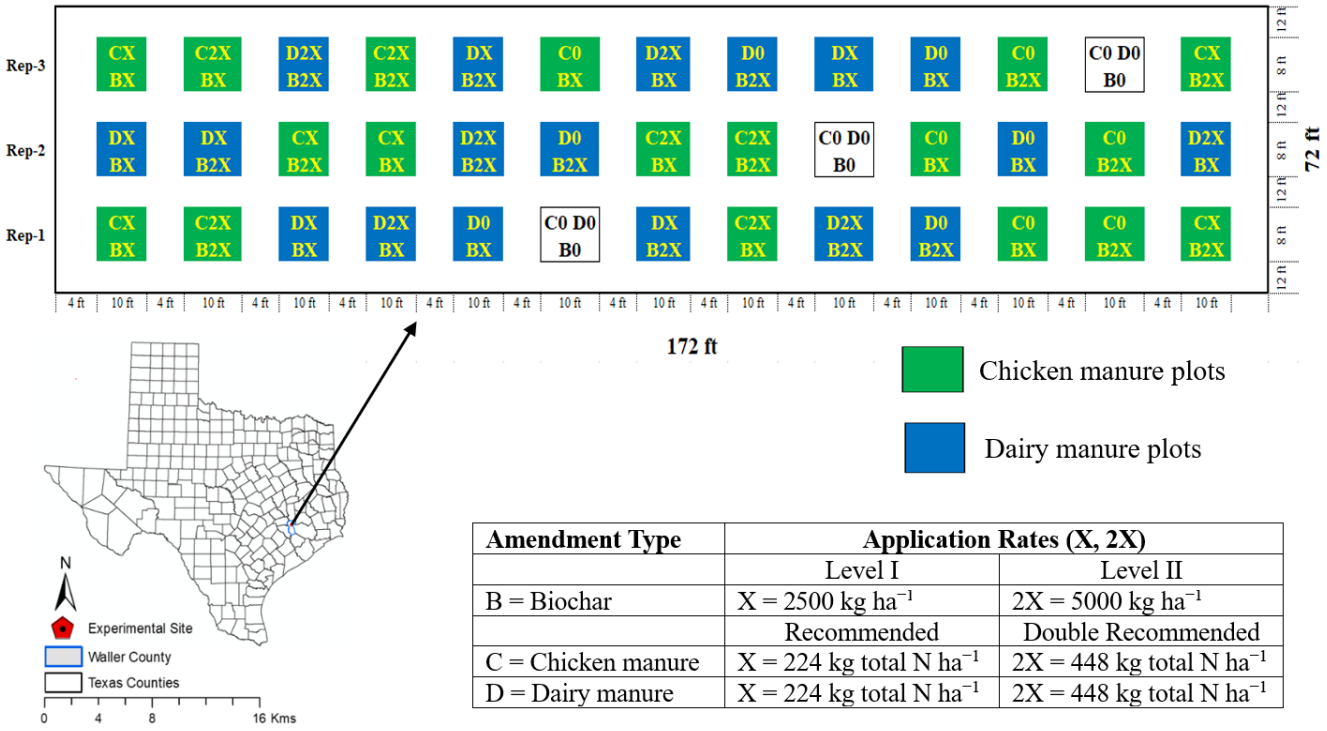
2.1. Location of Experimental Field and Plot Design

The study was conducted at the Prairie View A&M University (PVAMU) College of Agriculture, Food, and Natural Resources (CAFNR) Research Farm (Lat 30.093° N and Long -95.979° W). The University is located at Prairie View, northwest of the Houston Metropolitan area of Texas (Figure 1). The 30-year (1991–2020) annual average precipitation at the study site is 1183 mm, with most occurring in fall (PRISM data: http://www.prism.oregonstate.edu/, accessed on 9 September 2024). The Eastern Texas climate division is humid subtropical, with a mean annual temperature of 17 °C, and July is the hottest month (average July temperature is 35 °C) [31,32]. The study site's soil classification is Wockley fine sandy loam (Fine-loamy, siliceous, semiactive, hyperthermic Plinthaquic Paleudalfs). The selected general characteristics of field soil, considering the depth up to 2.03 m, are illustrated in Table 1. The topsoil is fine sandy loam, with 61–70% sand, and the bottom soil is sandy clay loam. The texture of Wockley soil allows for decent water infiltration and retention, making it suitable for various agricultural uses. Wockley soil may require careful management to prevent erosion and nutrient leaching, especially in the humid subtropical climate [33].

The experimental design was a factorial Randomized Complete Block Design (RCBD) with three replications (Figure 1). This experiment used two organic amendments: chicken and dairy manure, applied at 0, 224, and 448 kg N ha^{-1}, denoted as control, recommended, and double recommended rates, respectively. Additionally, biochar was introduced as a subfactor, applied at rates of 2500 and 5000 kg ha^{-1}, referred to as Level I and II, respectively. Each treatment was replicated three times to ensure statistical reliability. The experimental layout shows X marking the recommended/Level I application rate, while 2X represents double-recommended/Level II application rates. Sweet corn was cultivated in the plots, and a drip irrigation system was employed for consistent irrigation. The biochar used in this study was derived from coconut husk and sourced from the Andersons BioChar DG Organic Soil Amendment. Coconut husk, as a feedstock, is characterized by relatively high ash content. The chemical properties of the biochar are listed in Table 2.

IrrigWise, a web-based irrigation scheduling tool, was used to quantify the accurate irrigation requirements. This tool uses near-real-time site-specific rainfall, reference evapotranspiration, soil water content, and plant growth stage [34]. Before sowing, organic amendments were broadcasted, mixed, and incorporated in the top 15 cm. Incorporating organic amendments into the top 15 cm of soil is standard agronomic practice for several reasons, including root zone accessibility and enhanced nutrient utilization, and this depth is commonly used in studies and field trials, ensuring comparability with existing research and standard practices [14,33,35]. The plot size was 3 m × 2.4 m, and sweet corn was sown

at a rate of 7.62 kg ha^{-1} with a spacing of 0.3 m between plants and 0.6 m between rows on 15 April 2022. Soil chemical properties were measured before manure application and after biomass harvest. The physical properties were measured after the biomass harvest. This timing was selected to assess the cumulative effects of the applied organic amendments on the soil's physical properties during the growing season.



Amendment Type	Application Rates (X, 2X)	
	Level I	Level II
B = Biochar	X = 2500 kg ha^{-1}	2X = 5000 kg ha^{-1}
	Recommended	Double Recommended
C = Chicken manure	X = 224 kg total N ha^{-1}	2X = 448 kg total N ha^{-1}
D = Dairy manure	X = 224 kg total N ha^{-1}	2X = 448 kg total N ha^{-1}

Figure 1. The experimental plots are located at Prairie View A&M University, Waller County, Texas. The plots' layout includes representations of treatment types and treatment rates. The green plots represent the organic amendment with chicken manure, the blue represents dairy, and the white are control plots without any amendments.

Table 1. Selected soil characteristics of the experimental site [14].

Soil Depth (cm)	Soil Texture	Percent (%)		
		Sand	Silt	Clay
0–18	Fine Sandy Loam	61–70	26–32	4–7
18–56	Fine Sandy Loam	51–62	29–40	6–9
56–147	Sandy Clay Loam	45–52	17–31	22–37
147–203	Sandy Clay Loam	38–46	19–23	31–46

Table 2. Nutrient concentration, pH, and electrical conductivity of the initial soil condition, chicken manure (CM), dairy manure (DM), and biochar. C (carbon), Nitrogen (N), Phosphorus (P), Potassium (K), Calcium (Ca), Magnesium (Mg), Boron (B), Copper (Cu), Iron (Fe), Zinc (Zn), Mn (Manganese), S (Sulfur), pH, Electrical Conductivity (EC) unit mS cm^{-1} [35].

Amendment	C (%)	N (%)	P (g/kg)	K (g/kg)	Ca (g/kg)	Mg (g/kg)	B (mg/kg)	Cu (mg/kg)	Fe (mg/kg)	Zn (mg/kg)	Mn (ppm)	S (%)	pH	EC (mS cm^{-1})
Soil	0.50	0.09	0.09	0.07	0.39	0.07	6.38	-	253	2.00	8.00	0.28	6.89	0.11
CM	27.3	3.05	9.60	27.2	16.2	5.64	50.1	817.9	2494	465	500	1.37	7.02	17.7
DM	14.6	0.50	5.75	12.6	72.3	4.79	18.98	25.2	6025	129	335	0.64	8.40	8.73
Biochar	58.7	1.46	1.08	5.45	29.9	6.68	10.96	8.90	1203	22.0	90.0	3.15	5.67	18.9

2.2. Soil Sample Collection to Determine Bulk Density and Porosity

The sampling methodology randomly collected undisturbed soil core samples (internal radius, 2.5 cm; height, 5 cm) from each treatment plot's top 10 cm soil layer, including the control, chicken manure, and dairy manure plots. The samples were taken from areas within the plots subjected to the respective treatments, ensuring they represented the soil enriched with fertilizer where applicable. This approach allowed us to compare the effects of the different treatments on soil physical properties while maintaining consistency in sampling depth and methodology across treatments. The inclusion of control plots provided a baseline for comparison, highlighting changes attributable to the organic amendments.

(i) The bottom of the soil cores was covered with fine nylon mesh to secure soil in the core.

(ii) The core samples were then placed in a tray filled with water for 24 h. This process slowly saturated the soil from the bottom.

(iii) The saturated samples were oven-dried for 72 h at 105 °C.

(iv) The soil ρ and β were determined by following the standard procedure developed by Grossman & Reinsch [36] and Flint & Flint [37] using the following equations.

$$\rho = W_d / V \tag{1}$$

$$\beta = (W_s - W_d) / V \tag{2}$$

where W_s is the saturated soil samples' weight, W_d is the oven-dried sample weight, and V is the volume of core samples.

2.3. Field Infiltration Measurement for Saturated Hydraulic Conductivity

In this study, we measured the soil infiltration using a tension infiltrometer (Soil Measurement System, Arizona, United States). This instrument has been used to determine K_{sat} under different field conditions [11,38]. The tension infiltrometer used in the study has the following parts: (i) disc (diameter = 20 cm), (ii) water reservoir (inside diameter = 5.1 cm, length = 81 cm), (iii) bubbling tower (inside diameter = 2.54 cm, length = 30 cm). A brief description of the instrument's usage is as follows:

(i) The perforated disc was soaked in water to remove all entrapped air bubbles.

(ii) The disc was placed on a thin layer of sand, prepared at the equal diameter of the disc to ensure good contact between the disc and soil. The sand may affect the initial unsteady rates, and here, we assumed that the thin sand layer did not impact the steady-state infiltration rate used for K_{sat} calculations.

(iii) The field infiltration test was performed at three tensions: −10 cm, −5 cm, and −2.5 cm (i.e., in order of low to high pressure).

(iv) The falling head of water in the bubble tower was noted every two minutes up to a steady state condition was reached (i.e., three constant rate readings for each tension level).

The resulting infiltration data were used for calculating K_{sat} based on the equation developed by Wooding [39].

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

where Q (LT^{-1}) is steady state water flux, r (m) is circular source radius, α (T^{-1}) is inverse macro porosity capillary length, $\psi\ (L)$ 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 higher tension (ψ_2); the Hussen & Warrick [40] equation was used to calculate α.

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

2.4. Soil Nutrient Analysis

Composite soil samples from the top 0–15 cm were collected from each plot using a core soil sampler from three different spots and thoroughly mixed. The soil sample was first air-dried, ground, and passed through a 0.2 mm sieve. A precise amount of the air-dried soil sample was weighed using a microbalance. Soil pH and electrical conductivity (EC) were measured in deionized water at a soil: water ratio of 1:2. Soil nutrient parameters: carbon (C), nitrogen (N), and sulfur (S), were measured using a CHNS analyzer (Elementar Americas, Inc., Ronkonkoma, NY, USA). These values are reported as the percentage of the total dry weight of the soil. This method is accurate and widely accepted in soil science [41]. Phosphorus (P), Potassium (K), Calcium (Ca), Magnesium (Mg), Boron (B), Copper (Cu), Iron (Fe), Zinc (Zn), and Mn (Manganese) were measured using the Coupled Plasma Optical Emission Spectroscopy (ICP-OES) instrument (Agilent Technologies, Inc., Santa Clara, CA, USA). Soil nutrient concentrations are presented in Table 2.

2.5. Statistical Analysis

2.5.1. Analysis of Variance and Tukey Test

The analysis of variance (ANOVA) for K_{sat}, ρ, and β was conducted using RStudio [42] to quantify the impact of manure type, rate, and biochar level. The K_{sat}, ρ, and β were dependent variables, and type, rate, and level were covariance factors. Tukey mean separation (least significant difference) test was used to separate the effect of type, rate, and level of amendments on K_{sat}, ρ, and β following the ANOVA. In Tukey's HSD (Honestly Significant Difference) bar plots, the error bars represent the standard error of the mean (SEM), which quantifies the variability of the group means. These error bars are calculated to provide intervals around the mean values, reflecting the precision of the estimates. SEM is derived from the standard deviation of the group and the sample size. Tukey's HSD test identifies significant differences between group means by accounting for pooled variability and adjusting the critical threshold to control for multiple comparisons.

2.5.2. Sensitivity Analysis

To quantify the response of soil physical properties and nutrients to K_{sat}, we applied the concept of non-parametric elasticity [43]. This approach measures the proportional change in one variable about the change in another variable, emphasizing the magnitude and sensitivity of this response [44,45]. The elasticity is calculated as follows.

$$\phi = median\left(\frac{y_i - \bar{y}}{x_i - \bar{x}} \times \frac{\bar{x}}{\bar{y}}\right) \quad (5)$$

where ϕ the non-dimensional quantity is called elasticity. y_i is the K_{sat} calculated from each plot, and x_i is the corresponding soil nutrient level measured from that plot, or ρ or β. $\overline{y}$ and $\overline{x}$ represents the mean of y and x values, respectively.

The elasticity distinguishes between positive and negative sensitivities. For example, a positive elasticity value suggests that increasing a particular soil nutrient may enhance K_{sat}. Meanwhile, a negative elasticity value indicates that increasing a particular soil nutrient may decrease K_{sat}. Therefore, this approach is found to be suitable for quantifying the influence of soil nutrients on K_{sat}.

2.5.3. Correlation Analysis

The bivariate correlation between soil hydraulic conductivity and physical and chemical properties was analyzed using the Pearson correlation coefficient, r (Equation (6)). r values range from -1 to + 1, and there is no correlation between two variables when this value equals 0. Also, the p-value of correlations reflects the significance of the correlation.

$$r = \frac{\sum_{k=1}^{n}\left(K_{sat} - K_{sat(m)}\right)(\rho - \rho_m)}{\sqrt{\sum_{k-1}^{n}\left(K_{sat} - K_{sat(m)}\right)^2 \sum_{k-1}^{n}(\rho - \rho_m)^2}} \quad (6)$$

where K_{sat} (m) and $\rho(m)$ represent the mean values of hydraulic conductivity and bulk density, respectively.

3. Results and Discussion

3.1. Variability of Soil Physical and Hydrological Properties

The variability of ρ, β, and K_{sat} due to the experimental blocks, manure types, rates, and biochar levels is shown in Figure 2. The differences in ρ across replications (blocks) can be attributed to the inherent variability in soil properties and management practices associated with each replication. Replication one, where a higher ρ was observed, may have had more compacted soil, potentially due to higher initial bulk density or greater machinery traffic. The result indicated a relatively higher ρ in dairy manure plots than in chicken manure plots. The increased porosity primarily causes a decrease in bulk density due to manure application. We observed median porosity values of 26% in the control plots, 29% in the recommended plots, and 33% in the double-recommended plots. The bulk density decreased by 4.6% from the control plots to the double-recommended plots. A similar result was reported by Ahmad et al. [46], who found that a 4%, 8%, and 9% decrease in bulk density resulted from cow manure applications of 165, 335, and 670 kg N ha^{-1}, respectively. In addition, ρ decreased concerning the biochar levels. In the case of K_{sat}, replication three showed the highest value with a median of 1.4 cm hr^{-1}. In addition, K_{sat} showed an increasing pattern with the manure rates and biochar levels. Studies have shown conflicting results regarding the effects of soil amendment applications on soil physical and hydrologic properties. The extent to which these amendments influence the soil depends on the physical and chemical characteristics of the manure used, as well as various management and environmental factors such as application rate and timing, soil type, and climate conditions [47].

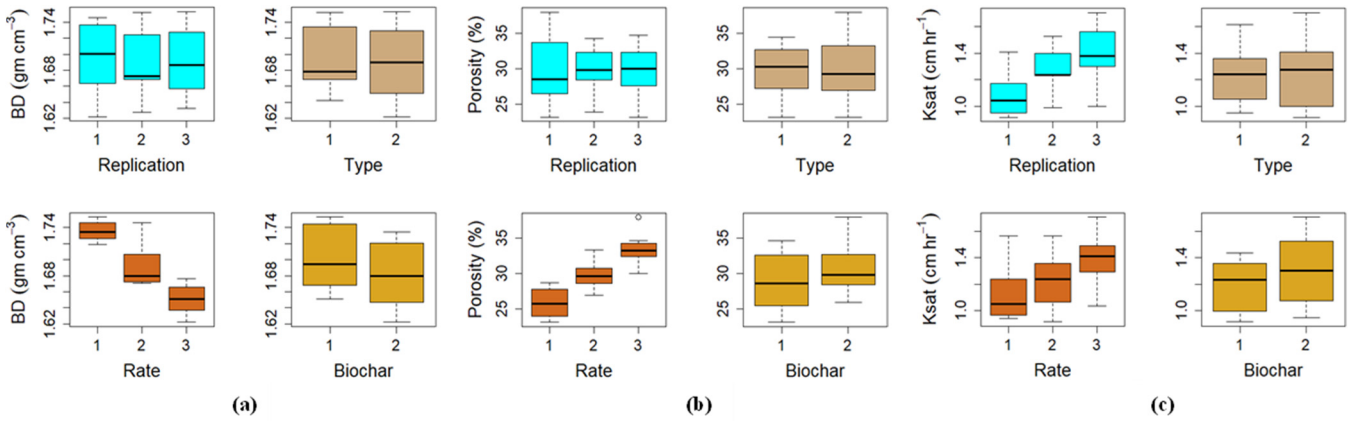


Figure 2. Box plot showing the distribution of (**a**) bulk density (g cm^{-3}), (**b**) porosity (%), and (**c**) hydraulic conductivity (K_{sat}; cm hr^{-1}) with the replications (blocks), manure type, application rates, and biochar levels. Type 1: Chicken, Type 2: Dairy, Rate 1: Control, Rate 2: Recommended, Rate 3: Double-recommended, Biochar 1: Level 1, Biochar 2: Level 2. The box represents the Inter Quartile Range (IQR). The lower edge of the box represents the 25th percentile, the upper edge of the box represents the 75th percentile, and the line inside the box represents the median (50th percentile) of the data. Lines extending from the box show the range of the data, excluding outliers, and the individual dots indicate the outliers.

3.2. Organic Amendments' Effect on Bulk Density

ANOVA results indicated that the manure rate and biochar levels significantly ($p < 0.05$) affected soil bulk density (Table 3). The interaction of type, rate, and biochar was insignificant for ρ. The manure type was also insignificant for ρ. The mean values of ρ were not significantly different for chicken and dairy applications. Biochar Level 2 showed a significantly lesser mean value for ρ (Figure 3). The Level 2 application decreased the ρ by 1.2% compared to the Level 1 application. The error bar indicates a significant difference in the mean for different groups (Figure 3b). The double recommended rate of manure also showed a significant ($p < 0.05$) decrease in ρ compared to the control and recommended application rates. Bulk density decreased by 2.6% and 4.8% for the recommended and double-recommended rates of manure compared to the control. This result suggests that higher manure applications may lead to substantial soil structural improvements, likely due to the increased organic matter content that improves soil aggregation and reduces compaction. These results align with previous studies showing the positive effects of organic amendments, such as manure and biochar, on improving soil structure and reducing compaction, leading to lower bulk density [11,48]. In addition, the mean bulk density for both chicken and dairy manure applications was not significantly different, indicating that the type of manure may not play a significant role in influencing bulk density under the conditions of this study. In the case of interaction, the manure types and rates showed a significant effect on bulk density (Table 3). Figure 3c illustrates the interactive effects of manure types and rates on bulk density, indicating that a higher application of chicken and dairy manure decreased bulk density. For example, the mean bulk density across the double-recommended chicken and dairy manure plots was 1.66 and 1.65 gm cm^{-3}, respectively, which was less than 4.6% compared to the recommended rate of applications.

Table 3. Analysis of variance for ρ data as a function of manure type and rate and biochar level.

Source	DF	SS	MS	F	P
Replication	2	0.00014	0.000145	0.653	0.42969
Type	1	0.00017	0.000173	0.78	0.38888
Rate	2	0.04348	0.021741	98.171	2.08×10^{-10}
Biochar	1	0.00323	0.003232	14.594	0.00125
Replication × Rate	2	0.00038	0.000192	0.866	0.43745
Type × Rate	2	0.00162	0.000811	3.662	0.04629
Replication × Biochar	1	0.00041	0.000409	1.848	0.19084
Type × Biochar	1	0.00014	0.000144	0.649	0.43111
Rate × Biochar	2	0.00004	0.00002	0.092	0.91277
Replication × Rate × Biochar	2	0.00041	0.000205	0.925	0.41443
Type × Rate × Biochar	2	0.00058	0.000289	1.306	0.29541
Residuals	18	0.00399	0.000221		
Total	35	0.05459			
Coefficient of Variation = 0.05%					

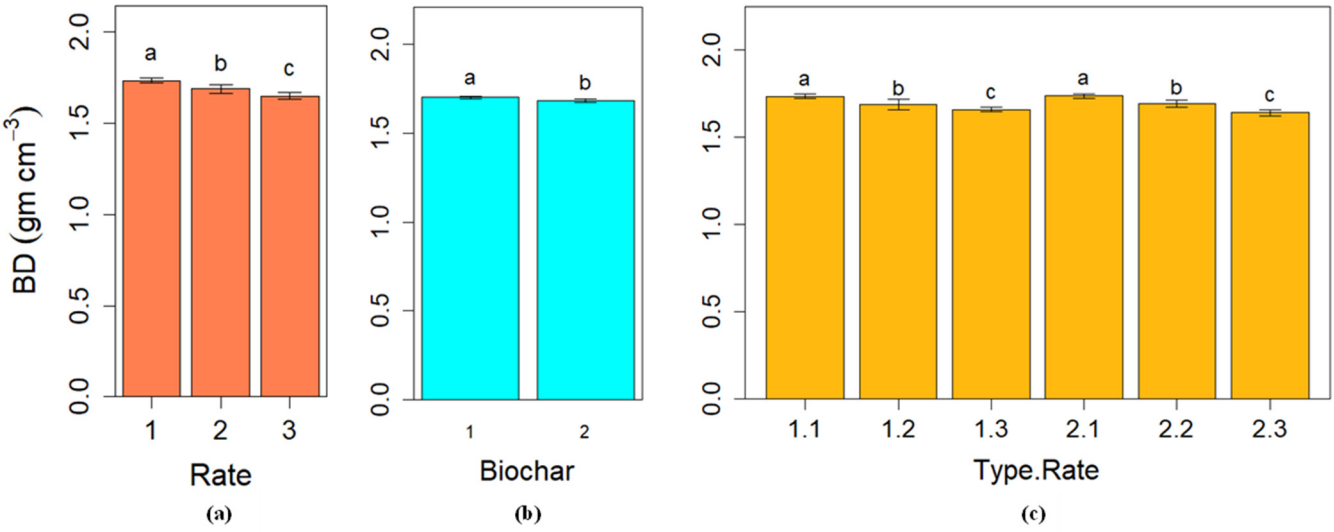


Figure 3. Effect of (**a**) manure rates and (**b**) biochar levels on bulk density, BD (g cm^{-3}). (**c**) Interaction between manure types and rates on bulk density (g cm^{-3}). The *X*-axis label represents the 'type' first and 'rate' second. For example, 2.3, 2 is the type, and 3 is the rate. Note: The same letter in the figure indicates no significant difference among means by least significant difference (LSD) comparison of means at $\alpha = 0.05$.

3.3. Organic Amendments' Effect on Soil Porosity

The biochar levels and manure rates significantly affected the soil porosity (Table 4). Like ρ, ANOVA results showed that manure type had no significant effect on β. Tukey mean separation results indicated significantly ($p < 0.05$) different mean values for biochar levels. The Level 2 biochar application increased soil porosity by 5.5% compared to the Level 1 application (Figure 4). Similarly, manure application rates also showed an increasing pattern of soil porosity. The soil porosity increased by 15 and 29%, respectively, for recommended and double recommended manure rates compared to the control. Manure type and rate interaction significantly ($p < 0.05$) affected β (Table 4, Figure 4). Tokova et al. [48] and Guo et al. [49] also reported similar results, consistently showing that organic amendments, such as biochar and manure, improve soil structure by increasing porosity. Enhancement in soil porosity generally improves water-holding capacity, aeration, and root penetration, which are essential for plant growth and agricultural productivity [50]. The interaction of manure rates and biochar levels also significantly affected soil porosity. Such interactions may reflect differences in the physical and chemical properties of chicken and dairy manure (Table 2), which could impact how manure types interact with biochar and other soil constituents to affect porosity. In the case of interaction, higher manure rates showed higher porosity. For example, double-recommended chicken and dairy manure application rates showed a porosity higher than 33% (Figure 4c).

Table 4. Analysis of variance for β data as a function of manure type and rate and biochar level.

Source	DF	SS	MS	F	P
Replication	2	0.1	0.15	0.063	0.80494
Type	1	0.2	0.21	0.092	0.76453
Rate	2	344.2	172.09	74.192	2.03×10^{-9}
Biochar	1	22.4	22.42	9.666	0.00606
Replication × Rate	2	6.5	3.23	1.394	0.27372
Type × Rate	2	7.5	3.75	1.618	0.22593

Table 4. *Cont.*

Source	DF	SS	MS	F	P
Replication × Biochar	1	8.9	8.92	3.845	0.06556
Type × Biochar	1	2.6	2.59	1.116	0.30482
Rate × Biochar	2	17.9	8.94	3.854	0.04044
Replication × Rate × Biochar	2	9	4.48	1.932	0.17376
Type × Rate × Biochar	2	8.9	4.46	1.925	0.17479
Residuals	18	41.8	2.32		
Total	35	470			
Coefficient of Variation = 5.13%					

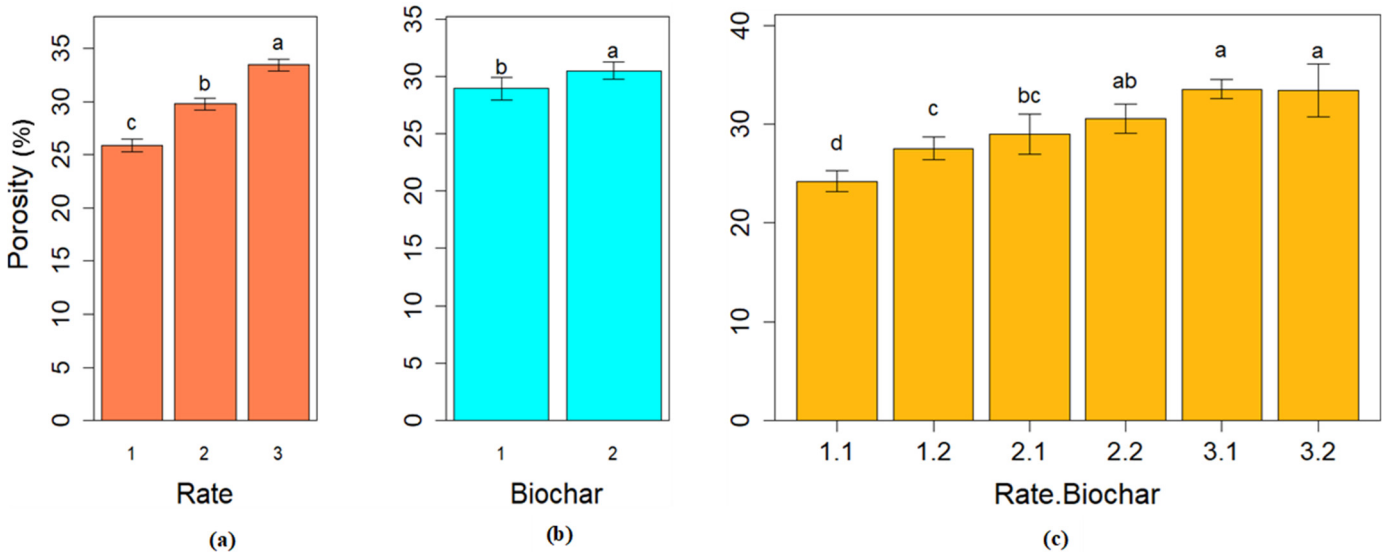


Figure 4. Effect of (**a**) manure rates and (**b**) biochar levels on porosity (%). (**c**) Interaction between manure rates and biochar levels on porosity. The *X*-axis label represents the 'rate' first and 'biochar level' second. The same letter in the figure indicates no significant difference among means by least significant difference (LSD) comparison of means at $\alpha = 0.05$.

3.4. Organic Amendments' Effect on Saturated Hydraulic Conductivity

Unlike ρ and β, K_{sat} was significantly ($p < 0.05$) affected by the randomized blocks. Figure 5a illustrates that K_{sat} in replication one was significantly less than the other two replications. This can be due to the impact of higher bulk density across replication one plots. In addition, K_{sat} significantly varied with the manure rates and biochar levels, while their interaction did not significantly affect K_{sat} (Table 5). The K_{sat} values increased in terms of the biochar level (the mean K_{sat} was significantly different). We noticed an 11.3% increase in K_{sat} for the Level 2 application compared to the Level 1 application rate (Figure 5). The porous nature of biochar can improve the soil pore space, thereby increasing K_{sat} [51]. Also, the variation in K_{sat} depends on the biochar particle size. For example, Edeh & Masek [52] reported that K_{sat} increased with decreasing biochar particle sizes compared to larger ones. Also, the K_{sat} for chicken manure plots showed comparatively higher values than dairy manure plots. However, this difference was not statistically significant. The Tukey mean separation test results reflected the significant effect of rates of manure on *Ksat*. The K_{sat} values were significantly different for double-recommended rates compared to the control (Figure 5). However, the K_{sat} measured at the recommended application rates was not significantly different from control plots. K_{sat} increased by 25% in double-recommended

rate plots compared to the control. However, the result indicated that the interaction between any source variables was insignificant for soil hydraulic conductivity.

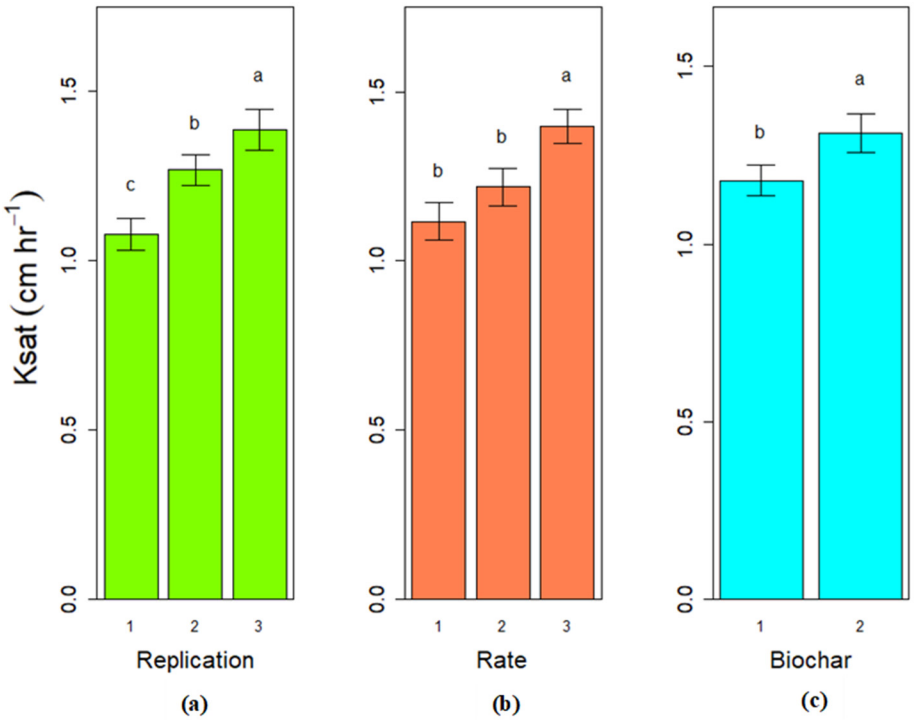


Figure 5. Effect of (**a**) replications and (**b**) manure rates, and (**c**) biochar levels on saturated hydraulic conductivity (K_{sat}). The same letter in the figure indicates no significant difference among means by least significant difference (LSD) comparison of means at $\alpha = 0.05$.

Table 5. Analysis of variance for K_{sat} data as a function of manure type and rate and biochar level.

Source	DF	SS	MS	F	P
Replication	2	0.5733	0.5733	30.521	3.03×10^{-5}
Type	1	0.0101	0.0101	0.537	0.473273
Rate	2	0.4878	0.2439	12.987	0.000323
Biochar	1	0.1599	0.1599	8.515	0.009179
Replication × Rate	2	0.0181	0.0091	0.483	0.62482
Type × Rate	2	0.0079	0.004	0.211	0.811453
Replication × Biochar	1	0.0131	0.0131	0.7	0.413759
Type × Biochar	1	0.0015	0.0015	0.08	0.780459
Rate × Biochar	2	0.0239	0.012	0.637	0.540306
Replication × Rate × Biochar	2	0.0008	0.0004	0.022	0.978642
Type × Rate × Biochar	2	0.0093	0.0047	0.248	0.782824
Residuals	18	0.3381	0.0188		
Total	35	1.6438			
Coefficient of Variation = 0.46%					

The mechanism through which organic amendments, such as manure and biochar, influence soil physical and hydraulic properties revolves around their ability to enhance soil structure, aggregate stability, and pore connectivity [11,30]. Manure introduces organic matter rich in nutrients and carbon, stimulating microbial activity when applied. Microor-

ganisms decompose the organic material, producing binding agents like polysaccharides that aggregate soil particles. This aggregation reduces soil compaction, leading to a decrease in ρ and an increase in β. The improved porosity creates more interconnected pore spaces, which enhances water infiltration and retention, thereby increasing K_{sat}. Similarly, due to its porous and lightweight structure, biochar physically alters the soil matrix by creating additional macropores and increasing aeration. Together, these amendments improve pore connectivity, water movement, and retention, providing a beneficial mechanism for enhancing soil health and agricultural productivity.

The findings of this study revealed that while several treatments significantly affected soil physical and hydrological properties, some comparisons did not yield statistically significant results. These non-significant outcomes may stem from a combination of environmental factors, application rates, and soil types, which collectively could mask the potential effects of the applied amendments. For example, the Wockley fine sandy loam, characterized by high sand content in the topsoil, inherently has limited organic matter and nutrient retention capacity. This could moderate the impact of organic amendments, especially at lower application rates. Additionally, the humid subtropical climate of southeast Texas introduces variability in soil moisture and temperature, which might alter nutrient availability and microbial activity. Another potential explanation for non-significant results lies in the temporal scale of the study. The effects of organic amendments, particularly biochar, often require more extended periods to manifest fully. Soil properties such as porosity and hydraulic conductivity depend on cumulative changes in soil structure and organic matter content. Additionally, exploring a broader range of application rates and testing amendment combinations could help identify optimal strategies for improving soil health.

Environmental factors, such as soil type and climate, suggest that site-specific management practices are important. Tailoring amendment applications to local conditions and integrating these strategies with complementary practices, such as cover cropping or reduced tillage, may enhance their effectiveness. In summary, while this study demonstrated several significant benefits of organic amendments, the non-significant outcomes provide valuable insights into the limitations and challenges associated with short-term field studies and the intricate interplay of environmental and management factors. Future research should address these gaps to develop more robust and scalable soil management strategies.

3.5. Linking Soil Hydraulic Conductivity with Physical and Chemical Properties

The differences in the soil's physical parameters are associated with the types and rates of organic amendments [11,53]. Increasing soil bulk density associated with compaction can dramatically impact soil hydraulic properties, and a high porosity increases hydraulic conductivity by providing more channels for water movement. We checked the correlation among the soil's physical properties using the Pearson correlation coefficient (r). Figure 6 illustrates the Pearson's correlation between different soil characteristics, and the correlation values are shown if the p-value is less than 0.05. The results indicated a strong negative correlation ($r = -0.6$) between bulk density and K_{sat} and a positive correlation between porosity and K_{sat} ($r = 0.55$).

Similarly, the correlation between K_{sat} and soil nutrient levels collected at the end of the season was also analyzed by plotting a correlation matrix (Figure 6). The soil nutrients considered in this analysis are Total Organic Carbon (TOC), Total Nitrogen (TN), Phosphorus (P), Potassium (K), Calcium (Ca), Magnesium (Mg), Manganese (Mn), Iron (Fe), Zink (Zn), Aluminum (Al), Boron (B), Sodium (Na), and Sulphur (S) (Table 2). Also, soil pH and Electrical Conductivity (EC) were considered in the analysis. The correlation matrix allowed us to identify the interdependence of physical and chemical parameters with hydraulic conductivity. For example, TOC showed an r-value of 0.21 ($p > 0.05$) with the soil hydraulic conductivity. The macronutrients, such as TN, P, and K, showed an r-value of 0.33, 0.37, and 0.36, respectively. B showed a higher correlation among the soil nutrients with an r-value of -0.56, followed by Mn with an r-value of 0.48. The correlation

coefficients for Ca, Mg, Fe, Zn, Al, and Na were 0.40, 0.34, 0.15, 0.24, −0.22, and −0.10, respectively. Also, soil pH and EC showed a less correlation with the K_{sat}.

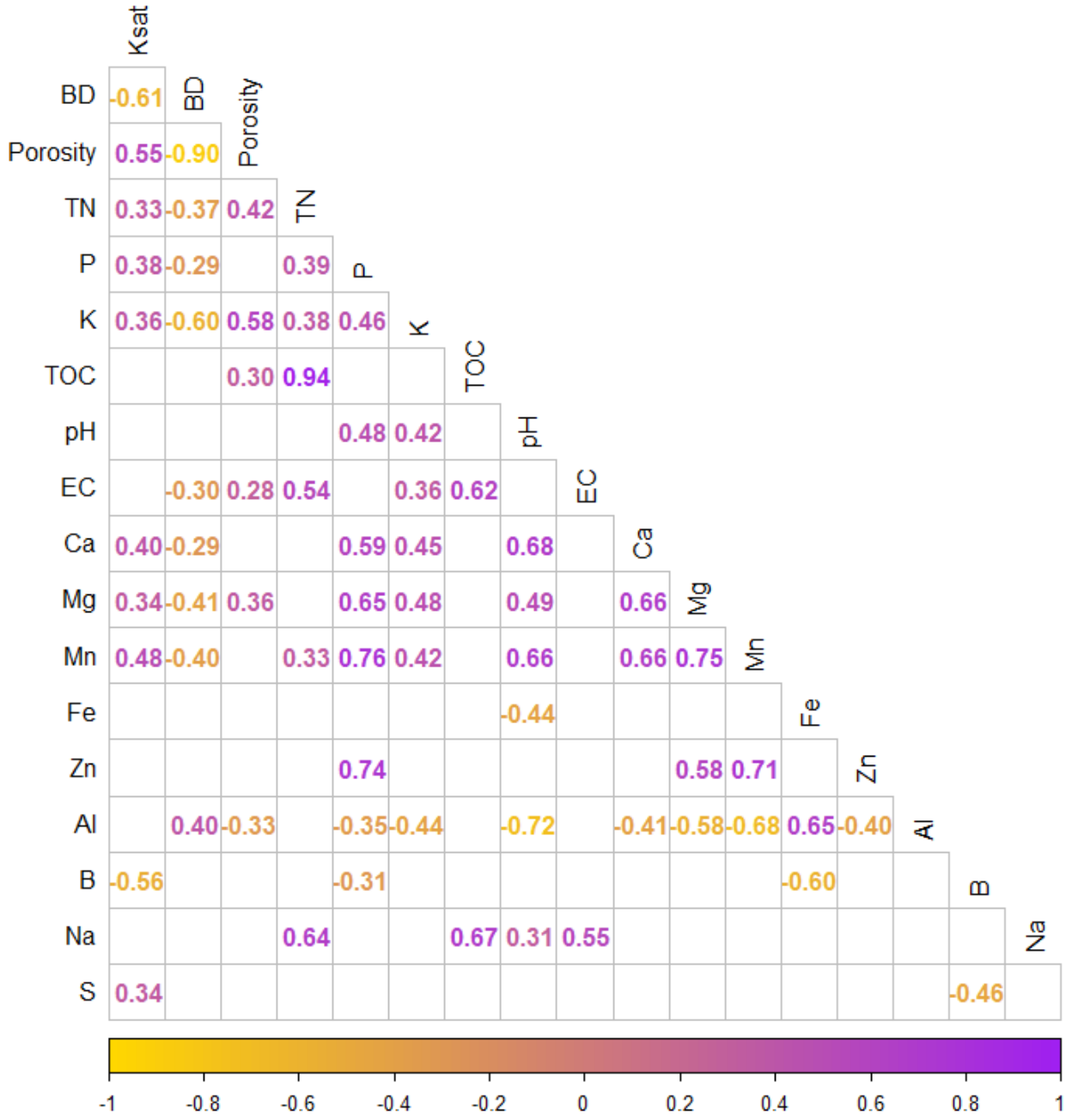


Figure 6. The correlation matrix shows the Pearson correlation between all the soil physical and chemical parameters. Pearson correlation values are only visible if the *p*-value is less than 0.05.

Boron is a trace element essential for plant growth, and several factors, such as concentration and soil type, influence its effects on K_{sat}. At low concentrations, B can enhance soil structure and promote plant growth. At higher concentrations, it may harm plants and soil microorganisms, reducing organic matter input and deteriorating soil structure, consequently reducing soil porosity and hydraulic conductivity [54]. In this experiment, we observed a negative correlation of B with K_{sat}, indicating that the B concentration negatively affects hydraulic conductivity. The highest B concentration was observed in the double-recommended chicken plots, with an average concentration of 4.96 ppm in the C2XB2X plots, followed by C2XBX (4.46 ppm). The dairy manure plots resulted in compar-

atively lower B concentrations. The impact varies with soil type, Boron concentration, and other soil factors such as salinity. Soil elements, such as Ca, Mg, Mn, and Fe, are crucial in aggregating soil stability, reducing dispersion, and maintaining consistent hydraulic conductivity [55]. These elements can also reduce soil compaction by supporting root growth and increasing microbial activities. They also provide a pH-neutral environment, indirectly increasing the soil's physical properties. However, potential negative impacts of these elements include poor plant and microbial growth, leading to soil compaction. Also, managing soil pH and ensuring balanced micronutrient levels are crucial for mitigating potential negative impacts and enhancing the positive effects of Zn and Fe on soil hydraulic conductivity. Like these elements, TOC affects soil structural properties, helps maintain soil structure, and enhances water infiltration and movement through the soil profile. However, TOC concentration did not show a specific trend concerning the type and rate of application, and it showed a weak correlation with soil hydraulic conductivity.

3.6. Sensitivity of Soil Physical and Chemical Properties to Hydraulic Conductivity

The concept of elasticity was employed to explore how hydraulic conductivity (K_{sat}) responds to soil's various physical and chemical properties. This analysis quantitatively assesses the sensitivity of K_{sat} to changes in soil characteristics, such as nutrients, bulk density, and porosity, providing valuable insights for soil management and agricultural practices (Figure 7). Bulk density emerged as the most sensitive factor affecting hydraulic conductivity. The elasticity value for bulk density was −4.3, indicating a significant inverse relationship, which means that a 10% increase in bulk density results in a 43% decrease in K_{sat}. The high sensitivity underscores the importance of managing soil compaction to maintain optimal water movement and availability in the soil profile. Porosity, another crucial physical property of soil, showed a positive sensitivity with an elasticity value of 0.84, indicating that a 10% increase in soil porosity leads to an 8.4% increase in K_{sat}. Since porosity directly affects the soil's ability to transmit water, maintaining or enhancing soil porosity through practices such as organic matter addition or reduced tillage can significantly improve hydraulic conductivity [11,56,57].

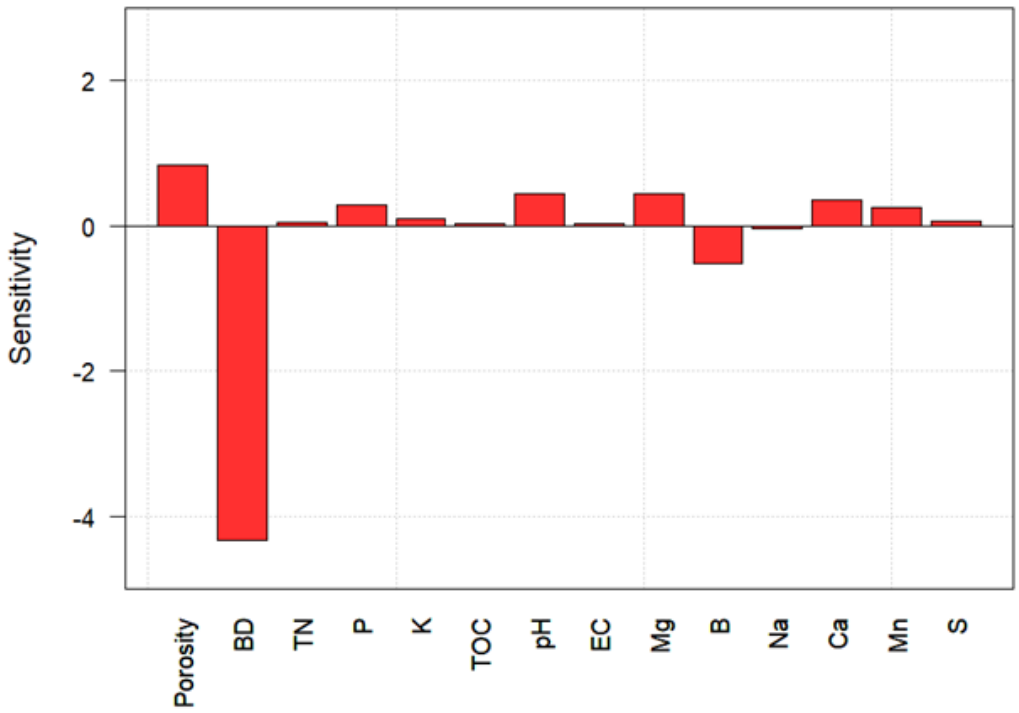


Figure 7. Sensitivity of hydraulic conductivity with the selected soil's physical and chemical parameters.

Among soil nutrients, Boron (B) displayed the highest sensitivity, with an elasticity value of −0.51. The negative sensitivity suggests that an increase in Boron concentration leads to a decrease in K_{sat}. This finding is crucial for managing Boron levels in soils, particularly in regions where Boron toxicity might impede water infiltration and movement [58]. Many crops are susceptible to B, and keeping an acceptable concentration of B is crucial for maintaining a good yield. A high concentration of B is associated with soil salinity in semiarid or arid climates [59]. In this analysis, Na exhibited a slightly negative sensitivity value. A combined impact of B and Na will reduce water movement and increase soil compaction [60]. Other nutrients, including Magnesium (Mg), Calcium (Ca), Phosphorus (P), and Manganese (Mn), showed positive elasticity values, indicating that increases in these nutrients can enhance K_{sat}. These results suggest that balanced fertilization, considering the specific sensitivity of K_{sat} to different nutrients, can optimize soil hydraulic properties [27,28].

Boron is an essential micronutrient for plant growth, but its impact on soil hydraulic properties, particularly K_{sat}, depends on its concentration and interaction with other soil factors. The study observed a negative correlation between Boron concentration and K_{sat}, which aligns with findings that excessive Boron can negatively impact soil structure and water movement. At higher concentrations, Boron can contribute to the dispersion of soil particles, particularly in soils with low organic matter or high salinity. Dispersion reduces the formation of stable soil aggregates, which is critical for maintaining pore spaces and hydraulic conductivity. Dispersion leads to soil sealing and clogging of pores, thereby decreasing K_{sat} [54,61]. In addition, at excessive levels, Boron can inhibit microbial activity, reducing the breakdown of organic matter and the formation of stable aggregates that facilitate water movement [62]. Therefore, there is a need to carefully manage Boron levels in the soil to prevent adverse impacts on hydraulic conductivity and overall soil health [63].

Soil pH also notably influenced hydraulic conductivity, with an elasticity value of 0.44. A 10% increase in pH results in a 4.4% increase in K_{sat}, highlighting the importance of maintaining appropriate pH levels for optimal soil water movement. Soil pH affects the solubility and availability of nutrients, influencing soil structure and porosity [64]. Interestingly, Total Organic Carbon (TOC) did not show substantial sensitivity to K_{sat} in this analysis. This result suggests that while TOC is vital for overall soil health and fertility, its direct impact on hydraulic conductivity may be less pronounced than other factors, such as bulk density, porosity, and specific nutrients.

The novel contributions from this study involve the unique and combined evaluation of biochar and manure (chicken and dairy) types and rates on soil health parameters, such as porosity, bulk density, and hydraulic conductivity. Although Fares et al. [11] and Liu et al. [65] evaluated biochar and manure separately, they reported improved soil properties without addressing their combined interactions in a humid subtropical environment. In addition to ANOVA, using non-parametric elasticity analysis to quantify the sensitivity of K_{sat} to soil physical and chemical properties resulted in bulk density and porosity emerging as the most sensitive factors. At the same time, nutrients such as Boron (B), Magnesium (Mg), and Calcium (Ca) exhibited notable impacts. Also, this study identified a strong negative correlation between Boron concentration and K_{sat}, with elasticity analysis highlighting Boron as the most sensitive nutrient affecting K_{sat}. The study was conducted in a humid subtropical climate with Wockley fine sandy loam soil, providing insights into the performance of organic amendments under conditions prone to leaching and nutrient loss. The results underline the importance of application rates and amendment types in enhancing soil properties, specifically for sandy loam soils, which are underrepresented in the current literature. Toková et al. [48] investigated biochar application in silty loam soils, but their findings are less applicable to sandy soils where water and nutrient dynamics differ significantly.

4. Conclusions

This study demonstrates how organic amendments, including varying manure types (chicken and dairy manure), rates (recommended and double-recommended), and biochar levels, significantly influence soil physical and hydrological properties, as confirmed by ANOVA results. The analysis revealed that manure rate and biochar level were the most influential factors, with double-recommended manure rates and higher biochar levels consistently reducing bulk density, increasing porosity, and enhancing hydraulic conductivity. Sensitivity analysis highlighted that bulk density and porosity were the most sensitive parameters influencing K_{sat}, while correlation analysis identified a strong Pearson correlation between bulk density and K_{sat}. Among soil nutrients, Boron showed the highest correlation with K_{sat}, followed by Calcium, Magnesium, and Zinc, emphasizing the role of both physical and chemical properties in determining soil hydrologic properties. The novelty of this research lies in the integration of ANOVA and sensitivity analysis to quantify and prioritize the effects of multiple climate-smart-based amendments on soil health. These findings demonstrate the complex interplay between soil physical and chemical characteristics, highlighting the importance of soil management strategies. By integrating statistical and mechanistic approaches, this study offers actionable insights into improving soil hydraulic conductivity through climate-smart agricultural practices, such as optimizing organic amendment rates and managing nutrient levels. Future research should focus on validating these findings under diverse soil types and climatic conditions and exploring long-term amendment effects on soil physical and chemical properties. Incorporating modeling approaches to predict the cumulative impacts of soil amendments on hydraulic conductivity under varying environmental scenarios can further enhance the practical applicability of these results. This study lays the background for developing integrated soil management strategies that promote climate-smart practices by improving water infiltration and crop productivity.

Author Contributions: Conceptualization, R.A. and A.F.; methodology, A.V.V., A.R., N.D.M., R.A. and A.F.; software, A.V.V.; validation, A.V.V.; formal analysis, A.V.V. and A.R.; investigation, A.V.V., A.R., R.A., A.F., N.D.M., B.T., A.E. and S.W.; resources, R.A. and A.F.; data curation, A.V.V., A.R. and R.A.; writing—original draft preparation, A.V.V.; writing—review and editing, A.V.V., A.R., R.A. and A.F.; visualization, A.V.V. and R.A.; supervision, R.A. and A.F.; project administration, R.A. and A.F.; funding acquisition, R.A. and A.F. All authors have read and agreed to the published version of the manuscript.

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