

## Article

# Effects of Char and Amendments on Soil Properties and Sugar Beet Yield in Sandy Clay Loam Soil

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## Abstract

Carbon-rich products such as biochar and coal char have emerged as promising soil amendments to improve soil properties and support plant growth in semiarid climates. Coal char is produced from the pyrolysis of coal, while biochar is a biomass-derived product from pyrolysis. A two-year field study was conducted to evaluate the comparative impacts of coal char, biochar, inorganic fertilizer, and manure amendments on soil properties, plant growth indices, and soil and plant nutrient dynamics in a semiarid, sandy clay loam soil in Wyoming, USA. The study demonstrates the value of multivariate approaches for capturing the complex, interactive effects of amendments and plant covariates on crop performance. Results show that, while char and amendment treatments did not significantly alter soil pH, EC, or CEC, both char type and fertilizer amendments significantly affected soil nutrient availability and plant tissue nutrient concentrations. Multivariate multiple linear regression (MMLR) showed coal char at 22–44 Mg ha<sup>-1</sup> increased yield by up to 4.4 t ha<sup>-1</sup>, with higher Normalized Difference Red Edge (NDRE) and leaf sulfur (S) concentrations associated with reduced sugar loss to molasses. Our results suggest that coal char has potential as a sustainable amendment for improving sugar beet productivity in semiarid, sandy clay loam soils, especially when integrated with inorganic fertilizer and manure. Further research is needed to assess the variability of coal char and biochar and their cumulative impacts on soil health and productivity across different cropping systems.

**Keywords:** soil amendment; soil carbon; coal char; biochar; sustainable agriculture



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## 1. Introduction

Soil degradation, declining water availability, and the need for sustainable crop production in semiarid regions have amplified interest in soil amendments that can improve soil physical properties, enhance water retention, and support plant growth. Among such amendments, biochar has been extensively studied for its ability to improve soil structure, nutrient availability, and water-holding capacity, particularly in light-textured or degraded soils [1,2]. However, emerging alternatives such as coal char, a carbon-rich product produced from the pyrolysis of coal, are gaining attention as potentially valuable and sustainable soil amendments [3–6]. Like biochar, coal char is an alkaline-high carbon-containing material with a low bulk density, high surface area, and high porosity. Sugar beet, a shallow-rooted root crop with high water and nutrient demand, is particularly

sensitive to soil physical constraints such as compaction and low water availability [7]. Improvements in soil aeration and water-holding capacity are crucial for its productivity, especially in sandy clay loam soils that are prone to rapid moisture loss. Studies on biochar application in sugar beet systems have shown increases in root yield, water use efficiency, and soil organic matter content [8,9]. Previous studies report that biochar application increases soil organic matter, soil fertility, soil water holding capacity, and soil porosity, while decreasing soil bulk density [10–13]. These impacts on soil properties have been reflected in crop yield enhancements and plant growth in biochar amended soils [2,14,15]. Applying biochar as a soil amendment increases soil moisture, alters soil pH and cation exchange capacity, increases plant available nutrient forms, and enhances crop yield [16,17]. A recent meta-analysis indicated that biochar co-application with inorganic fertilizer increased crop yield by 48% compared with inorganic fertilizer only [16,18]. Previous study [19] reported that, in a sandy loam soil, sugar beet yield was significantly lower when biochar was used as a soil amendment applied at concentrations between 2.5 and 10% (*v/v*) compared to fertilizer-only treatments. However, there was an increase in sugar beet root and leaf yield ( $\text{g plant}^{-1}$ , >2 times compared to the control) and also increased sugar content (2.4 times) when biochar and manure were co-applied (2 and 5% *w/w*, respectively) in a loamy sand regosol [20]. A greenhouse pot study on biochar application (0, 0.5, 1, 2% *w/w*) reported the greatest increase in shoot-dry biomass at 2% biochar concentration [21].

Unlike biochar, very few studies can be found on using coal char as a soil amendment. A study in a low-quality loamy sand range soil for two consecutive years in 2018 and 2019 documented that coal char applied in the field at a rate of 10% (*v/v*) produced greater dry grass biomass yield by 12–26% compared to the control [22]. A similar study [23] reported that coal char treatment (22.3  $\text{Mg ha}^{-1}$  to 133.8  $\text{Mg ha}^{-1}$ ) did not result in significant changes in sugar beet root yield. However, coal char rates greater than 22.3  $\text{Mg ha}^{-1}$  increased the maize yield compared to the no coal char added control. Another study [24] reported that there was an effect of coal char obtained from coal combustion residue on some soil chemical properties, such as increased mean values for soil C, Mg, and Na concentrations, as well as an increased mean value of cation exchange capacity (CEC).

Semiarid landscapes are characterized by low annual average precipitation, resulting in low primary productivity and soils with low soil organic carbon (SOC) content [25,26]. The concentration of carbon is considered to be an important indicator in predicting soil health and productivity, as it affects various physical, chemical, and biotic processes and properties throughout the soil profile [24,27]. The application of char materials and increase in soil moisture have been considered effective techniques shown to be applicable in semiarid regions to increase soil carbon [26].

While biochar has been used for decades to improve soil properties, plant growth, and crop yield in different soils, coal char has not yet been extensively evaluated as a potential soil amendment in sugar beet production. Additionally, uncertainties remain regarding its optimal application rates, soil carbon dynamics, and long-term impacts on soil health. This creates a significant knowledge gap in evaluating coal char's suitability for sustainable sugar beet cultivation. Hence, the objective of this study was to determine the effects of pyrolyzed coal on soil properties and sugar beet yield in semiarid, sandy clay loam soil. Additionally, this study also examined and compared beet yield results obtained from soils amended with coal char and biochar.

## 2. Materials and Methods

### 2.1. Study Area

The research was conducted at the University of Wyoming's Powell Research and Extension Center (PREC) in northwest Wyoming, USA (44° 45' 13.8276" N 108° 45' 26.4708" W), about 60 miles east from the Yellowstone National Park. The approximate annual average precipitation of the study site in 2021 was 166 mm and in 2022 was 158 mm, and the 20 year (2002–2022) average annual precipitation was 156 mm. The mean annual average temperature in 2021 was 9.31 °C and in 2022 was 7.53 °C. The elevation of the study area was 4374 ft. (1333 m) from sea level [28]. Weather data were downloaded from the PREC weather resources website. The study area's soil is a well-drained, Garland clay loam, and is classified as a Typic Haplargid (Soil Web, USDA-NRCS). The field was planted to dry beans before the sugar beet study. Before coal char and biochar application, the following chemical properties of the soil were found from laboratory analysis (Table 1).

**Table 1.** Selected initial soil properties of the study site before treatment application.

Soil Chemical Properties	Test Results
pH	8.2
EC (mmhos cm <sup>-1</sup> )	1.2
CEC cmol(+) kg <sup>-1</sup>	22.3
OM (%)	1.95
NH <sub>4</sub> -N mg kg <sup>-1</sup>	3.4
NO <sub>3</sub> -N mg kg <sup>-1</sup>	10
P mg kg <sup>-1</sup>	12
K mg kg <sup>-1</sup>	187
Ca cmol(+) kg <sup>-1</sup>	157
Soil texture (USDA, NRCS soil textural triangle)	Sandy clay loam
Sand (%)	53
Silt (%)	21
Clay (%)	26

### 2.2. Experimental Design

The study design was a complete randomized block design with 15 treatments, each replicated three times, resulting in 45 plots. Each plot measured 6.10 m × 3.35 m, covering an area of 20.44 m<sup>2</sup>, resulting in a total study area of 919.56 m<sup>2</sup>. The main factors were char application rate and fertilizer/manure addition. In 2021, coal char and biochar were applied at the rate of 22 Mg h<sup>-1</sup> (CC22 and BC22, respectively) and 44 Mg h<sup>-1</sup> (CC44 and BC44, respectively) in the respective plots. Manure was incorporated at 66 Mg ha<sup>-1</sup> in the treatments with manure in 2021. In the fertilizer treatments, N and P fertilizers were applied at rates of 168.13 kg N h<sup>-1</sup> and 112.09 kg P h<sup>-1</sup> in 2021, and 100.88 kg N h<sup>-1</sup> and 78.46 kg P h<sup>-1</sup> in 2022. Additionally, 112.10 kg N h<sup>-1</sup> was side dressed in both years at V8.6 leaf stage in all treatments to ensure N was not limiting sugar beet growth and yield. The study field was irrigated with lateral sprinkles.

### 2.3. Char and Manure Application

Atlas Carbon LLC (Gillette, WY, USA) produced coal char for this study by pyrolyzing (up to 850 °C) sub-bituminous coal of the Powder River Basin (PRB). During the pyrolysis, coal and natural gas were fed to Atlas Carbon's calcine reactor (pyrolizer), and the pyrolysis temperature was maintained between 800 and 850 °C at atmospheric pressure. The coal char produced from this process was then sent to a solid cooler and later placed in 1000 lbs. super sacks to transport to the agricultural experiment field. Biochar for this study was

obtained from Genesis BioChar, Somers, MT, USA, which was produced from the pyrolysis of forest biomass residues made up of a mix of woodchips (processing lumber waste) and tree bark. During the biochar production process, tree bark and chips were pyrolyzed in a wood-burning power plant at about 800 °C input. The manure for the study was obtained from a local ranch cattle feedlot. Chemical properties of coal char, biochar, and manure were analyzed using the methods followed in previous study [22].

Soil amendment materials (coal char, biochar, and manure) were spread with the help of a tractor (John Deere, 7810, Waterloo, IA, USA) equipped with a front end loader. All materials were incorporated into the soil with a vertical tiller to a depth of about 15 cm immediately after spreading in the field (to prevent wind blowing of material) in late March of 2021. Coal char, biochar, and manure were applied only in 2021. Sugar beet (Beta 336n) was chosen for this study and was planted at 51,000 seeds acre<sup>-1</sup> by the planter (John Deere, 7300 Planter, Moline, IL, USA) in early April of the cropping years. The field was irrigated with the lateral sprinkler weekly, and the total estimated irrigated water in each growing season was recorded to be approximately 584 mm.

#### 2.4. Soil Sampling

Soil samples were collected from each plot from the surface to a depth of 15 cm, the coal char and biochar incorporated soil depth level, with the help of a JMC Backsaver N-2 Handle and JMC 3 cm in diameter metal core sampler (JMC Soil Samplers, Newton, IA, USA). This technique was adapted from [29]. The four sampling points for all plots were made close to the center of the plots, and one point was at the approximate center of the plot, making five replicate soil samples from each plot. All five soil samples from a plot were kept in a plastic zip lock/sealed bag and mixed properly to homogenize the soil for laboratory analysis. Soil particle size was determined by the hydrometer protocol [30], and soil textural class was established by using the USDA textural triangle. Soil chemical analysis of the samples was performed by the Soil, Water, and Plant Testing Laboratory of Colorado State University, Fort Collins, CO, USA, using standard laboratory procedures [22].

#### 2.5. Plant Growth Indices Measurement and Leaf Sampling

Plant growth variables were measured in the middle of the sugar beet growing season (mid-July). Normalized Difference Red Edge Index (NDRE) data were taken by recording canopy reflectance at a distance of 1 m above the canopy with a handheld sensor Rapid SCAN CS-45 (Holland Scientific, Lincoln, NE, USA). Among the six rows in each plot, two middle rows (third and fourth rows) were chosen for NDRE sampling to minimize the border effect. Canopy greenness and health were evaluated by this sensor with its default vegetation indices: NDRE as shown in Equation (1) [31]. Leaf Area Index (LAI) measurement was performed with the help of an LAI-2200C plant canopy analyzer (Li-COR Bioscience, Lincoln, NE, USA) with four random below-canopy observations and one above-canopy observation recorded from each plot prior to LAI being calculated by the device.

$$NDRE = \frac{NIR - REDGE}{NIR + REDGE} \quad (1)$$

where Red is ~680 nm and RedEdge is ~720 nm.

To obtain leaf tissue samples for the determination of nutrient content, the uppermost fully developed (the youngest fully developed) [32] sugar beet leaves from each plot were taken randomly on the same day of NDRE and LAI measurement [33]. Leaves were cut, placed directly into paper bags, and taken to the laboratory where samples were oven dried at 65 °C ± 5 °C for 72 hrs. Dried leaves were ground to a fine powder. The plant powder samples were sent to Midwest Laboratories (Omaha, NE, USA) for elemental analysis.

### 2.6. Beet Root Harvesting

Sugar beet roots were harvested six months after sowing by using a beet digger in early September 2021. The central two rows (third and fourth rows) from the six rows of a treatment plot were harvested to avoid border effect. The total mass of beets from each plot was recorded, and six to eight beets were collected and bagged in sample bags to determine sugar concentrations in the lab. Sugar content of beets was determined in the lab of the local sugar beet company (Wyoming Sugar Company, Worland, WY, USA).

### 2.7. Statistical Analyses

Data were initially examined for normality and outliers using descriptive statistics and graphical approaches. Multivariate normality was assessed using Mardia's tests (implemented in the MVN package in R) for groups of dependent variables. In cases where the normality assumptions were not met, dependent variables were transformed using rank transformation before further analysis.

To assess the overall effects of experimental factors (i.e., char treatment, fertilizer amendment, and their interaction) on groups of related response variables, we performed multivariate analysis of variance (MANOVA). Separate MANOVA models were constructed for different sets of response variables, including soil properties (e.g., Soil\_pH, Soil\_EC, Soil\_CEC, Soil\_OM), soil nutrients (e.g., NO<sub>3</sub>-N, P, K), vegetation indices (e.g., LAI and NDRE), and plant chemical constituents (N, P, K, Ca, S). For each MANOVA, Pillai's Trace was used as the multivariate test statistic to assess collective significance of treatment effects on dependent variables. The significance of main effects and interactions was determined by comparing the approximate F-values and corresponding *p*-values from the MANOVA output. When the overall multivariate effect was significant, follow-up univariate ANOVAs were performed on each dependent variable to identify specific responses contributing to the overall effect.

In addition to MANOVA, a multivariate multiple linear regression model (MMLR) was employed to predict sugar beet yield and quality parameters (yield, sugar content, and SLM) using the predictor variables (char treatment and fertilizer amendment) along with co-variables with significant *p*-values from MANOVA. Model performance was evaluated by examining coefficient estimates, standard errors, and associated *p*-values, as well as by assessing the overall model fit via adjusted *R*-squared values. The predictive performance of multivariate model predicted values were derived, and the root mean square error (RMSE) was computed for each response.

## 3. Results

### 3.1. Characteristics of Coal Char, Biochar, and Manure Used in the Study

Soil amendment materials coal char, biochar, and manure are highly alkaline, with pH ranging from 9.3 to 9.6, and rich in organic carbon, ranging from 25.5 to 78.9% as shown in Table 2. Total nitrogen in coal char and biochar exhibited very low concentrations, 0.9 and 0.5%, compared to manure (1.9%) used in this study. Phosphorous and potassium are also significantly lower in coal char and biochar than in manure (Table 3).

**Table 2.** Selected chemical properties of coal char, biochar, and manure used in the study.

Parameter	Coal Char	Biochar	Manure
Dry Matter—Total Solids, %	95.5	98.5	77.4
Moisture, %	4.4	1.5	22.5
Soluble Salts, mmhos cm <sup>-1</sup>	7.5	0.1	27.3
pH 1:5	9.6	9.3	9
Organic Nitrogen, %	0.9	0.5	1.8
Ammonium, %	0.001	<0.001	0.002
Nitrate, %	<0.001	<0.001	0.005
Total Nitrogen, %	0.9	0.5	1.9
Phosphorus as P <sub>2</sub> O <sub>5</sub> , %	0.2	0.3	1.6
Potassium as K <sub>2</sub> O, %	0.05	0.1	1.6
Organic C (%)	78.9	53.2	25.5

**Table 3.** Summary of MANOVA and univariate ANOVA results. \* denotes multivariate *p*-values are significant at  $\alpha = 0.05$ .

Analysis Group	Factor	Multivariate Results (Pillai/ <i>p</i> -Values)	Univariate ANOVA Results ( <i>p</i> -Values)
Soil Properties (Soil_pH, Soil_EC, Soil_CEC, Soil_OM)	Char Treatment	0.21849/0.37	NS
	Fertilizer Amendment	0.12675/0.28	NS
	Treatment × Amendment	0.18413/0.99	NS
Soil Nutrient (NO <sub>3</sub> -N, P, K, Ca, Mg)	Char Treatment	0.375/0.03	NO <sub>3</sub> N: 0.56 P: 0.94 K: 0.24 Ca: 0.66 Mg: 0.90
	Fertilizer Amendment	0.637/<0.001	NO <sub>3</sub> N: <0.001 P: 0.006 K: <0.001 Ca: 0.02 Mg: 0.21
	Treatment × Amendment	0.18413/0.99	NS
Vegetation Indices (LAI, NDRE)	Char Treatment	0.13436/0.22	NS
	Fertilizer Amendment	0.17319/0.008 *	LAI: 0.3951 NDRE: 0.01015 *
	Treatment × Amendment	0.09856/0.95	NS
Plant Chemical Constituents (N, P, K, Ca, Mg, S, Na, Fe, Mn, B)	Char Treatment	0.52813/0.39	NS
	Fertilizer Amendment	0.52950/0.00157 *	Leaf_N_R: 0.2309 Leaf_P_R: 0.05 * Leaf_K_R: 0.78 Leaf_Ca_R: 0.78 Leaf_Mg_R: 0.53 Leaf_S_R: 0.002 * Leaf_Na_R: 0.84 Leaf_Fe_R: 0.81 Leaf_Mn_R: 0.99 Leaf_B_R: 0.069
	Treatment × Amendment	0.95946/0.4953	NS

### 3.2. Impact of Char Treatment and Fertilizer Amendment on Soil Properties

To assess the changes in soil properties due to char and fertilizer, multivariate analysis of char treatment and fertilizer amendment on soil chemical properties was carried out. The MANOVA showed no significant effects for char treatment (Pillai's Trace = 0.2185,

$p = 0.3702$ ), fertilizer amendment (Pillai's Trace = 0.1268,  $p = 0.2828$ ), or their interaction (Pillai's Trace = 0.1841,  $p = 0.9958$ ).

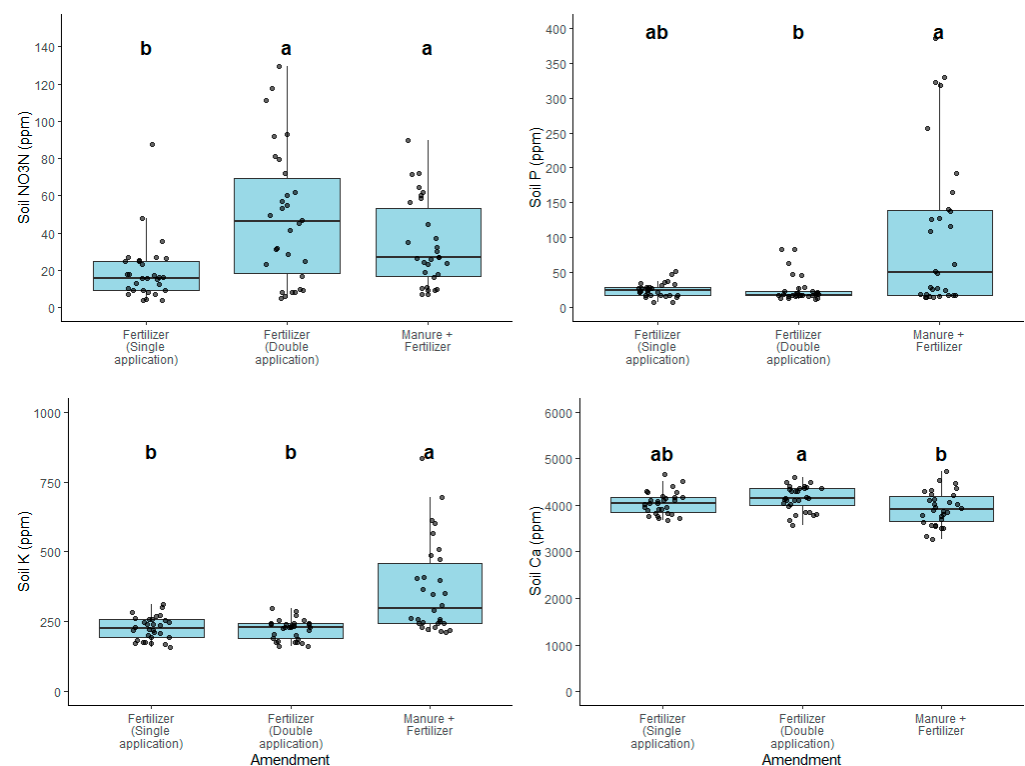
### 3.3. Impact of Char Treatment and Fertilizer Amendment on Soil Nutrients

MANOVA results showed char treatment (Pillai's Trace = 0.376,  $p = 0.032$ ) and fertilizer amendment (Pillai's Trace = 0.637,  $p < 0.001$ ) significantly influenced soil nutrient content. Further univariate analyses showed that amendment had significant influence on  $\text{NO}_3\text{-N}$ , P, K, and Ca. Highest  $\text{NO}_3\text{-N}$  ( $48 \text{ mg kg}^{-1}$ ) and Ca ( $4146 \text{ mg kg}^{-1}$ ) were observed in plots with double application of fertilizer. P ( $105 \text{ mg kg}^{-1}$ ) and K ( $366 \text{ mg kg}^{-1}$ ) were highest in the plots applied with manure + fertilizer. Although char treatment and fertilizer amendment had a significant effect on collective soil nutrients, it was not significant for individual nutrient variables.

### 3.4. Impact of Char Treatment and Fertilizer Amendment on Vegetation Indices

The overall multivariate test showed the fertilizer amendment effect was statistically significant (Pillai's Trace = 0.173,  $p = 0.008$ ), as shown in Table 3.

Neither char treatment (Pillai's Trace = 0.1344,  $p = 0.2231$ ) nor their interaction (Pillai's Trace = 0.0986,  $p = 0.9510$ ) had significant influence on vegetation indices. Univariate follow-up ANOVAs indicated that the significant multivariate effect of fertilizer amendment was due to NDRE. For the NDRE index, the effect of fertilizer amendment was significant ( $p = 0.01$ ), whereas no significant effect was observed for LAI ( $p = 0.39$ ). Post hoc testing for NDRE showed that the double application of fertilizer increased mean NDRE (0.3), while control plots (0.28) or plots with manure application (0.28) did not differ significantly from each other, as shown in Figure 1.



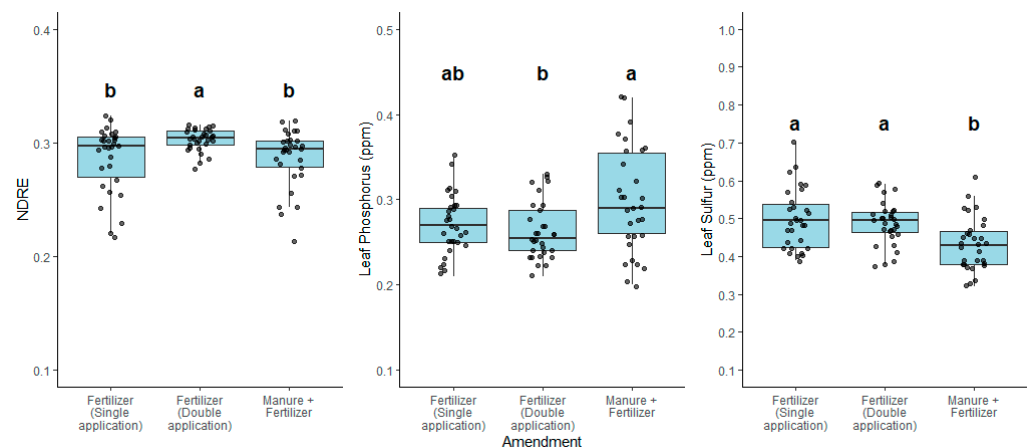
**Figure 1.** Post hoc test result for soil  $\text{NO}_3\text{-N}$ , P, K, and Ca content variation among different fertilizer amendments. Different letters above box plots indicate a significant difference between the fertilizer amendment at  $\alpha = 0.05$ .

### 3.5. Impact of Char Treatment and Fertilizer Amendment on Plant Nutrients

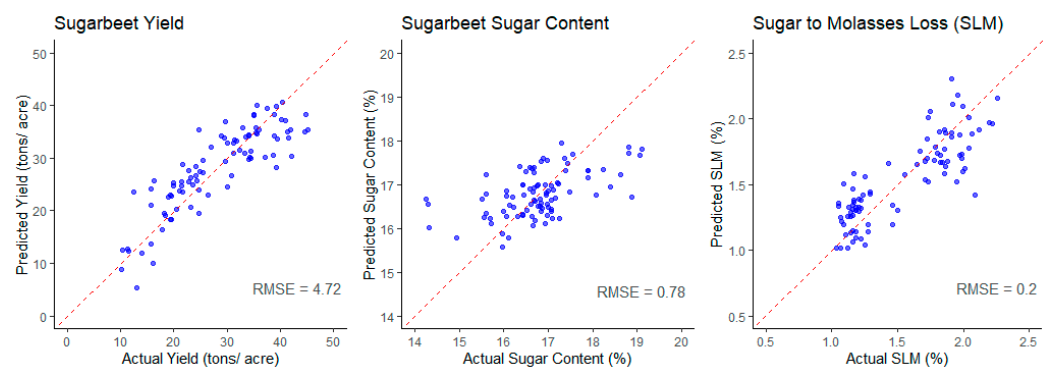
A multivariate analysis of variance was performed to examine the effects of char treatment and fertilizer amendment on leaf chemical constituents, including leaf N, P, K, Ca, Mg, S, Na, Fe, Mn, and B. The overall MANOVA indicated that, while the main effect of char treatment was not statistically significant (Pillai's Trace = 0.478,  $p = 0.40$ ), fertilizer amendment had a significant multivariate effect on the leaf chemical constituents, as shown in Table 3 (Pillai's Trace = 0.498,  $p < 0.001$ ).

Follow-up univariate analyses showed that the significant multivariate effect was primarily driven by leaf phosphorus and sulfur content. For leaf P, the univariate ANOVA indicated a significant effect of fertilizer amendment ( $p = 0.04$ ), with no significant effect of char treatment ( $p = 0.7495$ ). Similarly, for leaf sulfur, fertilizer amendment significantly influenced its concentration ( $p = 0.00120$ ), whereas char treatment did not ( $p = 0.6439$ ). The remaining nutrient parameters (leaf N, K, Ca, Mg, Na, Fe, Mn, and B) showed no significant responses to either factor.

The post hoc test for leaf P showed that plants with manure as an amendment (mean =  $0.3 \text{ mg kg}^{-1}$ ) had significantly higher leaf P than those with the fertilizer as an amendment (mean =  $0.26 \text{ mg kg}^{-1}$ ), while plants without any amendment (mean =  $0.27 \text{ mg kg}^{-1}$ ) were intermediate. For leaf S, post hoc comparisons indicated that plants with a single or double fertilizer application exhibited significantly higher leaf S ( $0.49 \text{ mg kg}^{-1}$ ) compared to the plants with manure as the amendment (mean =  $0.43 \text{ mg kg}^{-1}$ ), as shown in Figures 2 and 3, respectively.



**Figure 2.** Post hoc test result for Normalized Difference Red Edge (NDRE), leaf phosphorus, and leaf sulfur content variation among the fertilizer amendments. Different letters above box plots indicate a significant difference between the fertilizer amendment at  $\alpha = 0.05$ .



**Figure 3.** Scatter plots of model-predicted versus observed values for three key response variables: sugar beet yield, sugar content, and sugar-to-molasses loss (SLM).

### 3.6. Impact of Char Treatment and Amendment on Yield and Quality of Sugar Beet

For the yield model, the results indicated that NDRE was the strongest predictor ( $\beta = 294$ ,  $p < 0.01$ ). These results are shown in Table 4. Compared to the control char treatment, CC22 increased yield by 4.4 ( $\beta = 4.4$ ,  $p = 0.02$ ) and CC44 increased yield by 4.3 ( $\beta = 4.3$ ,  $p = 0.02$ ).

**Table 4.** Coefficient estimates,  $p$ -values, and adjusted  $R^2$  for the multiple multivariate regression model predicting sugar beet root yield, sugar content, and sugar-to-molasses loss (SLM). Bold numbers indicate the coefficients are significant at  $\alpha = 0.05$ .

Predictor	Yield		Sugar Content		SLM	
	Estimate $\pm$ SE	$p$ -Values	Estimate $\pm$ SE	$p$ -Values	Estimate $\pm$ SE	$p$ -Values
(Intercept)	$-99.3 \pm 14.78$	<0.001	$23.7 \pm 2.54$	<0.001	$5.7 \pm 0.67$	<0.001
Treatment CC22	<b><math>4.7 \pm 1.75</math></b>	<b>0.019</b>	<b><math>-0.7 \pm 0.3</math></b>	<b>0.028</b>	$-0.1 \pm 0.08$	0.076
Treatment CC44	<b><math>4.1 \pm 1.7</math></b>	<b>0.018</b>	$-0.4 \pm 0.29$	0.15	<b><math>-0.2 \pm 0.08</math></b>	<b>0.012</b>
Treatment BC22	$1.4 \pm 1.71$	0.399	$0 \pm 0.29$	0.913	$-0.1 \pm 0.08$	0.506
Treatment BC44	$2.5 \pm 1.68$	0.138	$-0.2 \pm 0.29$	0.471	$0.01 \pm 0.08$	0.813
Amendment Double Fertilizer	<b><math>-3.7 \pm 1.54</math></b>	<b>0.015</b>	<b><math>0.55 \pm 0.26</math></b>	<b>0.043</b>	$0.004 \pm 0.07$	0.95
Amendment Fertilizer + Manure	$2.9 \pm 1.53$	0.054	$-0.04 \pm 0.26$	0.885	$-0.1 \pm 0.07$	0.095
Soil NO <sub>3</sub> -N	$0.023 \pm 0.02$	0.345	$-0.006 \pm 0.004$	0.146	$0.002 \pm 0.001$	0.107
Soil P	$-0.004 \pm 0.02$	0.862	$0.002 \pm 0.004$	0.591	$0.000005 \pm 0.001$	0.953
Soil K	$-0.007 \pm 0.01$	0.561	$-0.003 \pm 0.002$	0.178	$0.00003 \pm 0.001$	0.951
Soil Ca	<b><math>0.008 \pm 0</math></b>	<b>0.005</b>	$-0.001 \pm 0.0005$	0.07	<b><math>0.0005 \pm 0.0001</math></b>	<b>&lt;0.001</b>
NDRE	<b><math>294 \pm 32.06</math></b>	<b>&lt;0.001</b>	$-10.3 \pm 5.31$	0.056	<b><math>-6.3 \pm 1.4</math></b>	<b>&lt;0.001</b>
Leaf_P	$13.5 \pm 15.88$	0.399	$-2.6 \pm 2.73$	0.342	$0.5 \pm 0.72$	0.453
Leaf_S	$9.8 \pm 9.06$	0.281	$2.3 \pm 1.56$	0.092	<b><math>-1.2 \pm 0.41</math></b>	<b>0.002</b>
Adjusted R <sup>2</sup>	0.69		0.18		0.65	

The model explained 69% of the variance in sugar beet yield. For the sugar content, fertilizer application increased sugar content of the sugar beet ( $\beta = 0.5$ ,  $p = 0.04$ ). Char treatments CC22 contribute to reduced sugar by 0.7 ( $\beta = -0.7$ ,  $p = 0.03$ ). The overall model explained 18% of variability.

In the case of SLM, char treatments CC22 reduced loss by 0.2 ( $\beta = -0.2$ ,  $p = 0.02$ ). Higher NDRE and leaf S content reduced sugar loss to molasses by 6.2 ( $\beta = -6.2$ ,  $p < 0.001$ ) and 1.28 ( $\beta = 1.82$ ,  $p = 0.0163$ ), respectively. The model explained 26% of the variance in SLM. The RMSE values were 4.72 for yield, 0.78 for sugar content, and 0.20 for SLM (Figure 3).

## 4. Discussions

### 4.1. Impact of Char Treatment and Amendment on Soil and Plant Covariates

This study on sandy clay loam soil did not find significant effects of char treatment or fertilizer amendment on soil properties. Biochar and coal char influence soil properties partly by modifying the soil's surface area [3]. Typically, soil surface area ranges from  $1 \times 10^3 \text{ m}^2 \text{ kg}^{-1}$  in sandy soils to  $8 \times 10^3 \text{ m}^2 \text{ kg}^{-1}$  in soils with high clay and organic matter content [34]. Pyrolyzed coal or coal char from Powder River Basin coal in Wyoming reported the specific surface area of char as  $2.62 \times 10^3 \text{ m}^2 \text{ kg}^{-1}$ , suggesting that soils with already higher surface area may be less affected by the additional char application.

Although char application has been associated with increases in soil organic matter, electrical conductivity, and cation exchange capacity in sandy loam soil, our findings suggest that these effects were less pronounced in our sandy clay loam soil [22]. The higher baseline concentrations of OM and CEC could have diluted the impact of the char treatment. OM in coal char and biochar treatments was found greater than the control, which was the expected result as soil organic carbon is directly added in the soil. However, most of the organic carbon in the char materials is recalcitrant carbon, which is non-decomposable by soil microorganisms but helps on improving soil physical properties like decrease in soil bulk density and increase in soil porosity. High pyrolysis temperature increases the aromatic condensation degree of biochar that has a greater ability to resist oxidation, resulting in greater stability in the soil [35]. While char treatments and fertilizer amendment did not significantly alter most soil properties, the combination of inorganic fertilizer and manure increased soil N, P, and K. These increments align with previous findings on the benefits of organic and inorganic fertilizer on soil [4,36,37]. These changes in soil nutrient availability were further correlated to the better vegetative growth of sugar beets, as shown by higher NDRE values and elevated P and S concentrations in sugar beet leaves.

### 4.2. Impact of Char Treatment and Amendment on Sugar Beet Yield and Quality

One of the primary aims of char application in soil is to reduce leaching and enhance nutrient retention in soil [3,38]. We hypothesized that fertilizer amendment would supply essential nutrients to plants, while char treatment would retain the nutrients throughout the sugar beet growing season. To assess this, we included selected predictor covariates such as soil nutrient constituents and vegetation parameters in our analysis to measure the direct and indirect effects of char treatment and fertilizer amendment on sugar beet yield and quality.

Our results show that the application of coal char could contribute to sugar beet yield due to sorption of  $\text{NO}_3^-$  on coal char [38]. Biochar's effects in yield were less pronounced in this study, possibly due to preparation conditions, which have been recorded to influence biochar efficacy [39,40]. Additionally, the higher total N and organic C content in coal char compared to the biochar used in the study may explain biochar's low impact on sugar beet yield and quality in this study. Fertilizer amendment did not significantly influence overall yield or quality, with the exceptions of a negative impact of double fertilizer application on yield, and a positive effect on sugar content. These observations are consistent with previous studies indicating that excess nitrogen, particularly after the early vegetative stage, can increase vegetative biomass at the expense of root yield [41]. While earlier studies found that excessive fertilizer application can degrade sugar quality [42], our study found an increased sugar content due to reduced yield when applied with double-fertilizer, potentially due to the higher root water content associated with lower yield [43].

Overall, higher soil calcium (Ca) levels and NDRE index values were positively associated with sugar beet yield, suggesting an indirect benefit of fertilizer amendment such as manure and fertilizer on sugar beet yield. Higher NDRE and leaf S concentration were

linked to lower sugar-to-molasses loss in our study. Prior work has indicated that sulfur concentrations below 0.3% in leaves can substantially limit sugar beet productivity [44]. Given that coal char can be rich in sulfur, its use may have contributed to the reduction in SLM losses observed in our study.

Overall, we demonstrated the multivariate influences of char treatments and fertilizer amendments on sugar beet yield and quality in this study. While certain factors, such as increased vegetative indices from fertilizer applications, may indirectly contribute towards sugar beet yield, others, like double fertilizer applications, can have direct negative effects. The stronger positive coefficient of the NDRE index compared to that of double fertilizer suggests that moderate fertilizer applications—rather than excessive ones—can enhance yield without compromising quality [41,42,45]. Nitrogen application significantly enhanced root yield, but showed a negative and non-significant effect on sugar content, indicating that the optimal nitrogen rate must be adjusted according to local climate, soil properties, and management practices [46]. Therefore, optimal sugar beet quality and yield can be achieved with proper fertilizer management while coal char and biochar application as soil amendments could provide long term soil health benefits.

## 5. Conclusions

This study evaluated the comparative impacts of coal char, biochar, inorganic fertilizer, and manure amendments on soil properties, nutrient dynamics, and plant growth indices in relation to sugar beet yield and quality in a semiarid, sandy clay loam soil. Our findings suggest that coal char treatments, when applied at 22 and 44 Mg ha<sup>-1</sup>, can contribute to yield increase in sugar beets. Fertilizer amendment—especially the double application of inorganic fertilizer and combination with manure—improved soil and plant nutrient concentration as well as enhanced vegetation health. Given the complex interactive nature of coal char and biochar along with fertilizer and manure applications, the multivariate analysis method showed that char and fertilizer amendments may not directly contribute towards yield and quality of sugar beets, but instead may indirectly enhance the vegetation health as well as soil and plant nutrient content. Overall, our results indicate that coal char has potential as an alternative soil amendment for enhancing sugar beet productivity in semiarid, sandy clay loam soils, particularly when integrated with appropriate nutrient management. However, amendment responses are context-dependent, and further research is needed to assess the variability of coal char and biochar and their cumulative impacts on soil health and productivity across different cropping systems.

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