Received: 6 October 2023 | Accepted: 11 March 2024

DOI: 10.1002/agg2.20492

Agrosystems, Geosciences & Environment OPEN ACCESS

ORIGINAL ARTICLE

Agrosystems

Applying coal char to cattle pens for sustainable agriculture in the semiarid US High Plains

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Assigned to Associate Editor Lakesh Sharma.

Funding information
Western Sugar Cooperative

Abstract

Applying high carbon (C) additive to cattle pens and land application of the resultant manure mix offers a potential strategy for optimizing manure and soil management while mitigating environmental concerns. An experiment was conducted in western Nebraska from 2019 to 2022 to evaluate the effect of adding coal char (~290 g C kg^{-1} by wt.) on feedlot manure's properties and stability and the interacting effect of manure-char on crop yields in a corn (*Zea mays* L.)–dry bean (*Phaseolus vulgaris* L.)–corn rotation. Treatments in the crop field included manure from pens with or without char (each at 34 and 68 Mg ha^{-1}; low and high rate), urea at 100% recommended nitrogen (N) rate with or without 45 Mg char ha^{-1}, and a control. Applying char to pens kept them drier following snowfall events. The high surface area and cation exchange capacity of char improved soil and manure nutrient retention. The 100% urea-N plus char treatment had a greater corn yield than the low-rate char–manure mix or high-rate manure in 2020. In 2021, there was a trend for higher bean yields with the high char–manure rate treatment than the control. In 2022, all the fertilized treatments had greater grain yields than the control. A one-time high-rate char–manure mix or manure application could replace 314 kg N ha^{-1} and 90 kg P_2O_5 ha^{-1} over 2 years without any yield penalty. This study underscores the synergy between char and manure or chemical fertilizers to improve nutrient balance and supply, ultimately enhancing crop production.

1 | INTRODUCTION

The semiarid US High Plains region, spanning eight western states, including Nebraska, is renowned for its extensive livestock farming (Hart & Mayda, 1998). This region is known for its beef and dairy cattle production, encompassing cattle ranches and feedlots that generate more than 9.6 million metric tons of manure annually (Cunfer, 2004; Eghball & Power, 1994). Manure provides organic matter, beneficial microorganisms, and essential nutrients such as nitrogen (N), phosphorus (P), and potassium (K) (Eghball & Power, 1994; Maharjan, Das, et al., 2021). However, if not managed appropriately in feedlot operations, manure can lose these nutrients through leaching, runoff, and volatilization, which can contribute to groundwater contamination and eutrophication (Chadwick et al., 2011; Eghball & Power, 1994). In addition, improperly managed manure releases pollutant gases (ammonia, methane, nitrous oxide, etc.) and volatile organic compounds that reduce air quality, contribute to climate change, and increase human health risks

Abbreviations: CEC, cation exchange capacity; SOC, soil organic carbon.

(Chadwick et al., 2011; Leytem et al., 2011; Maurer et al., 2017). Therefore, manure management strategies that help mitigate nutrient loss and ensure efficient utilization of nutrients by crops are essential for maintaining environmental quality and sustainable production.

In addition to providing nutrients, manure acts as a soil amendment to improve degraded soil in water-limited semiarid regions. The semiarid US High Plains have lost 30%–50% of topsoil and associated carbon (C) through erosion since the cultivation began (He et al., 2018; Mikha et al., 2013). Mixing high C-containing additives with manure improves its effectiveness and enhances crop production (Cooper et al., 2022; Mariaselvam et al., 2015). Carbon additives act as a sorbent, helping capture and retain nutrients in the manure, thus reducing the risk of nutrient loss (Cooper et al., 2022; Sperber et al., 2022). The nutrient-rich mixture can then be applied to croplands, enhancing soil fertility and minimizing the need for synthetic fertilizers.

Applying high C-containing amendments like biochar extensively is cost-prohibitive in most cases, thus limiting wider adoption (Cooper et al., 2022). To serve as a convenient and low-cost substitute amendment for sustainability in manure management and crop production, high C products should be readily available within the local area and inexpensive. Coal char (henceforth referred to as char) is a by-product resulting from incomplete coal combustion at a sugar beet processing facility. Char is characterized by unique properties, including a high surface area (82.1 m^2 g^{-1}), cation exchange capacity (CEC; 47 meq 100 g^{-1}), C:N ratio (80:1), pH (7.6), calcium carbonate ($CaCO_3$; 190 g kg^{-1}), and C concentration of 293 g kg^{-1} (Blanco-Canqui et al., 2020; Panday, Mikha, Collins, et al., 2020; Panday, Mikha, Maharjan, et al., 2020). Moreover, it contains essential plant nutrients such as N, P, K, calcium (Ca), magnesium (Mg), sulfur (S), zinc (Zn), and iron (Fe) (Blanco-Canqui et al., 2020).

When mixed with manure in cattle pens, organic by-products from subbituminous coal, such as char, can offer multiple benefits. The porous structure of char provides room to hold more soil water, promote aeration, and create a favorable environment for the growth of beneficial soil microorganisms, contributing to nutrient cycling, thereby leading to enhanced crop productivity (Maharjan, Panday et al., 2021; Panday et al., 2021). Adding C-rich amendments to the manure mixture increases the C:N ratio of feedlot manures and adds to the total dry materials that can be applied to croplands (Mariaselvam et al., 2015). This increases organic C inputs into the soil, stores them in a stable form, contributing to long-term soil organic carbon (SOC) accumulation and climate change mitigation efforts by reducing greenhouse gas emissions (Gross & Glaser, 2021; Harrison et al., 2022; Maurer et al., 2017). Furthermore, incorporating C products into manure management systems helps reduce unpleasant smells by adsorbing and neutralizing volatile compounds responsible for malodors, minimizing the risk of respiratory issues, diseases, and parasite infestations, and promoting livestock health (Gerlach & Schmidt, 2014; Toth & Dou, 2016).

Core Ideas

- Adding char to cattle pens kept them drier with no effect on cattle performance.
- Char increased soil nutrient retention in soil and manure.
- There was an indication of yield benefits of adding char to the 100% N treatment.
- Additional benefits of adding char to cropland include C input to the soil.

Nutrient loss, specifically N, from feedlot manure depends on several factors, including duration of storage. Over time, N compounds undergo transformations, such as nitrification or denitrification, which affect their availability to plants (Robertson & Groffman, 2007). It is estimated that over 50% of the N consumed by livestock is lost through volatilization after excretion before it can be effectively applied to fields (Eghball & Power, 1994; Petersen et al., 1998). However, incorporating organic amendments with a high C:N ratio into manure shifts microbial processes toward N conservation in feedlot manure (Banik et al., 2023; Mariaselvam et al., 2015). Additionally, char might physically retain N through electrostatic adsorption on its exchange sites (Panday, Mikha, Maharjan, et al., 2020). Previous research has demonstrated that applying char at optimal rates in fertilized soils can reduce ammonia volatilization losses in a laboratory setting (Panday, Mikha, Collins, et al., 2020a; Panday, Mikha, Maharjan, et al., 2020). Reducing ammonia losses increases soil available N for crop uptake (Liu et al., 2019).

A comprehensive understanding of the interacting effects of char on the chemical composition and stability of feedlot manure will guide the decision-making process for efficient manure management and enhanced crop production in semiarid environments. The objective of this experiment was to evaluate cattle manure mixed with coal char in pens as a potential nutrient source and soil amendment to improve crop yields. It was hypothesized that incorporating C-rich char into cattle manure would improve nutrient use efficiency, resulting in higher crop yields than the control (without char).

2 | MATERIALS AND METHODS

2.1 | Study site, experimental design, and treatments

The first phase of this experiment involved the cattle pen experiment initiated in the fall of 2019 at the University of Nebraska-Lincoln (UNL) Panhandle Research, Extension, and Education Center (PREEC), Mitchell Agricultural Laboratory cattle pens, located 9 km north of Scottsbluff, NE (41˚53′32″ N, 103˚40′48″ W; elevation 1198 m). In a completely randomized design, cattle pens with an individual size of 40 × 8 m received char at 6 Mg pen^{-1} or no char in five replications each. Char is a by-product of incomplete coal combustion at a sugar beet processing facility in Scottsbluff, NE. Char was spread uniformly within the treated pen using a payloader to a thickness or depth of about 2.5 cm. After the char application, 10 heads of finishing steers were assigned to each pen. Before the steers were housed in the pens, they were limit-fed (2% body weight), a common diet to reduce gut fill and weight variation for 5 days. The steers were then weighed for two consecutive days, and the average weight (i.e., 319 ± 7 kg) was used as the initial body weight for the experiment. Steers were fed a common dry-rolled corn (*Zea mays* L.)-based finishing diet for 218 days. Based on the amount of added char and estimated manure from 10 steers in an allocated period of cattle raising, the resultant char–manure mix from each pen was targeted to be about 1:2. Hydra probe sensors, which measure soil moisture, electrical conductivity, and temperature, were installed at 13-cm depth in both the char-treated and control pens. The sensors were connected to a datalogger to collect high-frequency data during the first half of January 2020 (i.e., after a series of snowstorms in November 2019). The cattle pen experiment was completed in April 2020. Live weights of cattle were recorded at the end of the experiment. After scraping from the char-treated and control pens, subsamples of the piles were analyzed for nutrient contents.

In 2020, the crop field experiment was initiated at UNL PREEC Mitchell Agricultural Laboratory, Scottsbluff, NE. The study area has a semiarid climate with a mean annual precipitation of 394 mm and temperature of 9.8˚C. According to the US soil taxonomy, the soil at the experimental site was classified as Tripp, a very fine sandy loam (*coarse-silty, mixed*, *super active* and *mesic Aridic Haplustolls*). The experiment was laid out in a randomized complete block design with four replications. The main factor was different N treatments, including manure from pens with or without char (each at 34 and 68 Mg ha^{-1}; low and high rate), urea at 100% recommended N rate with or without 45 Mg ha^{-1} of char, and a control (0 N) (Table 1). Each year, the recommended N rate was calculated using the UNL algorithm, which accounts for spring soil test and yield goal (Hergert, 2013; Shapiro et al., 2019). Manure and char–manure mix were obtained from the cattle pens from the first phase of the experiment as described above. Char was brought from the factory, as in the pen experiment. All char, manure, and char–manure mix were uniformly spread using a manure spreader. Subsamples of applied materials were again collected during the field application. The plot was planted with corn in 2020. All treatment strips with no manure also received 67 kg P ha^{-1} based on the spring soil test (Table 1). Each treatment strip was 6.7 m wide and 207 m long.

In 2021, the plot was planted with dry edible beans (*Phaseolus vulgaris* L.). Fertilizer inputs were determined based on the spring soil test and the manure credits in the manured plots (Table 1). Treatments 2 and 3 received 67 kg N ha^{-1} and 23 kg P ha^{-1} each, respectively. Treatments 4 and 6, which had manure in 2020 but at a lower rate, received 23 kg N ha^{-1} each. In 2022, the plot was planted with corn, and all the treatment strips except for the control received 207 kg N ha^{-1}. Management activities, including irrigation and herbicides, were uniform across all treatments.

2.2 | Crop yields

Corn grain yields for each treatment strip were collected from a well-calibrated yield monitor data. Dry bean crops were undercut, followed by swathing, and left to dry in the field before combine harvest. Harvest occurred around the third week of September each year to estimate grain yield. Grain yields obtained for corn and beans were adjusted to 15.5% and 13.0% moisture levels, respectively.

2.3 | Soil sampling and laboratory analysis

In addition to the spring soil test to inform N and P recommendation for crops each year, soils were sampled after dry bean harvest in fall 2021 (September 24, 2021) and in spring 2022 (April 25, 2022) before corn planting to determine potential overwinter nutrient losses. Soil samples were collected using a hydraulic probe (5-cm diameter) and divided into 0- to 20-cm and 20- to 90-cm depths. All soil samples were cleaned of all visible plant materials (roots, stems, and leaves), and crop residues were removed by hand. Soil samples were then sent to a commercial laboratory (Ward Laboratories Inc.) for analysis of various parameters. Samples from the upper 20-cm depth were analyzed for complete nutrient concentrations (Table 2). Subsamples from depth 20–90 cm were analyzed for NO_3^--N.

2.4 | Statistical analysis

An analysis of variance was performed in RStudio using the "aov" function to determine the effects of treatments on crop yields, manure, and soil parameters. The "agricolae" package and "least significant difference test" (LSD) function associated with the "agricolae" package were used to conduct the

TABLE 1 Fertilizer treatments in 2020, 2021, and 2022.

	2020 Corn					2021 Dry bean		2022 Corn
Treatment[a]	Urea-N (kg ha^{-1})	P_2O_5 (kg ha^{-1})	Char (Mg ha^{-1})	Manure (Mg ha^{-1})	Char–manure mix (Mg ha^{-1})	Urea-N (kg ha^{-1})	P_2O_5 (kg ha^{-1})	Urea-N (kg ha^{-1})
1	0	67	0	0	0	0	23	0
2	247	67	0	0	0	67	23	207
3	247	67	45	0	0	67	23	207
4	0	0	0	0	34	23	0	207
5	0	0	0	0	68	0	0	207
6	0	0	0	34	0	23	0	207
7	0	0	0	68	0	0	0	207

[a]Treatments included the control; treatment 1 that received no N in all 3 years. Treatment 2 received 100% N each year based on the University of Nebraska-Lincoln (UNL) algorithm accounting for crop yield goal and spring soil test, treatment 3 received 100% N plus char from the factory in 2020, treatments 4–7 received char–manure mix and manure alone scrapped from the cattle pens in 2020. Treatments 4 and 6 received supplemental N in 2021; treatments 2–7 received 100% N in 2022. Treatments 1–3 received P based on spring soil tests in 2020 and 2021.

LSD test for mean separations when treatment effects were significant at $p < 0.05$. The grain yield data are represented as the mean of four replications ± standard deviation. The normality assumption of residuals was tested using the qqplot.

3 | RESULTS

3.1 | Cattle pen experiment

Two-week data collected in January 2020 using Hydra probe sensors revealed that volumetric water content was lower in char-treated cattle pens relative to the control (without char) (Figure 1). The soil temperature in char-treated pens had slightly higher temperatures in the first few days and lower temperatures in the remaining days than in control pens. There were no significant differences in initial or final body weight, average daily gain, dry matter intake, or gain:food ratio in cattle raised between char-treated and the control treatments (Table 3).

3.2 | Char, manure, and mix

Char applied to the pens in the fall of 2019 and crop field in the spring of 2020 were similar (≤±6%) in their characteristics except for Fe concentration (−30%) and boron (B) (−14%) (Table 2). Manure and char–manure mix, when analyzed right from the pile after scraping from the pens and during field application, were similar in their characteristics (≤±11%) with a few exceptions. Manure tested directly from the pile at pens had higher concentrations of Ca, Mg, Fe, and B by 25%, 14%, 16%, and 50%, respectively. Char–manure mix from the pile had a 67% lower Copper (Cu) concentration than the mix sampled during field application. Irrespective of sampling timing/place, the treatments significantly and similarly differed in chemical characteristics except for pH and cation concentrations. The moisture, organic N, total N, P, and S were in the order manure > mix > char. Among cations, all measured except for Zn were the highest in the char compared to manure or char–manure mix in both cattle pen and field application samples. All cations were similar in manure and char–manure mix treatments in cattle pen samples. The mix treatment had higher cations than manure except for Zn, where the relation was opposite in crop field samples. The pH was lower in the char–manure mix than in char or manure alone in crop field samples.

When the char–manure mix treatments were compared, actual versus intended (char-manure at 1:2), organic and total N, and Zn were higher in the actual mix than in the intended mix by 22%, 23%, and 20%, respectively, in pen samples and by 14%, 16%, and 14% in field samples. In cattle pen samples, P and pH (<1%) were also greater in the actual mix than in the intended mix. In field samples, P was 0.5% less in the actual mix than the intended mix. The rest of the parameters were greater in the intended mix than in the actual mix.

3.3 | Soil tests

The soil P, K, and Zn tests in the upper 20-cm soil depth differed among treatments in both samplings (fall 2021 and spring 2022) (Table 4). Soil P, K, and Zn followed similar trends in both samplings; manure applied at a high rate had higher concentrations of P, K, and Zn followed by low-rate manure or high-rate char–manure mix, preceding low-rate mix and chemically fertilized treatments (treatments 1–3) at the tail end. In spring 2022 samples, manganese (Mn), Cu, and B varied by treatments. Differences in soil test Mn, Cu, and B by treatments were complex; however, the control

TABLE 2 Chemical properties of char applied to the pens and crop field and manure and char–manure mix collected from piles after scraping from cattle pens and during field application. Char–manure mix was targeted at a ratio of 1:2.

Treatment	Moisture (%)	Organic N ($g\ kg^{-1}$)	Total N ($g\ kg^{-1}$)	P ($g\ kg^{-1}$)	S ($g\ kg^{-1}$)	Ca ($g\ kg^{-1}$)	Mg ($g\ kg^{-1}$)	Zn ($g\ kg^{-1}$)	Fe ($g\ kg^{-1}$)	Cu ($g\ kg^{-1}$)	B ($g\ kg^{-1}$)	pH ($g\ kg^{-1}$)
Cattle pen[a]												
Char	22.7c	2.5c	2.5c	7.8c	2.9c	77.4a	19.6a	0.05b	17.2a	0.18a	0.14a	7.9
Manure	31.8a	17.1a	17.3a	16.6a	4.1a	35.1b	9.1b	0.15a	8.2b	0.04b	0.04b	8.1
Mix	26.0b	14.9b	15.2b	14.6b	3.6b	33.6b	8.6b	0.14a	9.0b	0.03b	0.04b	8.1
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.004	<0.001	<0.001	0.594
Intended mix (1:2)[b]	28.8	12.2	12.4	13.7	3.7	49.2	12.6	0.12	11.2	0.09	0.07	8.0
Crop field[c]												
Char	24.1c	2.5c	2.5c	7.6c	2.9c	79.8a	18.4a	0.05c	22.3a	0.18a	0.16a	8.3a
Manure	32.1a	16.2a	16.4a	17.0a	4.2a	26.5c	7.8c	0.16a	6.9c	0.04c	0.02c	8.3a
Mix	25.8b	13.3b	13.7b	13.8b	3.2b	30.3b	8.5b	0.14b	9.1b	0.05b	0.04b	7.8b
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Intended mix (1:2)	29.4	11.6	11.8	13.9	3.8	44.3	11.3	0.12	12.0	0.09	0.07	8.3

[a]Cattle pen treatments include char applied to pens and manure and char–manure mix scrapped and piled from pens.
[b]Char–manure mix parameters at targeted 1:2 mix ratio based on the amount of added char to pens and estimated manure from 10 steers in the given feeding period.
[c]Crop field treatments include char applied to the field and manure and char–manure mix hauled from the pens and sampled during field application.

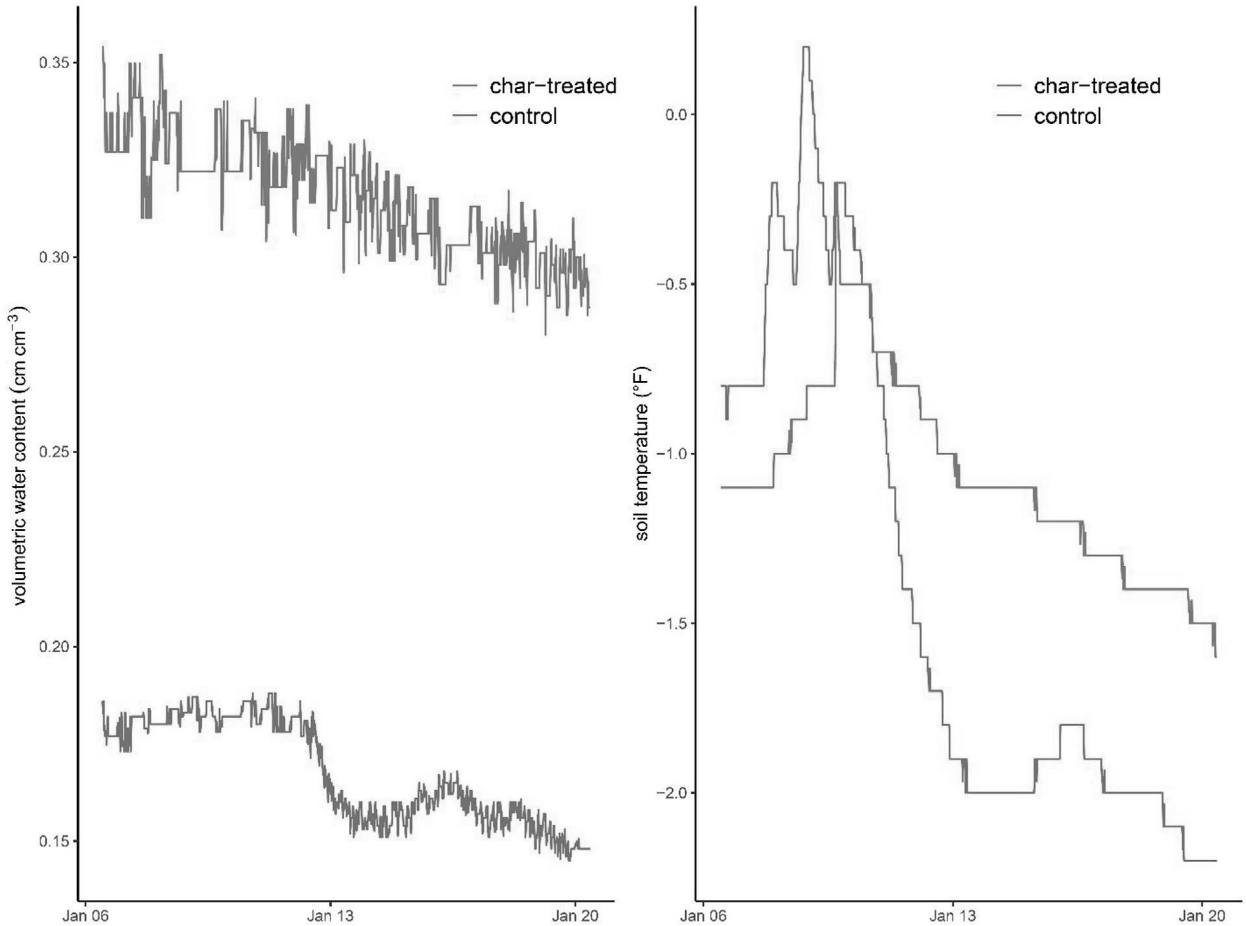

FIGURE 1 Volumetric water content (VWC) and soil temperature in the no-char and char-applied cattle pens in January 2020.

TABLE 3 Performance of finishing steers housed in cattle pens with or without char.

Response variables	Char-treated pens	Control pens	Standard error	*p*-value
Initial body weight, kg	319	319	7.0	0.99
Final body weight, kg	628	632	9.2	0.79
Daily gain, kg day^{-1}	1.81	1.83	0.02	0.51
Dry matter intake, kg day^{-1}	11.6	11.8	0.18	0.41
Gain:feed	0.156	0.155	–	0.72

treatment had generally low soil test values, and high-rate manure had one of the highest values.

When compared by soil sampling time, there were significant differences in soil organic matter (OM), nitrate-N, P, Fe, Mn, sodium (Na), B, and pH. All those properties, except for Na and pH, had lower values in soils sampled in spring 2022 than in fall 2021. On average, spring 2022 soil samples had lower OM by 11%, nitrate-N by 232%, P by 84%, Fe by 19%, Mn by 26%, and B by 17% compared to fall 2021 samples. Soil Na concentrations and pH were greater in spring 2022 samples than in fall 2021 by 13% and 2%, respectively. In sub-soil samples (20–90 cm), analyzed only for nitrate-N, the average soil nitrate-N was 2.8 mg kg^{-1} in fall 2021 samples and 4.5 in spring 2022. On average, there was a 61% increase in soil nitrate-N concentration in 20–90 cm soil samples in spring 2022 than in fall 2021.

3.4 | Crop yields

In 2020, the first year of the crop field experiment, corn grain yield significantly varied by treatments (Figure 2). The treatments 2 (100% urea-N), 3 (100% urea-N and 45 Mg char ha^{-1}), and 6 (34 Mg manure ha^{-1}) had greater corn

TABLE 4 Soil characteristics in the upper 20 cm in fall 2021 and spring 2022.

Treatment[a]	CEC me 100 g^{-1})	OM (g kg^{-1})	NO_3^--N (mg kg^{-1})	P (mg kg^{-1})	K (mg kg^{-1})	S (mg kg^{-1})	Zn (mg kg^{-1})	Fe (mg kg^{-1})	Mn (mg kg^{-1})	Cu (mg kg^{-1})	Ca (mg kg^{-1})	Mg (mg kg^{-1})	Na (mg kg^{-1})	B (mg kg^{-1})	pH (mg kg^{-1})	EC (mmho cm^{-1})
Fall 2021																
1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
2	12.7	18	7.2	11.3c	357c	16.0	0.8c	4.4	2.9	0.3	1749	338	56.3	0.7	8.0	0.2
3	13.0	20	7.9	12.8c	340c	20.2	0.9bc	5.6	2.7	0.5	1787	348	62.8	1.1	8.1	0.3
4	12.5	19	9.8	16.2bc	418bc	16.4	1.0bc	4.4	2.8	0.4	1686	326	60.0	0.8	8.0	0.2
5	13.5	20	11.5	34.8abc	486ab	16.6	1.2abc	5.4	2.8	0.5	1806	358	56.3	0.8	7.9	0.3
6	13.0	20	14.6	40.0ab	443bc	22.2	1.4ab	5.4	3.0	0.4	1755	339	63.8	0.7	8.0	0.3
7	13.0	21	13.1	58.8a	577a	20.0	1.7a	5.7	3.2	0.5	1653	357	74.8	0.8	7.9	0.3
p-value	0.952	0.658	0.251	0.006	0.002	0.637	0.018	0.095	0.602	0.344	0.959	0.505	0.252	0.362	0.081	0.065
Spring 2022																
1	14.5	16	2.6	7.3b	354cd	16.1	0.9c	3.6	1.7c	0.3c	2169	300	61.0	0.5b	8.3	0.2
2	12.8	17	2.3	7.6b	332d	15.6	0.7c	4.2	2.9a	0.4abc	1817	308	70.3	0.6b	8.1	0.3
3	14.0	18	3.1	9.1b	338d	21.1	0.8c	4.0	2.1bc	0.4bc	2014	330	68.0	0.8a	8.1	0.2
4	13.1	19	2.4	10.6b	432bc	17.2	0.9c	3.9	2.6ab	0.4bc	1768	340	72.0	0.7ab	8.2	0.3
5	12.8	17	4.5	32.4a	486ab	19.2	1.3b	5.5	1.9bc	0.4ab	1689	332	76.3	0.8a	8.1	0.2
6	13.1	16	2.6	9.4b	356cd	16.2	0.8c	3.7	2.0bc	0.3c	1827	330	76.5	0.6b	8.2	0.2
7	13.6	20	6.6	45.6a	567a	22.0	1.7a	5.2	2.6ab	0.5a	1777	357	70.5	0.7a	8.1	0.3
p-value	0.857	0.113	0.398	<0.001	<0.001	0.559	<0.001	0.123	0.034	0.038	0.696	0.185	0.564	0.006	0.669	0.381
Spring vs. fall[b]	2	−11	−232	−84	−5	−1	−18	−19	−26	−10	4	−4	13	−17	2	−14
Paired *t* test (*p* value)	0.405	0.014	<0.001	0.014	0.307	0.994	0.131	0.020	0.001	0.097	0.182	0.138	0.012	0.014	<0.001	0.395

Abbreviations: CEC, cation exchange capacity; EC, electrical conductivity; OM, organic matter.
[a]Treatments included the control; treatment 1 that received no N in all 3 years. Treatment 2 received 100% N each year based on the University of Nebraska-Lincoln (UNL) algorithm accounting for crop yield goal and spring soil test, treatment 3 received 100% N plus char from the factory in 2020, treatments 4–7 received char–manure mix and manure alone scrapped from the cattle pens in 2020. Treatments 4 and 6 received supplemental N in 2021; treatments 2–7 received 100% N in 2022. Treatments 1–3 received P based on spring soil tests in 2020 and 2021.
[b]Mean difference in soil test values between spring 2022 and fall 2021 samples expressed in percentage.

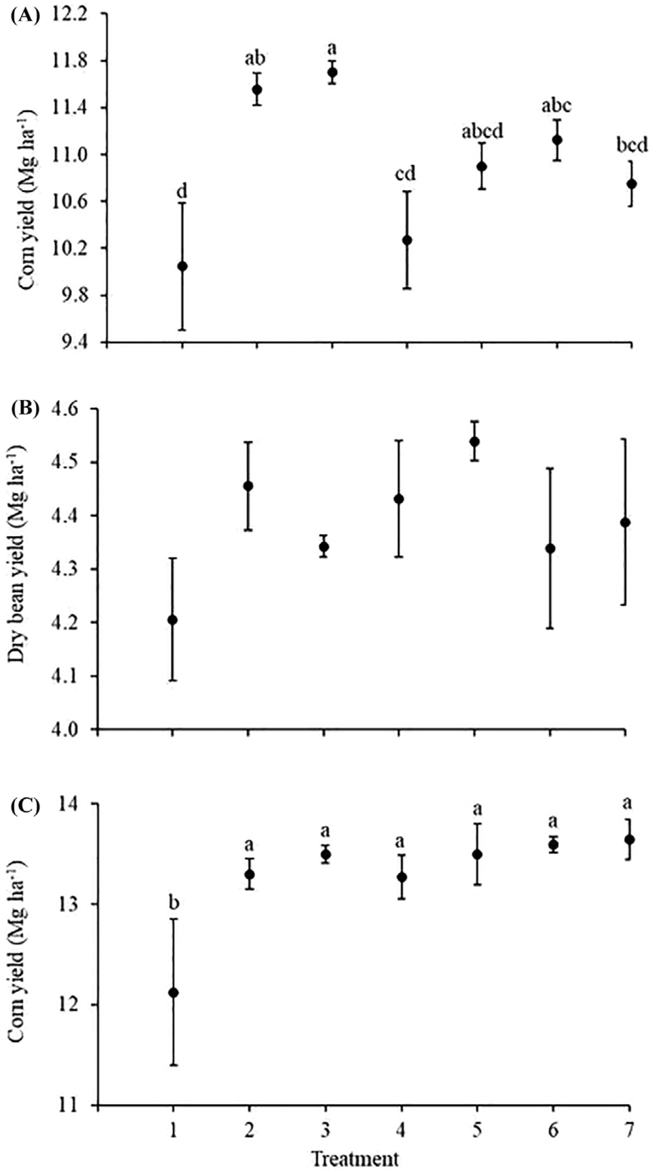

FIGURE 2 Grain yield for corn in 2020 (a), dry edible bean in 2021 (b), and corn in 2022 (c) by treatment. Different lowercase letters indicate statistical difference in mean values (± standard deviation) among treatments at $p < 0.05$. Treatments included the control; treatment 1 that received no N in all 3 years. Treatment 2 received 100% N each year based on the University of Nebraska-Lincoln (UNL) algorithm accounting for crop yield goal and spring soil test, treatment 3 received 100% N plus char from the factory in 2020, treatments 4–7 received char–manure mix and manure alone scraped from the cattle pens in 2020. Treatments 4 and 6 received supplemental N in 2021; treatments 2–7 received 100% N in 2022. Treatments 1–3 received P based on spring soil tests in 2020 and 2021.

grain yields than the control. Among the N-fertilized treatments, treatment 3 (100% urea-N + 45 Mg char ha^{-1}) yielded more than treatments 4 (34 Mg char–manure mix ha^{-1}) and 7 (68 Mg manure ha^{-1}). Treatment 2 (100% urea-N) yielded more than the low char–manure mix rate treatment. There were no significant yield differences among manure alone or char–manure mix applied at 34 or 68 Mg ha^{-1}.

In 2021, dry edible bean yield did not significantly differ by treatment (Figure 2). However, there was a trend for greater bean yield with the high char–manure rate treatment than the control ($p = 0.099$). The mean bean yield ranged from 4.21 Mg ha^{-1} in the control plot to 4.54 Mg ha^{-1} in treatment 5 that received 68 Mg char–manure mix ha^{-1} in 2020 and no supplemental nutrients in 2021. In 2022, there was a significant effect of treatment on corn grain yield (Figure 2). All the fertilized treatments (2–7) had greater grain yield than the control.

4 | DISCUSSION

Results obtained from the Hydra probe sensors and the finishing steers indicated that char is a viable option for maintaining a drier pen environment following snowfall events without impacting cattle performance (Figure 1; Table 3). Due to its porous structure and a higher surface area of 82.1 m^2 g^{-1} (Panday, Mikha, Collins, et al., 2020), char, when applied in cattle pens, absorbs moisture by capillarity (Sperber et al., 2022). The coarse texture of the char also promotes aeration in the char-soil mix in the pen, resulting in a decreased overall moisture content of the pen (Barghi, 2019). This helps reduce the production of ammonia and other odorous compounds, as well as diseases and parasite infestations often associated with wet and decomposing manure (McCrory & Hobbs, 2001; Sun et al., 2016). Additionally, the char-treated pens are exposed to freezing air temperatures more, enhancing soil freezing in winter, as evidenced by the soil temperature data (Figure 1). This, together with a drier manure mix, is conducive to the manure scraping process in the spring.

Cattle manure typically contains essential nutrients, including P. However, if applied to soil in its raw form in excessive amounts, it can lead to an imbalance of nutrients and the risk of overapplication of P and its runoff into water bodies, causing eutrophication and harmful algal blooms (Helton et al., 2008; Schoenau & Davis, 2006). The lower values of moisture, organic N, total N, P, S, and Zn observed in the char–manure mix compared to manure alone (Table 2) are due to the dilution effect of adding char to manure. However, the higher surface area and CEC of char might have collectively enhanced the adsorption of nutrients (particularly N) in char (Panday, Mikha, Collins, et al., 2020). The actual versus intended mix comparison showed that when most other measured properties were lower in the actual mix, organic and total N were 14%–23% higher in the actual mix (Table 2), suggesting enhanced N retention due to char in the mix. This aids in retaining and gradually releasing nutrients, making them more accessible to plants over time while also decreasing the risk of leaching and runoff. During field application, since elements such as Ca, Mg, Fe, Cu, and B were higher in char than in manure, the char–manure mix had a higher concentration than in the manure alone (Table 2).

Additionally, the char–manure mix shifted from alkaline toward neutral, accompanied by a decrease in pH of 0.5 units compared to manure alone (Table 2). This shift was likely caused by the dilution effect of adding char, which can be more favorable for plant growth, yield, and nutrient uptake (Sirisuntornlak et al., 2021). A similar observation was reported with char applied at ≤13.4 Mg C ha^{-1}, which reduced soil pH by 0.2 units compared to the control (Panday, Mikha, Maharjan, et al., 2020, 2021). This underscores the synergy between char and manure amendments to improve nutrient balance and supply, ultimately benefiting crop production.

The current experiment showed that adding char to manure or chemical fertilizer has no detrimental effect on crop production in the rotation (Figure 2). Instead, there was a potential yield benefit of adding char in addition to fertilizer N in the same year of its application (Figure 2a). The highest corn grain yield obtained with the 100% urea-N plus char treatment in 2020 (Figure 2a) could be attributed to enhanced soil fertility, improved nutrient availability, and soil conditions for crops. The greater retention of NO_3^--N and NH_4^+-N due to biochar or char addition in N-fertilized soils was reported in previous studies (Panday, Mikha, Collins, et al., 2020, Panday, Mikha, Maharjan et al., 2020; Wang et al., 2012). High C amendments such as char and biochar act as soil conditioners to increase fertilizer use efficiency compared to conventional fertilizer alone (Melo et al., 2022). In addition, adding char to agricultural soil along with chemical fertilizer or manure can provide other ecosystem service benefits such as SOC accumulation and soil health improvements. Maharjan, Panday et al. (2021) reported an enhanced corn yield in a low C soil (7 g C kg^{-1}; exposed subsoil) with char applied at >6.5 Mg C ha^{-1}. This suggests that C-deficient soils of water-limited regions may benefit more from soil amendments such as char or manure as they can increase soil water retention and nutrient cycling and supply (Blanco-Canqui et al., 2020; Panday et al., 2021). The current experiment demonstrated that one-time char–manure mix or manure application at 68 Mg ha^{-1} could replace 314 kg N ha^{-1} and 90 kg P_2O_5 ha^{-1} over 2 years without any yield penalty in moderately productive soil. Long-term monitoring of moderately or optimally productive croplands following char application can provide information regarding broader application and greater benefits from char.

Groundwater pollution resulting from nutrient leaching after crop harvest is a pressing concern globally (Rasouli et al., 2014). Irrespective of N sources, nitrate leaching can be significant during October–April (Bauder & Montgomery, 1979). The current experiment showed a considerable decline (on average, 66%) in nitrate-N in the top 20 cm and an average gain of 61% in 20- to 90-cm depth in spring compared to the previous fall (Table 4), suggesting the downward movement of nitrate-N over winter. Other factors, such as immobilization/mineralization and denitrification losses, could have affected this change in soil nitrate-N by depth. There was also a significant loss of P from the top 20 cm of soil between spring and the preceding fall (Table 4). These potential nutrient losses through leaching or erosion/runoff pose a risk of water quality issues and eutrophication in water bodies downstream (Chadwick et al., 2011; Eghball & Power, 1994). Between treatments of 100% urea-N, the one with char had 10% and 35% more nitrate-N in fall and spring top 20 cm soil samples than the other one without char (Table 4). Similarly, the char treatment had 13% and 20% more P in topsoil than the no-char treatment (Table 4). The presence of char in chemically fertilized soils helps as an adsorbent to retain nitrates, reducing the likelihood of nitrate leaching through the soil profile during snowmelt and early spring rain (Beegum et al., 2023; Panday, Mikha, Collins, et al., 2020).

5 | CONCLUSION

This experiment demonstrated that adding char with chemical fertilizer to croplands can improve soil productivity as char increases soil nutrient retention. Mixing char with manure in cattle pens before land application can enhance manure and soil management, benefit crop production, and reduce environmental implications. The potential char benefits include positive effects on the cattle pen environment, improved manure nutrient supply, and P dilution. Further investigation exploring the underlying mechanisms that govern these positive outcomes, as well as optimizing char application would help identify best practices for efficient soil, manure, and crop management. Additionally, assessing the socioeconomic and environmental implications of the widespread adoption of mixing locally available C additives with manure would help inform policy decisions and promote this practice in regions facing soil degradation and other resource constraints.

AUTHOR CONTRIBUTIONS

Vesh R. Thapa: Formal analysis; methodology; software; writing—original draft; writing—review and editing. **Bijesh Maharjan**: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; resources; software; supervision; validation; visualization; writing—original draft; writing—review and editing. **Karla Wilke**: Conceptualization; formal analysis; funding acquisition; investigation; methodology; project administration; supervision; validation; writing—original draft; writing—review and editing.

ACKNOWLEDGMENTS

This experiment was supported by the Western Sugar Cooperative, Denver, CO.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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How to cite this article: Thapa, V. R., Maharjan, B., & Wilke, K. (2024). Applying coal char to cattle pens for sustainable agriculture in the semiarid US High Plains. *Agrosystems, Geosciences & Environment*, *7*, e20492. https://doi.org/10.1002/agg2.20492