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Potential amendments for improving productivity of low carbon semiarid soil

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Abstract

Applying soil amendments with high C content can potentially improve soil properties and increase crop yields. The objective of this 3-yr field study was to evaluate the effects of organic amendments on soil organic C (SOC), chemical properties, crop nutrient uptake, and crop yields in a low C sandy loam soil near Scottsbluff, NE. The field was planted to dry bean (*Phaseolus vulgaris* L.) in 2017, maize (*Zea mays* L.) in 2018, and sugar beet (*Beta vulgaris* L.) in 2019. Char at 22.3, 44.6, 66.9, 89.2, and 133.8 Mg ha^{-1}; biochar at 5.6 and 11.2 Mg ha^{-1}; and composted manure and municipal compost each at 33.6 and 67.2 Mg ha^{-1} were applied and incorporated into the soil. In 1 yr after application, organic amendments increased SOC level in top 20 cm by 7–60%. In the second year, maize leaf tissue Fe was greater with char treatments and high biochar rate compared with the control. Greater Fe uptake in beet leaf tissue or trend for such was observed in amendment treatments at high rates compared with low rates and the control in the third year. Maize yield was enhanced with char, municipal compost, and high compost manure rate. Biochar was applied at lower rates than other amendments, and it had no effects on the parameters studied. Results suggest that locally available organic products can be potential soil amendments to increase SOC and enhance productivity. Care needs to be taken to prevent salt buildup and unwanted toxic material accumulation associated with amendments.

1 | INTRODUCTION

Soil degradation, nutrient depletion, and declining crop productivity are major constraints in agriculture, particularly in semiarid region of the U.S. Great Plains (MacCarthy et al., 2010; Mikha et al., 2017; Rajashekhara Rao et al., 2012). This region of the United States was exposed to the historic Dust Bowl of the 1930s as the cropland lost its top productive surface rich with organic material resulting in decreased land productivity (Larney & Angers, 2012; Stewart, 2004; Tanaka & Aase, 1989). The recovery of cropland from topsoil losses and decline in productivity may require a long period of restoration (Pimentel & Burgess, 2013). Previous research documented that the Dust Bowl caused some cropland to lose approximately 27–30 cm of topsoil and land productivity, both of which are not yet restored (Mikha et al., 2014, 2017). At present, the soils in the semiarid region of the Great Plains are characterized by low soil organic C (SOC) and low productivity due to intensive tillage, low precipitation, wind erosion, and frequent droughts (Mikha et al., 2014;

Abbreviations: SOC, soil organic carbon.

Nielsen & Calderon, 2011). Hence, it is important to improve soil properties to enhance soil productivity and optimize the benefits of agricultural inputs in semiarid region of the Great Plains.

Organic amendments can be alternative to and complement inorganic fertilizer for enhancing soil productivity (Uzoma et al., 2011). Extensive use of inorganic fertilizers in semiarid regions is not favored due to soil with low crop yield potential and subsequent reduced return on input cost (Wang et al., 2016). In contrast, organic amendments could supply essential plant nutrients and C to improve soil properties and productivity (Sanderman et al., 2009). For instance, composted manure was reported to improve soil physical and chemical properties and increase crop yield (Hergert & Nielsen, 2010; Maharjan & Hergert, 2019). However, in some cases, the composted manure benefits can be minimal due to their low amounts of nutrients and organic matter supplying capacity (Lentz et al., 2014; Schulz et al., 2014). Municipal compost, which is prepared under a controlled aerobic microbial process to decompose organic matter present in municipal solid waste, is another potential organic amendment that may benefit the soil, crop, and environment (Hosseinpur et al., 2012; Mbarki et al., 2018; Rodd et al., 2002). It can be particularly beneficial to restore degraded soils of semiarid regions by promoting the activity of microbial communities in soil (Bouzaiane et al., 2007; Jedidi et al., 2004).

Furthermore, adding C-enriched materials such as char and biochar containing more C compared with composted manure or municipal compost could be an effective strategy to increase soil C, improve soil chemical properties, and enhance soil productivity. Biochar is promoted to enhance C sequestration, reduce greenhouse gas emissions, and improve soil properties for the potential to increase crop yields (Filiberto & Gaunt, 2013; Kätterer et al., 2019; Smith, 2016). Coal char, which is the residue from the inefficient burning of coal in a sugar factory in western Nebraska, contains up to 293 g kg^{-1} C. Its application to fertilized soils at optimal levels can reduce ammonia volatilization loss (Panday et al., 2020). Blanco-Canqui et al. (2020) also found that char application increased SOC after 2 yr of its application, although its benefits on other soil properties or crop yields would take >2 yr.

There is a caveat in using some potential soil amendments as they can contain toxic compounds, such as heavy metals, particularly in industrial by-products such as char (Mantovi et al., 2003; Wuana & Okieimen, 2011). When such amendments are incorporated into the soil, it may have immediate or buildup through time toxic effects on microorganisms, crops, and human health (Antonious, 2016; Mahar et al., 2016). This warrants special attention to determine any potential accumulation of toxic constituents from soil amendment in soil, plant tissue, or grains.

The objectives of this study were to evaluate the effects of biochar, char, composted manure, and municipal compost on SOC, soil chemical properties, crop nutrient uptake, and crop yield in a low-yielding soil in the semiarid region of western Nebraska. We hypothesized that the application of organic amendment improves SOC, soil chemical properties, crop nutrient uptake, and crop yield.

Core Ideas

- Maize yield was enhanced with char, municipal compost, and compost manure.
- Crop Fe uptake was increased under char-treated plots.
- Low application rate of biochar masks its potential benefits to improve soil properties.
- Locally available potential soil amendment is worth an investigation.

2 | MATERIALS AND METHODS

A field trial was conducted at a grower's field near Scottsbluff, NE, in 2017–2019. The soil at the study site is a Tripp very fine sandy loam (coarse-silty, mixed, superactive, mesic Aridic Haplustolls) with <1% slopes. Soil pH was 8.2, and SOC was 7 mg kg^{-1}. Our study site falls within the farm area that lost the surface soil (especially the organic layer) while leveling off the field, and the subsurface soil was exposed. This practice of leveling the land for easy management is regular in the area that has rolling topography. Such leveling exposes subsurface soil to the surface and moves surface soil to the lower section of the field. The chosen study site exhibited low productivity and high alkaline soil property. Weather data for the entire trial period were collected from a nearby weather station associated with High Plains Regional Climate Center (HPRCC, 2019).

Four types of organic amendments (char, biochar, composted manure, and municipal compost) were used at different rates as follow: (a) no amendment or control; (b) five rates of char (22.3, 44.6, 66.9, 89.2, and 133.8 Mg ha^{-1}); (c) two rates of biochar (5.6 and 11.2 Mg ha^{-1}); (d) two rates of composted manure (33.6 and 67.2 Mg ha^{-1}); and (e) two rates of municipal compost (33.6 and 67.2 Mg ha^{-1}). The experimental plots were organized in a randomized complete block design with four replications, resulting in a total of 48 plots. Each plot size was 6.1 × 6.1 m^2. Char used in this field study was generated from the coal combustion in the sugar factory in Scottsbluff, NE (Panday et al., 2020). The char was applied to the field after passing through an 8-mm sieve. The biochar was prepared from pine trees and was provided by High Plains Biochar. Composted manure was obtained from a local feedlot, and municipal compost was provided by

TABLE 1 Chemical properties of the organic amendments (char, biochar, composted manure, and municipal compost) used in the study

Parameter	Char	Biochar	Composted manure	Municipal compost
	% (dry wt. basis)[a]			
Moisture	2.1	2.6	10.0	62.0
pH	7.6	7.0	7.0	7.3
Total C	29.3	85.4	12.5	18.2
Total N	0.4	0.7	1.1	1.5
P as P_2O_5	0.2	nd[b]	1.6	1.0
K as K_2O	0.2	nd	1.6	0.7
Ca	4.8	nd	nd	5.4
Mg	1.1	nd	nd	0.4
S	0.5	nd	0.3	nd
Fe	1.3	nd	0.7	nd
B	<0.1	nd	nd	nd
Zn	<0.1	nd	<0.1	nd
Ash	nd	6.2	nd	nd
Trace metals[c]	Yes	nd	nd	Yes

[a] All parameters except pH are reported on a percentage basis.

[b] Not detected (below detection limit).

[c] Char and municipal compost contain trace metals (As, Cd, Cr, Pb, Hg, and Se) concentrations that were below the phytotoxicity limits for heavy metal for soil contamination (Cameron, 1992).

the City of Scottsbluff, NE. The chemical properties of the amendments are presented in Table 1. All amendments were applied manually and uniformly to the plots and incorporated into 15-cm soil depth immediately after application using the disc harrow. The amendment application occurred once in 2017, whereas the tillage operations were carried out for land preparation every year after that.

The treatment plots were planted to dry bean (*Phaseolus vulgaris* L.) in 2017, maize (*Zea mays* L.) in 2018, and sugar beet (*Beta vulgaris* L.) in 2019. Dry bean was planted on 1 June 2017. Maize was planted on 4 May 2018, and sugar beet on 6 May 2019. Except for treatment application and crop harvest, all other management practices, including commercial fertilizer application, followed the producer's typical farming practices.

During the growing season, aerial imagery was taken early in the season to observe visual color differences due to amendment application. In 2018, soil samples from the top 20 cm were collected from all 48 treatment plots before maize planting. Each sample consisted of a composite of six cores collected with a 3-cm-diam. probe. Collected soil samples were analyzed for $pH_{1:1}$, organic C, N, P, K, Ca, Mg, S, Fe, B, Zn, and cation exchange capacity. Crop tissue samples from maize (around the V14–V15 growth stage) and sugar beet (mid-season) leaves were collected for nutrient analysis in the first week of July 2018 and 2019, respectively. Twenty recently matured leaves below the whorl from 20 maize plants per plot were collected in 2018, and four recently matured leaves from four plants per plot were collected for sugar beet crop tissue samples in 2019.

Dry bean and maize were hand harvested from the middle two rows of 1.5 m each from all treatment plots on 27 Sept. 2017 (dry bean) and 22 Oct. 2018 (maize) for yield calculation. The sugar beet was harvested from the middle two rows of 1.5 m each using a single row digger (Kodiak Manufacturing) on 3 Oct. 2019. Subsamples of grain samples from 2017 and 2018 associated with char and control treatments were analyzed for selected heavy metals.

The effect of amendment types and rates on parameters studied (SOC, soil chemical properties, crop nutrients uptake, and yields) were tested using PROC GLIMMIX procedure in SAS software version 9.4 (SAS Institute, 2015) with amendments type, rate, year, and their interaction considered as fixed effects. The replications and their interaction with other factors were considered as random effects. When main or interaction effects were significant, means were separated by the least square means (LSD) test (Littell et al., 2006). A paired *t* test was conducted to determine SOC in amendment treatments relative to the control treatment. Regression analysis for yield or nutrient uptake response to applied char rates were conducted in SAS. Carbon equivalents of amendment application rates were estimated by multiplying the actual amendment rate by C content in the product. Statistical significance was evaluated at $P < .05$ unless otherwise stated.

3 | RESULTS

3.1 | Weather

The average annual temperatures at the study site (Figure 1) were 9.8 ˚C in 2017, 8.9 ˚C in 2018, and 5.4 ˚C in 2019 compared with 9.4 ˚C in a 30-yr average (1981–2010). The average annual precipitation was 439 mm in 2017, 539 in 2018, and 557 in 2019. The annual precipitation throughout the study period (2017–2019) exhibited at least 10% greater annual precipitation than a 30-yr average (Figure 1). During the growing season (May–October), average ambient temperatures throughout the study period were within 1.0–1.5 ˚C of the 30-yr average. Occasionally, the ambient temperatures were greater than the 30-yr average such as in May of 2017 by 1.6 ˚C, in October of 2018 by 1.7 ˚C, and in 2019 during May by 4.5 ˚C and October by 4.8 ˚C. Growing season precipitation from May to October varied by year. Compared with the 30-yr average, the growing season precipitation was 2.5% less in 2017, 54.1% higher in 2018, and 37.4% higher in 2019. The hailstorm that occurred on 15 Aug. 2019 damaged sugar beet crop and affected its ripening stage. Throughout the growing season, 2019 was cooler, followed by 2017, than 2018, resulting in a slower rate of growing degree days accumulation.

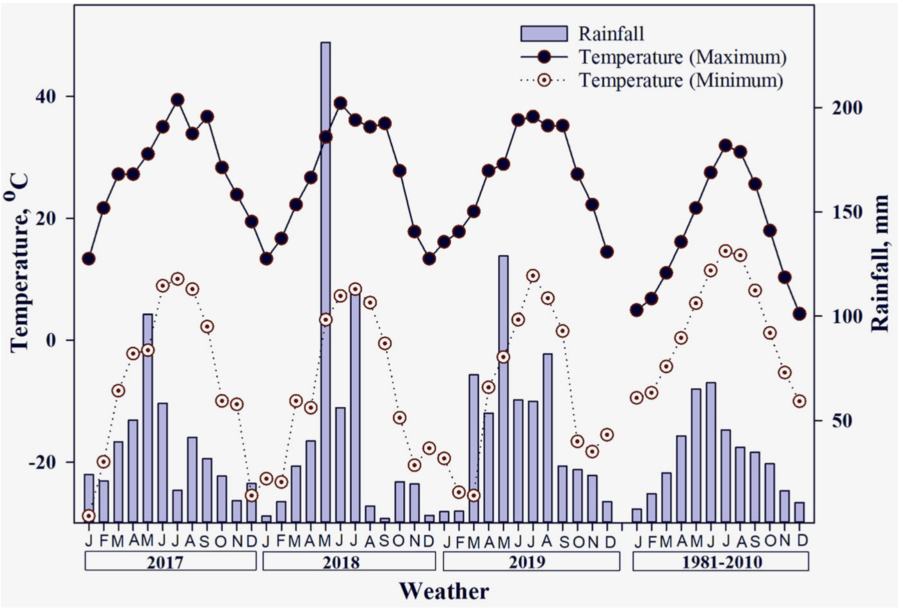

FIGURE 1 Monthly cumulative rainfall and average maximum and minimum air temperature in 2017, 2018, 2019 and a 30-year average (1981–2010) in Scottsbluff, NE

FIGURE 2 Aerial imagery showing visual color differences due to applied treatments in dry bean plots in 2017 (left) and maize in 2018 (right). Most dark crop rows correspond to char treatments. Treatments included no amendment or control, five levels of char (22.3, 44.6, 66.9, 89.2, and 133.8 Mg ha^{-1}), two levels of biochar (5.6 and 11.2 Mg ha^{-1}), two levels of composted manure (33.6 and 67.2 Mg ha^{-1}), and two levels of municipal compost (33.6 and 67.2 Mg ha^{-1})

3.2 | Crop leaf tissue

In the dry bean in 2017 and the maize in 2018, crop tissues exhibited chlorotic symptoms in early spring with most of the treatments except for the treatment that received char (Figure 2). In 2018, maize leaf tissue Fe concentrations were greater with all char treatments and high biochar rate compared to the control (Table 2). Maize tissue Fe concentrations with higher char rates (89.2 and 133.8 Mg ha^{-1}) were greater than any other amendments except for high biochar rate. Maize tissue B concentrations were greater with char at high rates (66.9, 89.2, and 133.8 Mg ha^{-1}) than the control, biochar, or municipal compost. Maize tissue N concentrations were also greater with higher char rates than some other amendments and the control treatment. Nitrogen concentration in maize leaf tissue was 2.5–5.5% higher, whereas B concentration was 32.2–35.3% higher when char was applied at rates ≥66.9 Mg ha^{-1} compared with the control (Table 2). Also, Fe concentration in maize leaf tissue linearly increased ($r^2 = .96$, $P = .001$) with increasing char rates (data not shown).

Greater Fe uptake in sugar beet leaf tissue or trend for such was observed in amendment treatments at the higher rates compared with low rates and compared to the control in 2019 (Table 3). Beet tissue B concentrations were greater with char at high rates (66.9, 89.2, and 133.8 Mg ha^{-1}) than the control, biochar, or municipal compost. In 2019, Fe concentrations in sugar beet leaf tissue were 117.8% higher with the char rate at 133.8 Mg ha^{-1} compared with the control. Biochar applied at 11.2 Mg ha^{-1} increased Fe concentration by 45% when compared with the control.

3.3 | Crop yield

Crop yield across the amendments ranged from 1.18 to 3.43 Mg ha^{-1} for dry bean in 2017, 11.30 to 17.08 Mg ha^{-1} for maize in 2018, and 8.70 to 16.06 Mg ha^{-1} for sugar

TABLE 2 Effects of amendments type and rate on maize leaf tissue nutrients concentration in 2018

Treatment	Rate	N	P	K	Ca	Mg	S	Zn	Fe	Mn	Cu	B	Mo
	Mg ha^{-1}	%						mg kg^{-1}					
Control	–	3.1bc[a]	0.4	3.4	0.5	0.2	0.3	36.0	41.0c	97.0ab	11.6	13.2cd	0.8
Char	22.3	3.0c	0.4	3.3	0.5	0.2	0.3	34.5	66.7ab	89.5bcd	10.7	15.7abc	0.7
	44.6	3.1bc	0.4	3.4	0.5	0.2	0.3	34.5	61.7ab	95.0abc	11.5	16.1abc	0.7
	66.9	3.2a	0.3	3.3	0.6	0.2	0.3	38.5	68.3ab	94.3abc	12.1	17.9a	0.8
	89.2	3.1ab	0.3	3.3	0.5	0.2	0.3	36.3	73.7a	91.0abcd	11.6	17.4ab	0.7
	133.8	3.2a	0.3	3.1	0.5	0.2	0.3	35.5	71.8a	84.0d	11.3	17.7a	0.9
Biochar	5.6	3.1bc	0.4	3.4	0.5	0.2	0.4	38.0	53.0bc	96.3ab	11.9	12.5d	0.3
	11.2	3.1abc	0.4	3.2	0.5	0.2	0.4	33.3	59.7ab	98.0a	11.2	12.3d	0.8
Composted manure	33.6	3.1bc	0.4	3.3	0.5	0.2	0.3	36.0	50.3bc	88.0cd	10.9	14.6bcd	1.0
	67.2	3.1bc	0.4	3.3	0.5	0.2	0.3	37.5	55.7bc	91.8abc	10.8	15.0abcd	0.7
Municipal compost	33.6	3.1bc	0.3	3.3	0.5	0.2	0.4	36.5	52.7bc	91.2abcd	11.2	12.4 d	1.1
	67.2	3.1abc	0.4	3.3	0.6	0.2	0.3	34.8	52.3bc	89.8bcd	11.5	14.0cd	0.8
Significance	–	***	NS[b]	NS	NS	NS	NS	NS	**	*	NS	***	NS

[a] Means for each nutrient followed by the same lowercase letters are not significantly different.
**$P < 0.01$,
*Significant at the .05 probability level.
**Significant at the .01 probability level.
***Significant at the 0.001 probability level.
[b] NS, not significant.

TABLE 3 Effects of amendments type and rate on sugar beet leaf tissue nutrients concentration in 2019

Treatment	Rate	N	P	K	Ca	Mg	S	Zn	Fe	Mn	Cu	B	Mo
	Mg ha^{-1}	%						mg kg^{-1}					
Control	–	4.4	0.3	4.5	1.0	0.8	0.3	24.0	377bc[a]	73.3	6.7	28.6	0.3
Char	22.3	4.5	0.4	4.2	1.0	0.7	0.3	23.3	622abc	78.3	7.0	26.5	0.2
	44.6	4.5	0.3	4.4	1.1	0.7	0.3	26.0	480bc	76.3	6.8	28.7	0.2
	66.9	4.4	0.4	4.4	1.0	0.7	0.3	24.5	475bc	72.8	6.8	29.1	0.3
	89.2	4.3	0.3	4.0	1.1	0.8	0.3	22.5	674ab	77.3	6.5	29.6	0.3
	133.8	4.4	0.4	4.1	1.1	0.7	0.3	21.8	820a	73.0	8.2	26.9	0.4
Biochar	5.6	4.6	0.3	4.6	1.0	0.8	0.3	24.5	322c	74.0	6.4	28.5	0.2
	11.2	4.5	0.3	4.2	1.1	0.8	0.3	26.3	546abc	80.8	6.8	28.1	0.3
Composted manure	33.6	4.6	0.4	4.3	0.9	0.8	0.3	20.5	416bc	76.8	7.7	28.5	0.3
	67.2	4.4	0.3	4.3	1.1	0.7	0.3	21.3	583abc	69.5	6.2	26.7	0.2
Municipal compost	33.6	4.4	0.4	4.2	1.0	0.7	0.3	23.3	444bc	70.0	7.6	29.3	0.3
	67.2	4.2	0.3	4.0	1.0	0.8	0.3	21.8	678ab	76.3	6.3	27.5	0.3
Significance	–	NS[b]	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	NS

[a] Means for each nutrient followed by the same lowercase letters are not significantly different.
*Significant at the .05 probability level.
[b] NS, not significant.

beet in 2019 (Table 4). Dry beans and sugar beet crops were not influenced by amendment types and rates. All char treatments except for the lowest char rate (22.3 Mg ha^{-1}) increased maize yield compared with the control treatment. Maize yield increased ($r^2 = .97$, $P = .001$) with increasing rates of char (data not shown). The highest char rate treatment (133.8 Mg ha^{-1}) had greater maize grain yield than all other treatments but char at 66.9 Mg ha^{-1} and municipal compost at 67.2 Mg ha^{-1}. Both municipal compost treatments (33.6 and 67.2 Mg ha^{-1}) and compost manure at 67.2 Mg ha^{-1} had yield greater than the control. In 2018, maize yield increased by 5.2–30.1% with char, 1.4–6.7% with biochar, 4.3–17.1%

TABLE 4 Mean crop yields as affected by the different amendments type and rate

Treatment	Rate	Yield		
		Dry bean (2017)	Maize (2018)	Sugar beet (2019)
	Mg ha^{-1}			
Control	–	1.79	12.41e[a]	10.62
Char	22.3	2.37	13.12de	10.81
	44.6	2.13	13.74cd	10.84
	66.9	2.02	15.12ab	10.94
	89.2	2.13	14.89bc	12.41
	133.8	2.73	16.21a	11.84
Biochar	5.6	2.04	12.30e	11.21
	11.2	2.08	13.24de	11.64
Composted manure	33.6	2.05	13.01de	10.87
	67.2	1.75	14.65bc	11.04
Municipal compost	33.6	2.05	13.94cd	11.31
	67.2	2.05	15.48ab	11.64
Significance		NS[b]	***	NS

[a] Means for each nutrient followed by the same lowercase letters are not significantly different.

***Significant at the 0.001 probability level.

[b] NS, not significant.

TABLE 5 Pairwise *t* test results comparing soil organic C under amendment treatment against the control

Treatment	Rate	Rate	Soil C	*P* value
	Mg ha^{-1}	Mg C ha^{-1}	g kg^{-1}	
Control	–	–	7.3	–
Char	22.3	6.5	10.2	.01
	44.6	13.1	11.7	.01
	66.9	19.6	9.0	.37
	89.2	26.1	11.4	.01
	133.8	39.2	10.7	.02
Biochar	5.6	4.8	9.5	.22
	11.2	9.6	9.9	.11
Composted manure	33.6	4.2	7.8	.87
	67.2	8.4	10.1	.13
Municipal compost	33.6	6.1	8.0	.54
	67.2	12.2	10.0	.04

with composted manure, and 12.2–24.6% with municipal compost compared with the control. The high application rate (67.2 Mg ha^{-1}) of composted manure and municipal compost increased maize yield by 11.1–12.6% relative to the low application rate of 33.6 Mg ha^{-1}.

The dry bean yield in 2017 and sugar beet yield in 2019 were not statistically influenced by the amendments (Table 4), but the amendments showed a trend for yield increase compared with the control treatment. For example, dry bean yield increased by 12.2–52.4% with char, 13.1–16.4% with biochar, 2.0–14.1% with composted manure, and 14.4% with municipal compost (for both rates) compared with the control treatment. Similarly, sugar beet yield increased by 1.8–11.5% with char, 5.6–9.6% with biochar, 2.4–4.0% with composted manure, and 6.5–9.6% with municipal compost compared with the control treatment.

3.4 | Soil chemical properties

In 1 yr after application, organic amendments increased SOC level by 7–60% in this low C soil (Table 5). Char treatments at ≥22.3 Mg ha^{-1} had significant increases in SOC compared with the control. Other amendment treatments that had C equivalent equal to or greater than that from 22.3 Mg ha^{-1} of char were biochar, compost manure, and municipal compost, all at their high rates (Table 5). There was a significant increase in SOC or trend for such with amendment addition at ≥6.5 Mg C ha^{-1} (char and municipal compost at $P < .05$, and biochar and compost manure at $P \leq .13$).

Amendments also had a significant effect on pH and Ca concentrations (Table 6). Soil pH increased in the municipal compost at 33.6 Mg ha^{-1} compared with the control. Char applied at 89.2 Mg ha^{-1} and biochar at 5.6 Mg ha^{-1} also increased Ca level in soil solution compared with the control. There was no effect of soil amendments on N, P, K Mg, S, Fe, B, Zn, and cation exchange capacity. The addition of composted manure or municipal compost did not significantly change the level of P or K in soil.

3.5 | Trace metal in grain samples

In 2017 and 2018, harvested grain samples from the control and char treatments (≥44.6 Mg ha^{-1}) analyzed for any potential trace metal accumulation showed no significant difference in metal concentrations. All measured trace metal concentrations were either below the detection limit or phytotoxicity limits of heavy metal for soil contamination (Cameron, 1992).

4 | DISCUSSION

The organic amendments showed no effect on dry bean yield, which could be related to the fact that these amendments were applied shortly before dry bean planting. Previous research documented that amendments such as char and biochar may need more than 1 yr to interact with soil (Fernández et al., 2007; Kammann et al., 2011). In the second year, maize yield was enhanced with organic amendment, especially with char, municipal compost, and high compost manure rate. The bad weather that occurred in 2019 negatively influenced

TABLE 6 Mean soil chemical properties as affected by the different treatments in 2018

Treatment	Rate	pH	N	P	K	Ca	Mg	S	Fe	B	Zn	CEC[a]
	$Mg\ ha^{-1}$		$mg\ kg^{-1}$									$cmol\ kg^{-1}$
Control	–	8.3b[b]	13.6	29.1	686	4,204bc	520	31.7	2.4	1.4	2.2	28.0
Char	22.3	8.4ab	12.1	26.4	693	4,310ab	545	35.7	2.3	1.3	2.1	28.3
	44.6	8.3b	15.2	28.3	720	4,249abc	518	37.0	2.3	1.4	2.0	27.9
	66.9	8.3b	16.4	57.8	799	4,296ab	496	38.1	2.9	0.9	2.4	27.7
	89.2	8.4ab	13.5	19.1	656	4,388a	533	48.8	2.1	1.4	2.4	28.5
	133.8	8.4ab	12.0	29.9	703	4,275abc	529	24.0	2.3	1.2	2.0	28.0
Biochar	5.6	8.4ab	12.1	21.1	649	4,380a	498	27.1	2.1	0.9	1.8	28.1
	11.2	8.4ab	10.4	28.3	714	4,214bc	486	30.6	2.3	0.9	2.0	27.4
Composted manure	33.6	8.4ab	15.6	43.7	751	4,147c	513	29.2	2.4	1.1	2.2	27.4
	67.2	8.3b	14.1	39.1	748	4,251abc	536	38.0	2.4	1.6	2.2	28.2
Municipal compost	33.6	8.5a	11.8	24.8	639	4,233bc	502	31.5	2.1	1.1	2.4	27.4
	67.2	8.4ab	20.3	34.8	752	4,262abc	500	37.4	2.2	1.3	2.2	27.8
Significance	–	*	NS[†]	NS	NS	*	NS	NS	NS	NS	NS	NS

[a] CEC, cation exchange capacity.

[b] Means in a column followed by the same lowercase letter are not significantly different.

*Significant at the .05 probability level. [†] NS, not significant.

sugar beet yield regardless of types and rates of amendments, including the control treatment.

Given all other management was the same, any yield benefit observed with these treatments would imply that these amendments might have improved soil nutrient availability, soil properties, and processes that subsequently affected yield. Compost materials are well recognized to improve soil properties and crop yield over time (D'Hose et al., 2012). Enhanced micronutrient uptake might have contributed to yield gain in maize in 2018 in case of char amendment. This result aligns with a report by Joseph et al. (2014) where improved canola and wheat yields were observed due to increased Fe and Zn uptake with pyrite amendment and sulfur-oxidizing bacteria.

Iron chlorosis is common in calcareous soil, particularly early in the spring when there is considerable precipitation. In the current study, the soil had a pH of 8.2, and in May of all 3 yr, there was >30-yr average precipitation (normal: 65 mm; 2017: 101 mm; 2018: 230 mm; and 2019: 129 mm). This led to chlorotic symptoms due to Fe deficiency to be visible in the amendment plots except char plots in 2017 and 2018. Although chlorotic symptoms often disappear in the later stages of growth, amendments that increased Fe concentration could reduce chlorosis symptoms and increase crop yields observed with maize in 2018 (Naeve, 2006).

Increased nutrient concentrations such as N, Fe, Mn, and B in crops' leaf tissue, in some amendments more than others, suggested that release of essential nutrients needed for different stages of crop establishment depends upon amendment type and composition (Dumroese et al., 2011; Gonzalez et al., 2001; Pandey et al., 2009). Char might enhance soil fertility through greater nutrient availability. Nitrogen volatilization loss is reduced after char application due to its considerably high surface area (82 $m^2\ g^{-1}$) and cation exchange capacity of 46.9 $cmol\ kg^{-1}$ (Panday et al., 2020) that jointly increase its sorption capacity (Jamieson et al., 2014). Previous research documented that crop nutrient uptake depends on vegetative growth rate that involves many factors affecting crop growth and development, including C assimilation of the crop (Gastal & Lemaire, 2002) and micronutrient uptake (Joseph et al., 2014).

Compared with other amendments, biochar was applied at much lower rates. Biochar contains a high C concentration (85.4% in this study) and often improves soil properties (Blanco-Canqui, 2017). Limited or no effect of biochar in the present study may be due to the low (11.2 $Mg\ ha^{-1}$) application rate (Blanco-Canqui, 2019) to slightly alkaline soil. Previous studies found positive effects of biochar on degraded and coarse-textured soils under application rate ≥50 $Mg\ ha^{-1}$ (Chan et al., 2008; Kammann et al., 2011). Most positive results on biochar were reported from acidic soils due to the potential liming effect of biochar on crop yields (Burell et al., 2016; Liu et al., 2012).

Blanco-Canqui et al. (2020) reported char that at >67.3 Mg ha^{-1} increased soil C where the initial SOC was >10 $g\ kg^{-1}$. In contrast, the current study soil had a much lower initial organic C (7 $g\ kg^{-1}$), and char as low as 22.3 $Mg\ ha^{-1}$ increased soil C compared with the control. The increase in SOC associated with amendment addition at ≥6.5 $Mg\ C\ ha^{-1}$ (char and municipal compost at $P < .05$, and biochar and compost manure at $P \leq .13$) supported our hypothesis regarding enhancing SOC with organic amendments at optimal rates.

It is anticipated that organic amendments can have broader impacts on soil chemical properties and crop yields in the period longer than the scope of this experiment. This 3-yr data supported the hypothesis that organic amendments such as char, compost manure, and municipal compost can improve crop yield compared with the control. The data partially supported our hypothesis regarding crop nutrient uptake. There was a minimal improvement with macronutrient uptake, but some of the amendments at specific rates improved micronutrient uptake.

There was no heavy metal accumulation in harvested grains under different rates of char. However, there may be other limitations, such as an increase in salt content (which could affect the growth of sensitive crops) and adverse effects of herbicide and pesticide sorption (Herrera et al., 2008; Singh & Ghoshal, 2010). Study shows that some biochar products may be toxic depending upon the source materials (Kookana et al., 2011). Composted manure and municipal compost often contain pathogens and high levels of dissolved salts in soil (Nicholson et al., 2003). Therefore, care needs to be taken when adding different types and rates of organic amendment to prevent salt buildup and unwanted toxic material accumulation in soil.

In the current study, all amendments except biochar were locally and abundantly available. It is important to account for added operational costs for any amendment depending on the source, availability, and transportation cost. Therefore, economics will be another important factor to consider before deciding on amendments.

5 | CONCLUSION

Our results suggest that locally available amendments including char, municipal compost, or composted manure can increase productivity of low organic C (7 g kg^{-1}) soils in semiarid regions. Increased maize yield after these amendments could be related to increased micronutrient uptake, and improved soil properties, including SOC. Biochar had a limited effect on crop yields as rates of application were low (as high as 11.2 Mg ha^{-1}). Long-term evaluation is required to determine the effects of amendments on soil properties and crop yields. Production and transport costs can make some potential additives prohibitive for broader use in agriculture. Locally available potential soil amendments should be evaluated in agricultural regions as done in this study.

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AUTHOR CONTRIBUTIONS

Bijesh Maharjan: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Software; Supervision; Writing-original draft; Writing-review & editing. Dinesh Panday: Formal analysis; Investigation; Writing-original draft; Writing-review & editing. Humberto Blanco: Investigation; Supervision; Writing-original draft; Writing-review & editing. Maysoon M. Mikha: Investigation; Writing-review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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