

RESEARCH ARTICLE

Impact of maize straw biochar and tied-ridge-furrow rainwater harvesting on soil erosion and soil quality in a semiarid region

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Abstract

In dryland areas, integrating biochar soil amendment with in situ rainwater harvesting systems may decrease soil erosion, improve soil quality, and increase crop productivity and yield. This study was conducted to investigate the effect of maize straw biochar amendment and ridge-furrow rainwater harvesting systems on run-off, sediment yield and the physico-chemical properties of a Calcic Cambisol soil in semiarid areas. The experiment was conducted on alfalfa (*Medicago sativa*) production land at the Anjiagou Catchment experimental station in Gansu province, China. The experimental layout was a split-plot design with three replications. Biochar was applied at a rate of 0 and 30 t ha⁻¹, respectively. The tillage treatments were flat planting, open-ridging, and tied-ridging (TR). Overall, the integration of maize straw biochar with TR decreased soil bulk density at 0–40 cm depth. Biochar application reduced run-off by 37.8% and soil loss by 55.5% during alfalfa-growing seasons compared to the control. In general, biochar addition increased soil total potassium, but the same effect was not observed for soil pH, total nitrogen, total phosphorus, and available phosphorus. These findings demonstrate the potential of integrating maize straw biochar and tillage systems to reduce soil erosion and improve soil quality for rainfed crop production in semiarid areas. Further studies on the effect of biochar-tillage system interaction are warranted to improve soil conditions for plant growth and increase crop yield in dryland areas.

KEYWORDS

maize straw biochar, run-off, sediment yield, soil physico-chemical properties, tillage system

1 | INTRODUCTION

Water scarcity and poor soil quality are major constraints to crop productivity in dryland areas. In the alfalfa (*Medicago sativa*) production systems in semiarid areas in China, the adverse effects of water scarcity and low soil quality are contributing to frequent crop failures and endemic

food insecurity. Water scarcity in the region is because of low rainfall (average = 400 mm, minimum = 150 mm and maximum = 750 mm). Rainfall in these regions is erratic with high evapotranspiration rates. Climate change and anticipated increase in water consumption owing to the burgeoning human population are projected to exacerbate water scarcity problems. For instance, water

consumption is expected to increase by 18% and 50% in developed and developing countries, respectively, in 2025 (Setegn & Donoso, 2015). Consequently, about 1.8 billion people worldwide are expected to face acute water shortages for domestic, agriculture and industrial purposes (Yannopoulos et al., 2019).

Sustainable and effective options for achieving water management in semiarid areas include the use of substitute or supplementary water sources such as conventional centred technologies and improving the efficiency in using existing water resources (Dongol et al., 2017). In the case of the former, rainwater harvesting (RWH), also known as water remediation and reallocation, has been suggested to be a viable way to conserve supplementary water for various uses. RWH is a feasible technology that can improve water availability and control floods. It encompasses a wide range of technologies for collecting and storing water, which can be categorized into *ex situ* and *in situ* technologies (Zhang et al., 2021). Terracing, pitting and conservation tillage practices are examples of *in situ* RWH methods that decrease run-off and soil erosion and improve rainfall infiltration. The rainwater capture area is located within the crop field, and the soil plays the role as a collection and a depository media. *Ex situ* methods involve capturing water outside the storage positions, such as land area with minimal drainage capabilities or a man-made ground surface with low or no drainage capability (Ebert, 2020). Until now, the potential of *in situ* RWH technologies in arid and semiarid regions of China to enhance soil productivity and the underlying mechanisms are not well understood.

Crop productivity in arid and semiarid areas such as China is constrained not only by water scarcity but also by poor soil fertility characterized by low soil organic matter (SOM) and essential soil nutrients for plant growth (MacCarthy et al., 2021). Soil quality is a key component of environmental quality, and thus, management practices that improve the quality of arable soils are crucial for sustainable food production. Poor soil quality in arid regions has been attributed to inappropriate land management and soil erosion (Ton et al., 2017). The susceptibility of dryland areas to soil erosion is because of short season heavy rainfall events which severely remove soil nutrients, extensive cultivation of steep farmlands (Grum et al., 2017), sparse vegetation cover and the general low SOM, which make the soil less resistance to disruptive forces like wind and water erosion, and mechanical disturbances (Wolka et al., 2021).

The application of organic amendments has been used for improving soil properties for crop production. The use of organic amendments such as biochar can reduce the need for synthetic fertilizers to alleviate the high production costs and the problems associated with the

excessive use of mineral fertilizers such as water pollution and emission of greenhouse gases (Khadem et al., 2021). Biochar is a stable carbon-rich material produced when a feedstock is pyrolysed in a closed chamber with limited oxygen available (Montanarella & Lugato, 2013). Addition of biochar can ameliorate soil quality through improving its physico-chemical properties, increase the resistance of soil to disruptive forces, sequester carbon and enhance several other ecosystem services (Ding et al., 2016), which can promote plant growth and increase crop yield. Bashagaluke et al. (2019) found that the incorporation of maize straw biochar significantly reduced soil loss resulting from erosion by 1.23–2.66 Mg ha⁻¹ for the three successive cropping seasons investigated compared with NPK fertilizer for the no-biochar-added soil. Jing et al. (2020) reported that the application of lantana biochar (at 30 g/kg) to a paddy soil significantly decreased soil bulk density, but increased the soil pH, soil organic carbon and available phosphorus (AP). In terms of crop yield, Dong et al. (2022) found that grain weight of wheat increased after 30 t ha⁻¹ of wheat straw biochar was applied. The average yield of maize and soya beans increased by 1.4 and 1.9 Mg ha⁻¹, respectively, after the application of lignocellulosic biochar in low-input acidic soil (Wakweya et al., 2022). It is important to emphasize that the effects of biochar addition on soil properties and its concomitant influence on crop yield depend on factors such as biochar characteristics, feedstock, soil type and experimental set-up and duration (Razzaghi et al., 2020) and experimental conditions like soil properties. In general, biochar can play a major role in promoting sustainable soil management for meeting the United Nations Sustainable Development Goals over the next decade (Hou, 2021). Thus, research to empirically establish the effects of biochar amendment on the properties of agricultural soils is prerequisite for developing biochar as a resourceful agronomic soil conservation material (Gao et al., 2022) and to provide basis for upscaling the adoption of biochar application technology by farmers. Although several studies have investigated the impact of biochar applications on soil properties, nutrients and crop yields, there is paucity of information on the effect of biochar in a tied-ridge-furrow RWH (TRFRWH) on soil erosion and quality in dryland areas. Tied-ridges are long, narrow and elevated strips of ridges crossed by earthbands within the furrow or ties constructed to enhance soil water conservation. Also, tying the furrows allows *in situ* water harvesting improves water infiltration into the soil and minimizes run-off (Silungwe et al., 2018).

The arid and semiarid region of China is an important region for maize production in China (Lamptey et al., 2019; Zhong et al., 2020). Pyrolysing the maize residues to biochar can offer a sustainable way to dispose of the agricultural waste and to improve soil conditions for

plant growth. Therefore, a field study was conducted to investigate the effect of maize straw biochar amendment integrated with TRFRWH system on run-off, sediment loss and the physico-chemical properties of a Calcic Cambisol in semiarid area of China. It is hypothesized that the integration of TRFRWH systems with maize straw biochar reduces run-off and sediment loss and improves soil properties in a semiarid condition.

2 | MATERIALS AND METHODS

2.1 | Experimental site description

The experiment was conducted at the Anjiagou Catchment experimental station (35°34' N, 104°39' E, 2075 m asl) in Fengxiang township of Dingxi city, Anding District, Gansu Province, China, from 2020 to 2021 during the alfalfa-growing seasons. The area has been subjected to severe water erosion partly because the topography of the area is hilly, with steep slopes. The average annual precipitation total from 1971 to 2018 was 404.5 mm, with 93% falling in the experimental months (April 10 to October 20). The average annual pan evaporation in the area is 1515 mm, while the average pan evaporation during experimental period was 986 mm (Wei et al., 2015). Average annual air temperature in the area ranges from 7.2 to 14.0°C. Average air temperature during the cultivation period ranged from -6.9 to 19.2°C. According to the USDA soil taxonomy, soil at the experimental station is a Calcic Cambisol. In this area, the distance between the soil surface and the water table varies between 30 and 100 m (Ton et al., 2017). Potato (*Solanum tuberosum*) is the main cultivated crop in the region, while alfalfa (*Medicago sativa* L.) and sainfoin (*Onobrychis viciaefolia*) are the main forage species cultivated.

2.2 | Experimental set-up

2.2.1 | Biochar properties

Biochar used in the study was commercially produced from maize straw feedstock through a slow pyrolysis process at 400°C thermal decomposition (Sanli New Energy Company; Luo et al., 2017). At the end of the pyrolysis, the biochar was air-dried for 24 h. The properties of the biochar were as follows: bulk density of 0.45 g/cm³, surface area of 44 m²/g, cation exchange capacity of 24.1 cmol/kg, pH of 7.5 (v/v 1:2.5 biochar: distilled water), water holding capacity of 288% (24 h) and total N and total C content of 0.3 and 89%, respectively. Before application to soil, the biochar was ground and subsequently sieved to 5 mm.

Thereafter, it was mixed with the soil in the plots at 10 cm depth manually.

2.2.2 | Experimental layout

The experimental layout was a split-plot design with three replications. Biochar amendment was the main treatment, and tillage practice, the subtreatment (Figure 1). Biochar rate of 30 t ha⁻¹ was applied, which was compared with the control, without any biochar application. The tillage treatments were flat planting (FP), open-ridging (OR) and tied-ridging (TR). Thus, in total, there were six different treatments (two biochar rates × three tillage practices). Except the FP, each treatment plot had nine ridges and ten furrows. The size of each plot was 52.5 m² (5 × 10.5 m). The RWH scheme had a ridge width of 45 cm and height varying from 15 to 20 cm. The width of the furrow of the OR and TR was 60 cm. The ties were 15 cm wide and 20 cm high. The space between two ties that were not staggered was 2.5 m. Ridges were mulched with biodegradable film (Ecoflex FS; BASF Co Ltd), 1.4 m in width and 0.008 mm in thickness, while ties in the TR were bare compacted soils. The ridges were used for run-off collection, whereas the furrow was used for planting and as infiltration territories. The eighteen experimental plots were 1.5 m apart. An intercepting trough was constructed to minimize rainwater and sediment loss at the upper slope of the plots. Each experimental plot had a gutter constructed downslope to transport run-off and sediments to a brick and cement-constructed sedimentation pond that had a volume of 3.375 m³ (1.5 m deep, 1.5 m wide, and 1.5 m long).

2.2.3 | Field management and agronomic activities

The experimental plots were manually constructed on 20 March 2020 in the proper slopes and sizes and positioned on 2 April 2020. On 12 April 2020, the plot borders sedimentation ponds, and ridges and furrows for the RWH treatments were constructed by moulding the soil into ridges and furrows across the length of the plots. The ridges were immediately covered with biodegradable films and secured beneath 3 cm of soil. In 2021, the procedures were repeated from March 20 to March 24. Before planting, the experimental plots were harrowed, and subsequently, the furrows were levelled. On 15 April 2020, a native alfalfa variety (No. 3 Gannong) was planted at 22.5 kg ha⁻¹. For the OR- and TR-treated plots, four rows, 20 cm spaced, were sown in a 60 cm furrow width on an area of 30 m² with 40 alfalfa-planted rows. The FP treatment plots were 50.25 m²

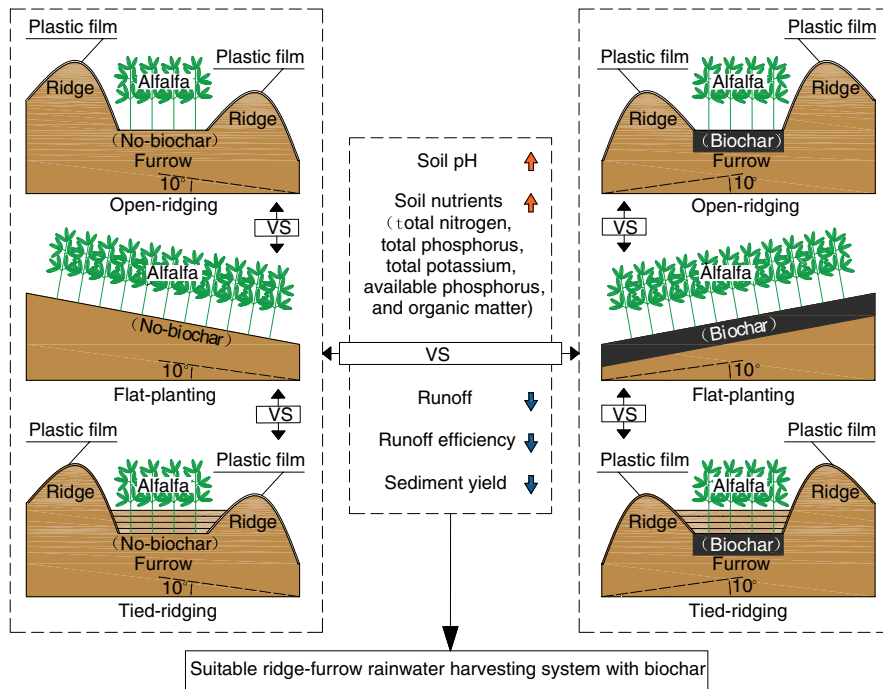


FIGURE 1 Hypothetical alternations of alfalfa production in ridge-furrow RWH system with biochar application on sloping land

with 66 alfalfa-planted rows. Approximately 2 months after seeding, ties in the TR treatments were manually banked and reinforced with soil. Before, during or after alfalfa cultivation, neither fertilizer nor irrigation was used. The experiment was repeated in the second season using the same RWH systems used in the first experimental season.

2.3 | Sampling and measurements

2.3.1 | Soil sampling

Undisturbed soil cores and bulk samples were collected using cylindrical metal rings and an auger during planting and after harvest in 2020 and 2021 from all the 18 experimental plots. For each plot, three subsamples were collected randomly at the 0–10, 10–20 and 20–40 cm depth representing the top, middle and bottom depth. For the bulk samples, the soils from the three depths were mixed thoroughly to obtain a composite sample. The samples were bagged in polyethylene and sealed. Thereafter, all the samples were carefully packed into an insulated box to minimize disturbances during transportation to the laboratory. Dry ice was positioned around the bags to maintain humidity and stop sublimation. To minimize ‘burning’ effects brought on by contact with carbon dioxide, a thin (25 mm) sheet of insulation (crushed newspaper) was positioned between the dry ice and the soil samples. This also helped slow down air movement in the box. To maintain the same thermal and moisture conditions present at the time of

sampling, a thin bead of room temperature vulcanizing silicone rubber caulking compound was applied around the edge of the lid before the box was closed. This made the cover of the container tightly fastened and airtight. The soil samples were then transported to the laboratory for measurement of soil physical and chemical properties.

2.3.2 | Soil bulk density and pH

Soil bulk density was determined using the core method (Blake & Hartge, 2018). In brief, the soil cores were oven-dried at 105°C for about 48 h. Soil bulk density was calculated as the weight of the dry soil core divided by the volume of the core.

To determine soil pH, 10 g of soil sample was sieved with a 2-mm-diameter sieve, weighed and then poured in a clean bottle. Distilled water with 1:2.5 soil/water ratios was poured into the bottle. The suspension was stirred and made to settle for 30 min after which pH meter with glass electrode was used to calibrate pH value.

2.3.3 | Soil temperature

During alfalfa growth period, soil temperature in the furrow and on the ridges of each plot was measured with a curved-tube mercury geothermometer. Soil temperature was recorded 8:00 AM, 2:00 PM and 6:00 PM, with 5-day intervals, and measurement was done at 5, 10, 15, 20 and 25 cm depths.

2.3.4 | Rainfall, run-off and sediment yield

An automatic weather station (WSSTD1, England) was mounted near the experimental field to measure rainfall. In 2020, total annual rainfall was 512.5 mm, with 452.7 mm falling during experimental months (April 2 to October 13, Figure 2). However, total annual rainfall was lower in 2021 (286 mm) with 273.7 mm falling during alfalfa cultivation period. Monthly rainfall totals were 7.5, 4.7, 13.4, 15, 75, 80.5, 91.2, 138.2, 44.8, 28.2, 10.2 and 3.8 mm from January to December, respectively (Figure 2). Rainfall from April to October yielded 88% of the total annual rainfall in the experimental years. The experimental plots' run-off quantity and sediment yield were measured after each precipitation event. Before the collection of the samples, the sedimentation ponds' run-off and sediment were rigorously stirred, and three 1000-ml flasks were used to take the samples immediately after stirring. To determine sediment transport, muddy water in three 1000 ml flasks was left to settle for 24 h and then oven-dried at 105°C for 24 h. Thereafter, total phosphorus (TP), total nitrogen (TN) and organic matter (SOM) were measured in the dry sediment. The following equations were used to calculate run-off, sediment yield and run-off efficiency:

$$V_{\text{runoff}} = A_{\text{pool}} \times D_{\text{pool}} \quad (1)$$

$$W_{\text{sediment}} = V_{\text{runoff}} \times (W_{\text{sample sediment}} / V_{\text{sample}}) \quad (2)$$

$$D_{\text{runoff}} = V_{\text{runoff}} / A_{\text{plot}} \quad (3)$$

$$W_{\text{sediment per area}} = W_{\text{sediment}} / A_{\text{plot}} \quad (4)$$

$$RE = V_{\text{runoff}} / (P \times A_{\text{plot}}) \quad (5)$$

where V_{runoff} (m^3) is the volume of run-off collected in the sedimentation pond, A_{pool} (2.25 m^2) is the inner basal area of the sedimentation pond, D_{pool} (m) is the depth of run-off in the sedimentation pond, W_{sediment} (g) is the weight of the sediment collected in the sedimentation pond, V_{sample} (L) is the sample volume, $W_{\text{sample sediment}}$ (g) is the sample sediment weight, D_{runoff} (L/m) is run-off depth, A_{plot} (m^2) is the projection area of the plot, and $W_{\text{sediment per area}}$ (g/m^2) is the weight of the sediment per area. The comparison of the no-biochar and biochar treatments yielded the rate of reducing soil loss (RSL, %) and the rate of reducing run-off (RR, %).

$$\text{RR (or RSL)} = (\text{no - biochar} - \text{biochar}) / \text{no - biochar} \times 100\% \quad (6)$$

If the outcome was positive, it indicated biochar decreased soil and water loss; if it was negative; it indicated that biochar increased soil and water loss.

2.3.5 | Total phosphorus and available phosphorus

The persulfate digestion spectrophotometer method was used to determine TP. To determine AP content, 4 g of air-dried soil sieved to 2 mm was transferred into a 100-ml flask. Thereafter, 14 ml of 0.03 M NH_4F and 0.025 M HCl was added. The mixture was mechanically shaken for 5 min, centrifuged at 1107 g for 5 min and filtered through a Whatman No. 42 filter paper. Afterwards, 5 ml of extract and 4 ml of ascorbic acid was pipetted into a volumetric flask and thoroughly mixed. Distilled water was added to bring the volume to 25 ml. The solution was left to stand for an hour for blue colour to develop. The filtered solution was placed in an atomic adsorption spectrometer (AAS), which

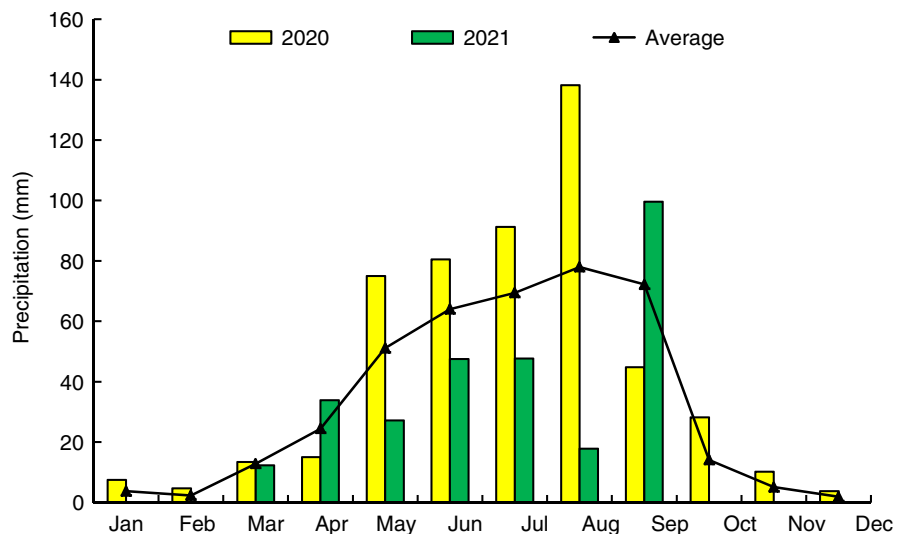


FIGURE 2 Distribution of the monthly precipitation at the experimental site from 2020 to 2021

detected phosphorus content automatically. AP was determined as:

$$AP = (\text{Reading data in AAS} \times 35) / 5 \quad (7)$$

2.3.6 | Total nitrogen and soil organic matter

The potassium dichromate-sulphuric acid titration method was used to determine soil total nitrogen (TN). Portion of the bulked soil samples were sieved to 0.25 mm prior to measurement to remove visible impurities and plant residues. The Kjeldahl method was used to determine TN. About 1 g of the air-dry soil sieved to 0.5 mm was poured into a Kjeldahl digestion flask, and distilled water was added. After that, 2.5 ml of Kjeldahl catalyst (1 part selenium powder + 10 parts CuSO_4 + 100 parts Na_2SO_4) was added to the sample solution and heated at 100°C for 2 h until a green colour appeared. After allowing the contents to cool, 2 ml of H_2O_2 was added, and the mixture was heated at 330°C for 4 h until a clear and colourless digest was obtained. Distilled water was then added to bring the volume of the solution to 75 ml. The excess acid in the distilled solution was titrated with sodium hydroxide until a pink colour appeared. The colour transitioned from green to pink and then to yellow. Then, the volume of sodium hydroxide used was recorded to the nearest 0.01 ml concentration. The TN content was then calculated using the following formula:

$$\text{Total nitrogen (g kg}^{-1}\text{)} = (V - V_0) \times C \times 14 \times ts \times 10 - 3m \quad (8)$$

V , Volume of H_2SO_4 used in sample titration (ml); V_0 = Volume of H_2SO_4 used in blank titration (ml); C = Concentration of H_2SO_4 (mol/L); m = weight of soil sample (g); ts = Correction factor.

Soil organic matter content was determined using the loss-on-ignition method (Prokop & Poręba, 2012). Portion of air-dried samples were combusted at a temperature of 360°C. At this temperature, organic matter compounds in the soil are converted to carbon dioxide gas, thus lowering soil sample weight. SOM was estimated by measuring weight loss after ignition.

2.4 | Statistical analysis

All research data were analysed using SPSS version 26 statistical software. Analysis of variance was used to examine variations between treatments, followed by a Tukey Pairwise comparison at 5% significance level.

3 | RESULTS

3.1 | Influence of biochar and tillage practice on soil erosion

Rainfall was the main source of run-off in the area, generating 79.96% of the total annual run-off during alfalfa-growing season. There was no significant ($p > .05$) effect of the interaction of biochar and tillage practice on run-off. For individual treatment effect, the application of maize biochar significantly ($p < .05$) reduced total run-off during alfalfa-growing seasons compared with the no-biochar-amended soil. However, inconsistencies were observed between the growing seasons. In 2020, run-offs in the biochar-treated plots ranged from 0.09 to 2.85 mm, compared with the no-biochar plots, which ranged from 0.21 to 4.21 mm (Figure 3a). In 2021, run-offs ranged from 0.11 to 2.85 mm for the biochar-treated plots compared with 0.77 to 4.25 mm for the no-biochar application (Figure 3b). During the experimental period, total run-off volumes for the biochar-amended plots were 29.31 and 47.12 mm for the no-biochar-treated plots.

Biochar application significantly ($p < .05$) reduced total run-off efficiency during alfalfa-growing seasons than the no-biochar-amended soil. In 2020, total run-off efficiency for the biochar-amended soil was 123.88 and 209.68 mm for the no-biochar-amended soil. The overall, run-off efficiency for biochar addition over no-biochar application was 40.92% during the growing season (Figure 4a). In 2021, total run-off efficiency for the biochar-amended soil was 124.03 and 208.98 mm for the no-biochar-treated soil (Figure 4b). Overall, the run-off efficiency in the biochar-amended soil was 40.65% compared with the no-biochar-treated plots during the growing season. There was no significant ($p > .05$) interaction effect of biochar and tillage practice on sediment yield. However, the individual effect of biochar and tillage practice on sediment yield differed significantly ($p < .05$) during the two growing seasons (Table 1). In 2020, the average annual sediment yields for the biochar-treated plots were lower (0.21–16.23 g/m^2) than the no-biochar plots (0.73–33.53 g/m^2 ; Figure 5a). Similar trends were observed in 2021, where the average annual sediment yield for the biochar-amended plot was lower (1.21–13.62 g/m^2) compared with the no-biochar plots (1.69–21.53 g/m^2). For tillage practice, the average sediment yield for the OR and TR treatments decreased by 61.79% and 73.14%, respectively, compared with the FP (Figure 5b).

FIGURE 3 Run-off during alfalfa-growing seasons of (a) 2020 and (b) 2021 in the various treatments

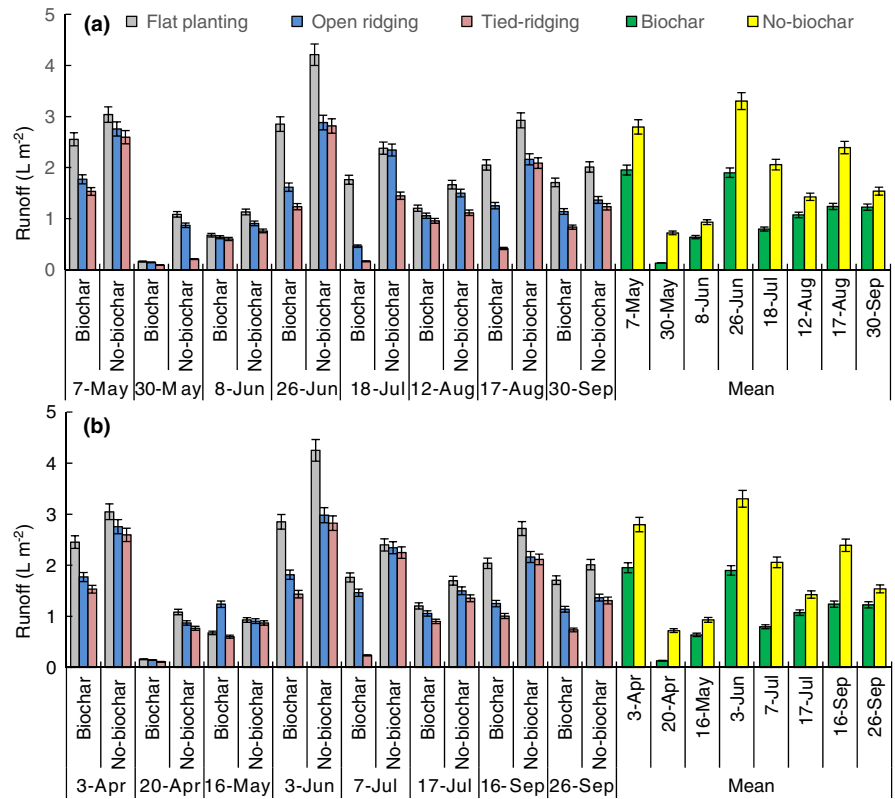
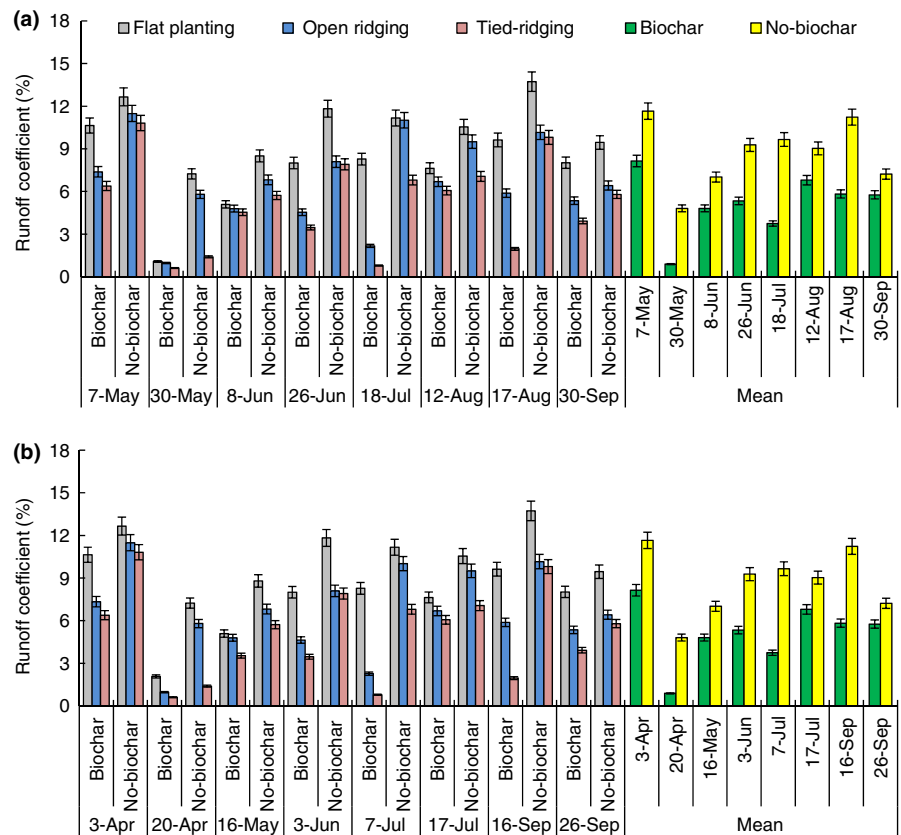


FIGURE 4 Run-off efficiency during alfalfa-growing seasons in (a) 2020 and (b) 2021 in the various treatments



3.2 | Effect of biochar and tillage practice on soil bulk density

For all the treatments investigated, soil bulk density increased with soil depth in both experimental years (Table 2).

Biochar amendment markedly ($p < .05$) reduced soil bulk density at 0–40 cm depth compared with the no-biochar-amended soil. For tillage practice, the TR treatment either with or without biochar generally reduced soil bulk density compared the counterpart treatments (Table 2).

TABLE 1 Analysis of variance of run-off, sediment yield and soil nutrients combined for 2020 and 2021

Source	Item	Biochar (B)	Tillage (T)	Year (Y)	B × T	B × Y	T × Y	B × T × Y	Error
Bulk density	df	1	2	1	2	1	2	2	24
	F	354.118	41.099	122.280	0.151	4.554	1.355	1.054	
	Sig	0.000	0.000	0.000	0.861	0.043	0.277	0.364	
Run-off	df	1	2	1	2	1	2	2	24
	F	331.722	107.002	4.070	2.012	0.156	1.813	1.471	
	Sig	0.000	0.000	0.055	0.156	0.696	0.185	0.250	
Sediment yield	df	1	2	1	2	1	2	2	24
	F	6531	9367	427.249	722.996	118.592	787.339	104.672	
	Sig	0.000	0.000	0.000	0.000	0.000	0.000	0.000	
pH	df	1	2	1	2	1	2	2	24
	F	0.186	0.108	0.476	0.085	0.570	0.242	0.023	
	Sig	0.670	0.898	0.497	0.919	0.458	0.787	0.977	
Total Nitrogen	df	1	2	1	2	1	2	2	24
	F	0.824	62.248	143.207	1.478	49.211	0.089	300.588	
	Sig	0.373	0.000	0.000	0.248	0.000	0.916	0.000	
Total Phosphorus	df	1	2	1	2	1	2	2	24
	F	22.118	12.516	15.570	8.711	37.596	30.206	23.556	
	Sig	0.000	0.000	0.001	0.001	0.000	0.000	0.000	
Total Potassium	df	1	2	1	2	1	2	2	24
	F	2.161	2.993	0.419	0.212	0.011	0.586	0.919	
	Sig	0.155	0.069	0.524	0.810	0.919	0.564	0.412	
Available Phosphorus	df	1	2	1	2	1	2	2	24
	F	21,954	24,424	82,954	1674	34,693	2255	731	
	Sig	0.000	0.000	0.000	0.000	0.000	0.000	0.000	
Organic Matter	df	1	2	1	2	1	2	2	24
	F	115.302	11.243	698.301	11.754	17.927	64.902	49.731	
	Sig	0.000	0.000	0.000	0.000	0.000	0.000	0.000	

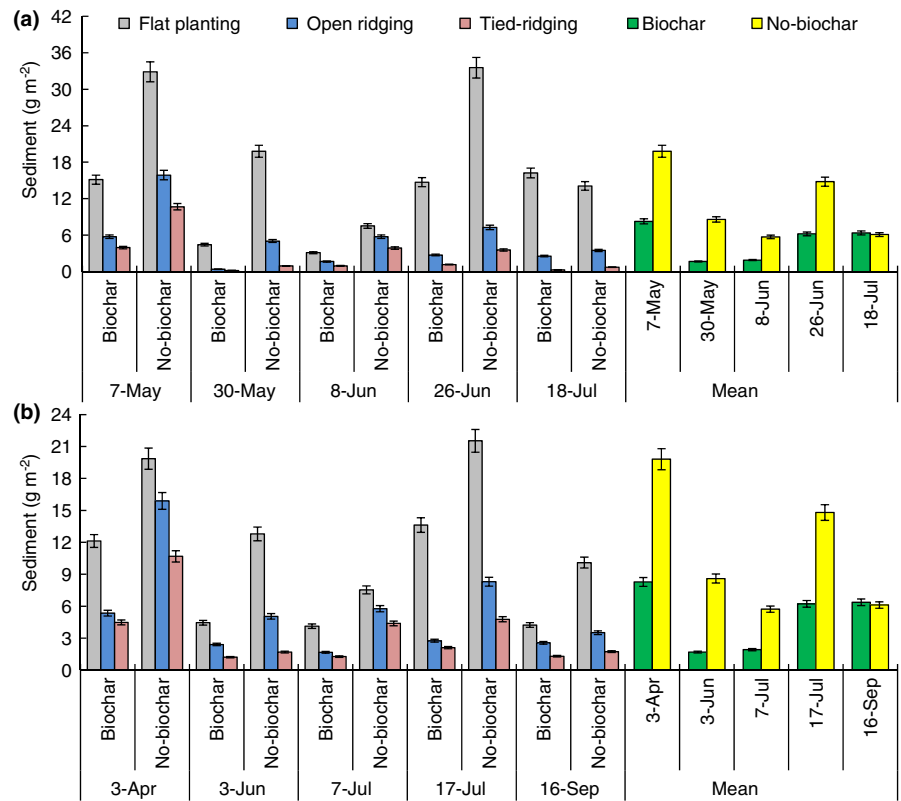
3.3 | Influence of biochar and tillage practice on soil pH and soil nutrients

Neither the interaction effect of biochar and tillage practice nor their individual effect significantly changed soil pH at 0–40 cm depth during two growing seasons (Table 3). On the contrary, the interaction of biochar and tillage practice significantly ($p < .05$) affected soil TN. In 2020, the maize straw biochar together with FP, TR or the OR significantly ($p < .05$) increased TN at 0–10 cm depth compared with the counterpart FP, OR and TR without biochar addition (Table 3). In 2021, biochar amendment significantly ($p < .05$) increased TN only for the FP at 0–10, 10–20 and 20–40 cm depth, but the same significant effect was not observed in the other treatments (Table 3). Overall, the application of maize straw biochar increased TN at 0–10 and 10–20 cm depths by 15.09% and 17.96%,

respectively, during alfalfa-growing seasons compared with the no-biochar-amended soil.

In 2020, the application of maize straw biochar decreased soil TP in the three tillage systems at 0–40 cm depths compared with the no-biochar-amended soil, albeit significant only for the FP and the OR treatment at 20–40 cm depth (Table 4). In 2021, maize straw biochar amended to the OR significantly ($p < .05$) increased soil TP at 0–10 cm depth. In 2020, biochar amendment consistently decreased soil-AP in all the tillage systems particularly at 0–10 and 10–20 cm depths (Table 4). In 2021, biochar addition considerably increased soil AP in all the tillage systems compared with the no-biochar application, except at 20–40 cm soil depth. Overall, increase in soil AP at 10–20 cm depth due to biochar addition was 78.23% during the two alfalfa-growing seasons.

FIGURE 5 Sediment during alfalfa-growing seasons of (a) 2020 and (b) 2021 in the various treatments



The effect of biochar application and the tillage practice on soil total potassium (K) content was inconsistent at different depths during the two alfalfa-growing seasons. In 2020, biochar addition significantly ($p < .05$) decreased soil total K content in the FP and TR (Table 5). At 10–20 cm depth, the application of the maize straw biochar significantly ($p < .05$) increased soil K for all the tillage systems compared with the counterpart treatments without biochar amendment. In 2021, biochar addition markedly increased soil K at 0–10 cm depth compared with the corresponding no-biochar treatments. In general, the amendment of maize straw biochar increased soil K by ~8 g/kg at 0–10 cm depth (Table 5). For SOM, in 2020, the amendment of biochar to the FP and OR treatment significantly ($p < .05$) increased SOM at 0–10 cm depth compared with the counterpart treatment with no-biochar application. In 2021, biochar amendment increased SOM at 0–10 cm depth in all the tillage systems, but the opposite was observed at 20–40 cm depth where SOM was lower for the FP and TR amended with maize straw biochar compared with the no-biochar-amended counterpart treatments (Table 5).

4 | DISCUSSION

4.1 | Run-off

Periodic precipitation in semiarid regions results in high run-off and soil erosion because of the weak and unstable

structure of soils in the regions (Feng et al., 2018). Results showed that high precipitation in 2020 slightly increased run-off compared with that in 2021. The application of maize straw biochar decreased run-off by 37.81% to 40.90% during alfalfa-growing seasons in 2020 and 2021. The results are consistent with the study by Smetanová et al. (2013), who found that the application of 10% maize straw biochar to a fluvial sand decreased run-off by 40%. The low run-off in biochar-amended soil in the present study could be attributed to biochar's influence on soil aggregation and stability, and infiltration, which might have reduced the time lag in run-off production. Kumar et al. (2020) and Sadeghi et al. (2016) reported that the amendment of biochar derived from *Eucalyptus saligna* Sm. Trees and vinasse, respectively, decreased run-off time by about 55% at a rainfall intensity of 50 mm/h compared with the no-biochar-amended soil. A reduction in run-off led to less soil erosion, which in turn reduced crop water stress and soil degradation (Mak-Mensah, Obour, Essel, et al., 2021; Mak-Mensah, Obour, & Wang, 2021). Ridge and furrow rainwater conservation methodologies can reduce sediment yield in run-off and improve soil conditions for crop productivity (Ranaivoson et al., 2018). Results showed that the application of maize straw biochar to the Calcic Cambisol led to lower total sediment yield during alfalfa-growing seasons compared with the no-biochar treatment.

The TR significantly reduced sediment yield compared with the OR treatment with and without biochar.

TABLE 2 Soil bulk density in different soil layers during alfalfa cultivation in 2020 and 2021

Biochar application	Tillage systems	2020			2021			Average		
		0–10 cm	10–20 cm	20–40 cm	0–40 cm	0–10 cm	10–20 cm	20–40 cm	0–40 cm	Average 0–40 cm
Soil bulk density (g/cm ³)										
No-Biochar	Flat planting	1.35 ± 0.03a	1.38 ± 0.04a	1.39 ± 0.03a	1.37 ± 0.02a	1.31 ± 0.01a	1.32 ± 0.02a	1.37 ± 0.01a	1.33 ± 0.01a	
	Open-ridging	1.30 ± 0.01ab	1.34 ± 0.03ab	1.37 ± 0.01a	1.34 ± 0.02a	1.23 ± 0.02b	1.24 ± 0.04ab	1.27 ± 0.03b	1.25 ± 0.01b	
	Tied-ridging	1.24 ± 0.02b	1.31 ± 0.03ab	1.33 ± 0.05ab	1.30 ± 0.04ab	1.19 ± 0.03b	1.19 ± 0.03bc	1.21 ± 0.03bc	1.20 ± 0.03bc	
Biochar	Flat planting	1.16 ± 0.02c	1.27 ± 0.04bc	1.29 ± 0.02bc	1.24 ± 0.02bc	1.11 ± 0.03c	1.12 ± 0.02cd	1.15 ± 0.02cd	1.13 ± 0.02cd	
	Open-ridging	1.13 ± 0.04c	1.21 ± 0.03cd	1.23 ± 0.02cd	1.19 ± 0.04cd	1.05 ± 0.03cd	1.06 ± 0.04de	1.10 ± 0.03de	1.07 ± 0.04de	
	Tied-ridging	1.10 ± 0.03c	1.16 ± 0.02d	1.18 ± 0.01d	1.15 ± 0.01d	1.02 ± 0.02d	1.03 ± 0.02e	1.06 ± 0.02e	1.04 ± 0.03e	
Mean	1.30 ± 0.04	1.34 ± 0.03	1.37 ± 0.04	1.34 ± 0.04	1.24 ± 0.03	1.25 ± 0.01	1.28 ± 0.03	1.26 ± 0.02		
	Biochar	1.13 ± 0.03	1.21 ± 0.02	1.24 ± 0.03	1.19 ± 0.02	1.06 ± 0.04	1.07 ± 0.04	1.10 ± 0.02	1.08 ± 0.03	

Note: For each column, mean values with different letters significantly differ at $p < .05$. ± indicates standard deviation of the mean.

Overall, biochar addition reduced soil loss by ca. 55.54% compared with the no-biochar-added soil during alfalfa-growing seasons investigated. The results corroborate that of Lee et al. (2018), who found that incorporating driftwood biochar into a Typic Paleudults decreased soil erosion by 45%–78%. The reduction in run-off and sediment yield for the biochar and TR treatment could be ascribed to increased soil porosity which improved water infiltration into the soil. Also, biochar application can reduce sediment yield through its ability to influence soil aggregation because of the interaction between soil SOM, soil minerals and microorganisms (Ma et al., 2016). Islam et al. (2021) argued that the ability of biochar to improve soil aggregation is highly influenced by biochar attributes such as feedstock type, pyrolysis temperature and experimental conditions like soil type. In general, soil aggregation increases for wood biochar, at higher pyrolysis temperature (>600°C) and in loamy-textured soils (Islam et al., 2021).

4.2 | Soil bulk density

Soil bulk density is a crucial soil physical property governing water and nutrient availability in the soil and root proliferation. High bulk density is an indication of soil compaction, which adversely affects plant growth. The application of organic amendments such as biochar can reduce soil bulk density and improve soil hydraulic properties (Schnee et al., 2021). Results showed that the application of maize straw biochar for 2 years reduced soil bulk density at 0–40 cm soil depth compared with the no-biochar treatment (Tables 1 and 2). The decrease in soil bulk density in the biochar-amended soil could be attributed to high porosity of biochar compared with soil minerals (Blanco-Canqui, 2017). For tillage practice, the TR treatment generally reduced soil bulk density which is consistent with the findings by Biazin et al. (2012) who reported that TR reduced surface bulk density of upland Alfisols, which increased soil aeration, promoted root growth and increased root access to nutrients and water. The present study further showed that the reduction in soil bulk density in the TR compared with the OR and FP was generally pronounced in the biochar amendment treatment. The low soil bulk density for the TR with biochar could be interpreted as soil fragmentation during the ridge preparation loosened the soil, which combined with the porous biochar material to reduce soil bulk density. The lack of significant difference between the TR and FP or OR at 0–10 cm depth in 2020 could be explained as due to local compaction from repacking of the fragmented soil aggregated in the ridge.

TABLE 3 Soil pH and soil total nitrogen in different soil layers during alfalfa cultivation in 2020 and 2021

Biochar application	Tillage systems	2020		Average		2021			Average 0–40 cm
		0–10 cm	10–20 cm	20–40 cm	0–40 cm	0–10 cm	10–20 cm	20–40 cm	
Soil pH [water]									
No-Biochar	Flat planting	8.13 ± 0.68a	8.24 ± 0.63a	8.42 ± 0.15a	8.26 ± 0.51a	7.96 ± 0.22a	7.95 ± 0.30a	7.98 ± 0.51a	7.96 ± 0.68a
	Open-ridging	8.01 ± 0.25a	8.11 ± 0.70a	8.22 ± 0.45a	8.11 ± 0.74a	8.07 ± 0.68a	7.99 ± 0.65a	8.03 ± 0.44a	8.03 ± 0.63a
	Tied-ridging	8.01 ± 0.26a	8.12 ± 0.26a	8.23 ± 0.64a	8.12 ± 0.34a	8.09 ± 0.55a	8.04 ± 0.67a	8.08 ± 0.65a	8.07 ± 0.79a
Biochar	Flat planting	7.94 ± 0.60a	8.04 ± 0.50a	8.18 ± 0.36a	8.05 ± 0.42a	8.04 ± 0.36a	8.09 ± 0.57a	8.16 ± 0.58a	8.10 ± 0.60a
	Open-ridging	7.79 ± 0.42a	8.13 ± 0.46a	8.26 ± 0.53a	8.06 ± 0.57a	7.99 ± 0.66a	8.08 ± 0.23a	8.10 ± 0.17a	8.06 ± 0.70a
	Tied-ridging	7.87 ± 0.20a	7.89 ± 0.57a	8.08 ± 0.55a	7.95 ± 0.40a	8.24 ± 0.14a	8.02 ± 0.56a	8.04 ± 0.49a	8.10 ± 0.37a
Mean	No-Biochar	8.05 ± 0.73	8.16 ± 0.70	8.29 ± 0.52	8.17 ± 0.51	8.03 ± 0.73	8.03 ± 0.78	8.07 ± 0.69	8.04 ± 0.33
	Biochar	7.87 ± 0.36	8.02 ± 0.66	8.17 ± 0.61	8.02 ± 0.45	8.09 ± 0.29	8.04 ± 0.55	8.08 ± 0.71	8.07 ± 0.59
Soil total nitrogen (g/kg)									
No-Biochar	Flat planting	1.44 ± 0.07a	0.54 ± 0.01c	0.81 ± 0.05a	0.93 ± 0.01a	0.85 ± 0.08c	0.66 ± 0.05c	0.72 ± 0.05b	0.74 ± 0.01c
	Open-ridging	0.77 ± 0.03cd	0.75 ± 0.04a	0.51 ± 0.04b	0.68 ± 0.04bc	1.12 ± 0.04c	1.06 ± 0.06b	1.05 ± 0.06a	1.08 ± 0.04b
	Tied-ridging	0.64 ± 0.03d	0.65 ± 0.03ab	0.51 ± 0.05b	0.60 ± 0.02c	1.18 ± 0.09b	0.92 ± 0.05b	1.06 ± 0.04a	1.05 ± 0.04b
Biochar	Flat planting	0.64 ± 0.06d	0.62 ± 0.02bc	0.92 ± 0.08a	0.73 ± 0.03b	1.72 ± 0.06b	1.46 ± 0.09a	0.99 ± 0.05a	1.39 ± 0.03a
	Open-ridging	0.94 ± 0.06b	0.72 ± 0.07ab	0.54 ± 0.05b	0.73 ± 0.04b	1.05 ± 0.07b	0.65 ± 0.02c	0.65 ± 0.03bc	0.78 ± 0.02c
	Tied-ridging	0.90 ± 0.05bc	0.75 ± 0.04a	0.64 ± 0.05b	0.76 ± 0.03b	0.86 ± 0.06a	0.99 ± 0.07b	0.59 ± 0.02c	0.81 ± 0.01c
Mean	No-Biochar	0.95 ± 0.05	0.65 ± 0.03	0.61 ± 0.05	0.74 ± 0.02	1.19 ± 0.06	0.95 ± 0.08	0.89 ± 0.07	1.01 ± 0.04
	Biochar	0.83 ± 0.06	0.70 ± 0.06	0.70 ± 0.04	0.74 ± 0.04	1.19 ± 0.09	1.02 ± 0.03	0.87 ± 0.07	1.03 ± 0.03

Note: For each column, mean values with different letters significantly differ at $p < .05$. ± indicates standard deviation of the mean.

TABLE 4 Soil total phosphorus and soil available phosphorus in different soil layers during alfalfa cultivation in 2020 and 2021

Biochar application	Tillage systems	2020			2021			Average	
		0–10 cm	10–20 cm	20–40 cm	0–40 cm	0–10 cm	10–20 cm		20–40 cm
Soil total phosphorus (g/kg)									
No-Biochar	Flat planting	0.51 ± 0.04ab	0.39 ± 0.02c	0.44 ± 0.04ab	0.45 ± 0.01b	0.44 ± 0.04b	0.38 ± 0.01b	0.43 ± 0.04b	0.42 ± 0.02b
	Open-ridging	0.52 ± 0.04ab	0.43 ± 0.02c	0.37 ± 0.03bc	0.44 ± 0.03b	0.50 ± 0.03b	0.45 ± 0.03b	0.53 ± 0.02a	0.49 ± 0.02ab
	Tied-ridging	0.51 ± 0.03ab	0.59 ± 0.04a	0.49 ± 0.04a	0.53 ± 0.03a	0.51 ± 0.05b	0.43 ± 0.02ab	0.44 ± 0.03b	0.46 ± 0.04b
Biochar	Flat planting	0.55 ± 0.04a	0.39 ± 0.01c	0.21 ± 0.01d	0.38 ± 0.02b	0.51 ± 0.05b	0.47 ± 0.01a	0.47 ± 0.04ab	0.48 ± 0.04b
	Open-ridging	0.44 ± 0.03b	0.52 ± 0.04ab	0.34 ± 0.02c	0.43 ± 0.03b	0.85 ± 0.07a	0.45 ± 0.03a	0.42 ± 0.02b	0.57 ± 0.03a
	Tied-ridging	0.49 ± 0.01ab	0.47 ± 0.04bc	0.39 ± 0.03bc	0.45 ± 0.04b	0.53 ± 0.03b	0.39 ± 0.02a	0.39 ± 0.02b	0.44 ± 0.03b
Mean		0.51 ± 0.02	0.47 ± 0.03	0.44 ± 0.04	0.47 ± 0.03	0.56 ± 0.01	0.44 ± 0.02	0.46 ± 0.02	0.49 ± 0.01
	Biochar	0.49 ± 0.03	0.46 ± 0.03	0.31 ± 0.03	0.42 ± 0.04	0.58 ± 0.01	0.44 ± 0.02	0.45 ± 0.04	0.49 ± 0.03
Soil-available phosphorus (mg/kg)									
No-Biochar	Flat planting	31.96 ± 1.13a	9.55 ± 0.40d	14.32 ± 0.82b	18.61 ± 0.89a	9.53 ± 0.78e	21.70 ± 0.64e	31.10 ± 0.25a	20.78 ± 1.97d
	Open-ridging	6.71 ± 0.30e	17.18 ± 1.06c	6.08 ± 0.16c	9.99 ± 0.82c	16.87 ± 0.42d	16.86 ± 0.83de	6.39 ± 0.40e	13.37 ± 1.17e
	Tied-ridging	27.38 ± 1.29b	16.74 ± 0.88d	2.74 ± 0.13d	15.62 ± 1.18b	10.02 ± 0.41e	11.96 ± 0.76d	7.34 ± 0.22de	9.77 ± 0.43e
Biochar	Flat planting	14.60 ± 0.64d	5.85 ± 0.08b	5.37 ± 0.41c	8.61 ± 0.63c	66.76 ± 0.59c	11.28 ± 0.80c	8.11 ± 0.49d	28.72 ± 2.59c
	Open-ridging	6.80 ± 0.10e	7.70 ± 0.45a	3.22 ± 0.15d	5.91 ± 0.23d	109.49 ± 0.21b	69.21 ± 0.60b	14.66 ± 0.85b	64.45 ± 2.21a
	Tied-ridging	21.33 ± 1.35c	5.30 ± 0.16a	30.33 ± 0.84a	18.99 ± 0.82a	126.62 ± 0.79a	9.56 ± 0.85a	10.03 ± 0.59c	48.74 ± 3.16b
Mean		22.02 ± 0.87	14.49 ± 0.45	7.71 ± 0.67	14.74 ± 0.59	42.53 ± 0.90	26.20 ± 0.65	13.52 ± 0.74	27.42 ± 1.47
	Biochar	14.24 ± 0.80	6.28 ± 0.38	12.97 ± 0.74	11.16 ± 0.79	65.95 ± 0.74	23.77 ± 0.69	9.31 ± 0.17	33.01 ± 2.14

Note: For each column, mean values with different letters significantly differ at $p < .05$. ± indicates standard deviation of the mean.

TABLE 5 Soil total potassium and SOM in different soil layers during alfalfa cultivation in 2020

Biochar application	Tillage systems	2020			2021			Average
		0–10 cm	10–20 cm	20–40 cm	0–10 cm	10–20 cm	20–40 cm	
Soil total potassium (g/kg)								
No-Biochar	Flat planting	10.55 ± 0.80a	9.41 ± 0.27b	11.15 ± 0.56a	10.04 ± 0.63a	10.31 ± 0.74a	11.06 ± 0.52a	10.47 ± 0.69a
	Open-ridging	11.06 ± 0.99a	10.92 ± 0.82ab	10.79 ± 0.43a	10.73 ± 0.97a	9.66 ± 0.57a	8.82 ± 0.73a	9.74 ± 0.04a
	Tied-ridging	10.66 ± 0.87a	11.37 ± 0.90a	11.58 ± 0.93a	10.88 ± 0.86a	10.21 ± 0.73a	8.96 ± 0.61a	10.02 ± 0.42a
Biochar	Flat planting	10.22 ± 0.58a	11.08 ± 0.49ab	11.61 ± 0.47a	10.82 ± 0.39a	10.37 ± 0.90a	8.92 ± 0.55a	10.04 ± 0.91a
	Open-ridging	11.98 ± 0.77a	11.91 ± 0.95a	11.38 ± 0.97a	11.11 ± 0.95a	10.27 ± 0.97a	9.09 ± 0.43a	10.16 ± 0.76a
	Tied-ridging	11.20 ± 1.10a	10.83 ± 0.48ab	11.36 ± 0.08a	11.02 ± 0.75a	10.53 ± 0.84a	10.08 ± 0.46a	10.54 ± 0.37a
Mean	No-Biochar	10.76 ± 0.63	10.57 ± 0.96	11.17 ± 1.08	10.55 ± 0.74	10.06 ± 0.95	8.82 ± 0.70	9.81 ± 0.42
	Biochar	11.13 ± 0.80	11.27 ± 0.51	11.45 ± 0.78	10.98 ± 0.97	10.39 ± 1.08	9.36 ± 0.47	10.24 ± 0.85
Soil organic matter (g/kg)								
No-Biochar	Flat planting	17.44 ± 0.69a	14.36 ± 0.76cd	13.46 ± 1.09a	6.15 ± 0.38c	8.63 ± 0.77ab	36.49 ± 0.65a	17.09 ± 0.92a
	Open-ridging	13.06 ± 0.92b	15.75 ± 1.15abc	10.2 ± 0.20c	12.65 ± 0.31a	10.24 ± 0.85a	14.51 ± 0.49e	12.47 ± 0.78c
	Tied-ridging	15.86 ± 1.41a	15.17 ± 1.22bcd	11.29 ± 0.68bc	4.32 ± 0.32d	6.52 ± 0.60c	24.66 ± 0.71c	11.83 ± 0.86c
Biochar	Flat planting	16.88 ± 0.28a	17.46 ± 1.24ab	12.44 ± 0.83ab	12.86 ± 0.41a	7.98 ± 0.64bc	26.96 ± 0.72b	15.93 ± 0.96ab
	Open-ridging	16.48 ± 0.81a	18.46 ± 1.31a	11.62 ± 0.78abc	11.36 ± 0.44b	9.64 ± 0.54ab	21.11 ± 0.67d	14.04 ± 1.02bc
	Tied-ridging	17.93 ± 1.35a	12.57 ± 0.84d	13.61 ± 0.68a	10.25 ± 0.57b	8.21 ± 0.71bc	7.57 ± 0.61f	8.68 ± 0.48d
Mean	No-Biochar	15.45 ± 1.17	15.09 ± 1.45	11.65 ± 0.49	9.47 ± 0.52	8.60 ± 0.64	24.75 ± 0.49	14.27 ± 0.47
	Biochar	17.10 ± 1.50	16.16 ± 1.50	12.56 ± 0.55	10.29 ± 0.37	8.52 ± 0.80	18.96 ± 0.56	12.59 ± 1.04

Note: For each column, mean values with different letters significantly differ at $p < .05$. ± indicates standard deviation of the mean.

4.3 | Soil organic matter and pH

Because of its rich carbon content, amendment of biochar to soil can increase SOM (Liu et al., 2016). Biochar is commonly colonized by bacteria, actinomycetes and arbuscular mycorrhizal fungi, so increased SOM could be an indication of microbial C responses (Kimetu & Lehmann, 2010; Lehmann et al., 2011). Through surface catalytic activity, biochar can oxidize soil organic molecules and boost its polymerization to produce organic matter (van Zwieten et al., 2010). In the present study, maize straw biochar amendment increased SOM, albeit some inconsistencies for the different tillage systems and soil depths investigated.

An increase in soil pH can improve soil quality in various ways. From the chemical point of view, increase in soil pH increases plant nutrient accessibility and, in some cases, decreases the abundance of harmful chemical elements like Al (Bedassa, 2020). Biochar naturally contains ash and supplies free bases to the soil (Glaser et al., 2002), which raise the pH of the soil, particularly acidic soils to make nutrients more readily available for plant growth. The present study showed that the application of maize straw biochar did not significantly affect the soil pH at any depth during the two alfalfa-growing seasons. The lack of significant effect of the maize straw biochar amendment on soil pH in this study is probably because the investigated soil had a pH ranging from neutral to alkaline. This suggests that perhaps, more time than just two growing seasons may be needed before any significant change in soil pH could be observed.

4.4 | Soil-available phosphorus

Bedassa (2020) reported that the highest phosphorus availability occurred between pH of 6.0 to 7.0. For mineral soils, however, phosphorus is most readily available near pH 6.5 (Bedassa, 2020). Biochar constitutes high soluble phosphorus salt content formed during organic materials charring (DeLuca et al., 2012). Results showed that the no-biochar treatment had higher soil-AP during alfalfa cultivation in the first season while biochar-amended soil had higher soil-AP in the second experimental season. This confirmed the previous findings, showing that biochar application has a mixed effect on soil P availability because it influences the P cycle indirectly and directly in different ways (Albuquerque et al., 2014; Lamptey et al., 2017). Biochar addition can increase soil P because of its direct P supply or decrease soil P because of increased microbial functionalities (Rasuli et al., 2022). According to Lehmann and Rondon (2006), an increase in soil P abundance after biochar application could be because of biochar's direct

nutrient supplementation and changes in soil microbial evolution.

4.5 | Soil total nitrogen and potassium

Intensive crop cultivation in addition to mining crop residues can lead to low soil TN content in agricultural soils. In this study, the effect of maize straw biochar application on soil TN was not consistent during the growing seasons in 2020 and 2021. For the first season, the biochar treatment had lower TN, while in the second season, the biochar treatment recorded higher soil TN compared with the no-biochar treatment. The variation in TN is affected by many factors including soil depth, vegetation coverage, climate and particle size (Liu et al., 2021). In the present study, drainage and biochar might have influenced the TN values because rainfall amount was higher in 2020 compared to that in 2021. Previous studies found that biochar can improve soil nitrogen through direct surface assimilation and/or indirect microbial immobilization effects (Cayuela et al., 2014; Ippolito et al., 2012). Biochar can preserve nitrogen because of its porous nature and large surface area and, thus, improve soil nitrogen levels (Huang et al., 2013; Spokas et al., 2012). Furthermore, biochar can improve nitrogen adsorption and retention, reduce soil nitrogen losses, improve ammonia to nitrite oxidation, and soil NO_3^- -N contents, which in turn can increase nitrogen availability (Case et al., 2015; Nelissen et al., 2013). In the present study, biochar amendment increased soil total K content during alfalfa-growing seasons compared with the no-biochar-amended soil. Karimi et al. (2020) reported that corn residue biochar increased K availability in calcareous soils by 1.52–2.59 times, with the highest increase being associated with biochar pyrolysed at a higher temperature (500°C). Khadem et al. (2021) also found that the application of corn biochar pyrolysed at 200–600°C increased available K by 12.41% in two calcareous soils.

5 | CONCLUSIONS

The integration of maize straw biochar at 30 t ha^{-1} to a Calcic Cambisol soil reduced total run-off and sediment yield compared to the no-biochar treatment. The results showed biochar amendment increased soil total potassium by 8 g/kg during the 2021 alfalfa-growing season compared to the no-biochar-treated soil. In general, the effect of maize straw biochar amendment and ridge-furrow rainwater harvesting system on soil-available phosphorus, total nitrogen, total phosphorus and pH in both alfalfa-growing seasons was not obvious at the investigated soil depths. This study highlights the potential

of integrating biochar and ridge-furrow rainwater harvesting system to reduce the risk of land degradation because of soil erosion in semiarid regions in China. However, the inconsistencies in biochar effects on soil-available phosphorus, total nitrogen, total phosphorus, and pH suggested a need for further studies longer than the two growing seasons in the present work to ascertain whether any significant changes will be observed. Such empirical evidence could provide strong basis for advancing the integration of maize straw biochar and suitable tillage technology among farmers to improve soil conditions for crop productivity and yield in dryland areas.

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CONFLICT OF INTEREST

The authors declare there are no competing interests.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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