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ORIGINAL PAPER

Influence of Tied-Ridge with Maize Straw Biochar on Alfalfa Fodder Yield, Nutritional Quality, and Production Economics

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Abstract

Alfalfa (*Medicago sativa* L.) is commonly fed to a wide range of livestock as hay or silage. However, the impact of management practices on alfalfa productivity is under-studied. Thus, the objective of this study was to investigate whether ridge-furrow rainwater harvesting technology with biochar compared to flat planting affects alfalfa fodder yield and nutritional quality in China's Loess Plateau. A study was carried out in a split-plot design. The treatments were maize straw biochar applied at 30 t ha^{-1} vs. no-biochar-amended soil (control) and rainwater harvesting methods namely tied-ridging (TR), open-ridging (OR), and flat planting (control). Application of biochar to TR significantly ($p < 0.05$) increased alfalfa fodder yield compared to the OR treatment. The CP concentration of alfalfa fodder for the OR with biochar addition increased by 37.62% compared with OR with no-biochar application. The ADF of alfalfa cultivated on the biochar-amended soil increased by 10.74% compared with the no-biochar application. Regardless of biochar application, NDF for the alfalfa grown on OR increased by 6.04% compared with the FP. Relative feed value and net economic benefit of alfalfa fodder tended to increase for the TR with biochar application than the no-biochar treatment during the two growing seasons. Evidence from the 2-year experiment suggested that integrating maize straw biochar and ridge-furrow rainwater harvesting significantly increased alfalfa fodder yield, CP, ADF, and NDF. Based on our findings, we recommend the use of ridge-furrow rainwater harvesting, together with the amendment of maize straw biochar, to help increase alfalfa fodder yield in semi-arid areas.

Keywords Alfalfa fodder yield · Alfalfa fodder quality · Maize straw biochar · Production economics · Ridge-furrow rainwater harvesting system · Tied-ridging

1 Introduction

Livestock production is an important component of agriculture worldwide, providing a high-value protein and several essential micronutrients such as iron and zinc and vitamins. Additionally, livestock provides an important source of draft power, farm manure, and income which helps in poverty alleviation (Wanapat et al. 2015). Thus, livestock production is vital to livelihood subsistence and socio-economic development and plays a crucial role in meeting the goals set out in the UN 2030 Agenda for Sustainable Development, especially Goal 1 (End poverty in all its forms everywhere) and Goal 2 (End hunger, achieve food security and improve nutrition, and promote sustainable agriculture) (Johnston 2016).

Domestic cattle including yak, bison, cow, and buffalo rearing is a major livestock production system across the globe. Cattle are kept as possessions, ceremonial objects, and source of meat, milk, leather, and manure for fertilizer (Oduniyi et al. 2020). Globally, cattle population is reported to have increased from around 989 million in 2019 to over one billion in 2020 (Shahbandeh 2022). In China, cattle production is widely practiced particularly in arid and semi-arid areas. The cattle herd in China was estimated to be ~61 million in 2020 (Liu et al. 2019). Production largely depends on the quality and quantity of feed (Mengistu et al. 2019). Cattle fed with high-quality forage deliver better milk and meat, which could benefit the nutritional health of consumers.

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Alfalfa (*Medicago sativa* L.) is a long-lived perennial legume fed to a wide range of livestock as hay or silage. Alfalfa has a high tolerance for warm and cold climates, and cultivation provides other benefits such as improving soil fertility and physical quality. Though the importance of alfalfa and other forages is gaining popularity, acreage and productivity are reported to have been stagnated or declined in some regions over the past two decades (Pereira 2018). This has been attributed to high competition for land for crops and construction to meeting the demands of the increasing population. More importantly, land degradation and climate change–related constraints like high temperatures, prolonged droughts, rainfall variability, and water scarcity have adverse effects on the productivity of alfalfa and other fodder (forage) plants (Ranjan et al. 2017). Consequently, at present, a large fraction of pasture fields, particularly in arid and semiarid regions, are unable to produce sufficient fodder to meet the nutritional needs of livestock (Özköse 2018).

Given the importance of forage plants like alfalfa production to the livestock sector, it is important to improve yield to ensure sustainable livestock production. Addressing challenges such as poor soil fertility could be achieved by increasing the use of mineral fertilizers. However, the option can be costly and can have several environmental problems if applied inappropriately or excessively (Khan et al. 2020). Rainwater harvesting and the use of organic amendments such as biochar have been suggested as sustainable ways of addressing plant water stress and improving soil quality for crop production, respectively (Agegnehu et al. 2017). Biochar is a stable carbon-rich material produced when the feedstock is heated in a closed container with little or no oxygen (Reddy et al. 2015). Though biochar characteristics differ depending on factors such as feedstock and pyrolysis temperature, the presence of hydrophilic domains, large specific surface, and high porosity characterizing biochar can improve soil physical, chemical, and biological properties for plant growth (Hossain et al. 2020). For example, Liu et al. (2017) reported that the addition of 20 and 40 t ha^{-1} wheat straw biochar increased the productivity of maize (*Zea mays* L.) by 6.1% and 6.9%, peanut (*Arachis hypogaea* L.) by 6.6% and 11.2%, and soybean (*Glycine max* L.) by 7.2% and 7.6%. However, Ye et al. (2020) argued that biochar addition to soil can promote crop productivity in tropical and subtropical climates more than in other types of climates.

Until now, the potential of combining rainwater harvesting technologies and biochar to improve the productivity and economy of alfalfa for livestock fodder in drought-stricken regions is under-studied. Such information is relevant to increase forage plant production for animal nutritional security. The objective of this study was to examine whether yield, nutritional quality in terms of concentrations of crude protein (CP), neutral detergent fiber (NDF) and acid detergent fiber (ADF), and net economic benefit of alfalfa herbage are affected by the integration of maize straw biochar application and ridge-furrow rainwater harvesting methods in Northwestern China. We hypothesized that the amendment of maize straw biochar to ridge-furrow rainwater harvesting methods increases alfalfa fodder yield and economic returns more than the no-biochar amendment and/or flat planting.

2 Materials and Methods

2.1 Experimental Site Description

The study was conducted at Anjiagou Catchment experimental station from 2020 to 2021. For decades, the experimental site has been subjected to severe water erosion. The average annual precipitation from 1971 to 2018 was approximately 404.5 mm. The average annual pan evaporation was 1515 mm. According to the USDA soil taxonomy, the soil at the experimental station is Calcic Cambisol. The permanent wilting point of the site was 5.16% and the field water holding capacity was 21%. The distance between the soil surface and the water table ranges from 30 and 100 m (Wei et al. 2015).

2.2 Experimental Design

The experimental design was a split-plot in three replications. Biochar application was the main treatment and rainwater harvesting methods were the sub-treatment (Fig. 1). There were two biochar treatments, 0 ha^{-1} and 30 t ha^{-1}. The biochar used was maize straw biochar produced with residence time up to 2 h at 400 ℃. The properties of the biochar are presented in Table 1. A detail of soil property characterization before and after growing seasons is presented in supplementary Table S1. The rainwater harvesting treatments were flat planting (FP), tied-ridging (TR), and open-ridging (OR). In total, there were six treatments (two biochar treatments and three rainwater harvesting methods). Except for treatments with FP, each treatment field had nine ridges and ten furrows. Each treatment field was 52.5 m^2 (5 × 10.5 m) in size. The rainwater harvesting scheme ridge width was 45 cm with height varying from 15 to 20 cm, and a furrow width of 60 cm for TR and OR treatment. The width of the ties was 15 cm, and the height was 20 cm. The space between two ties that were not staggered was 2.5 m. Ridges were mulched with biodegradable film (Ecoflex FS; BASF Co Ltd, Germany), 1.4 m in width and 0.008 mm in thickness, while ties in TR were naturally compacted through wetting and drying cycles. The ridges were used for runoff collection, whereas the furrow was employed for planting and for infiltration. Eighteen treatment plots were constructed 1.5 m apart by two cement adjacent borders, buried 20 cm in the soil and 15 cm above the ground.

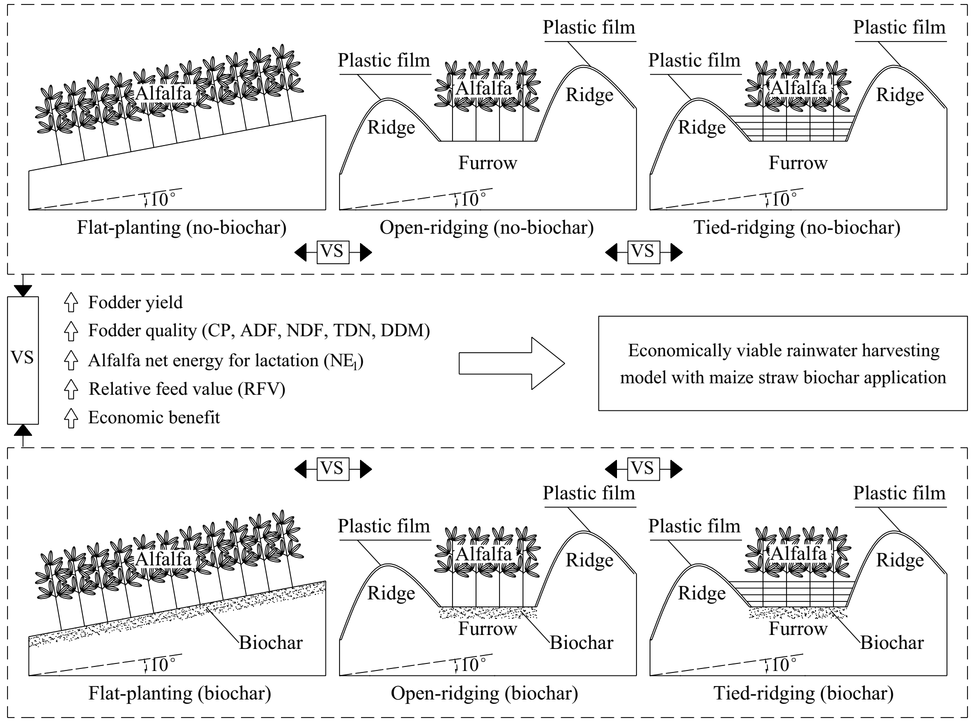

Fig. 1 Schematic representation of ridge-furrow rainwater harvesting system with maize straw biochar application on sloped land. VS = versus (against)

Table 1 Characteristics of the maize straw biochar

Bulk density g cm^{-3}	Surface area m^2 g^{-1}	Cation exchange capacity cmol kg^{-1}	pH v/v 1:2.5 biochar:distilled water	Water holding capacity (24 h) %	Total N %	Total C content %	Electric conductivity (µs/cm)
0.45	44	24.1	7.5	288	0.3	89	238

2.3 Field Management

The field site was cleared and raked on March 20, 2020. The plots were marked on April 2, 2020. On April 12, 2020, the treatment ridges and furrows for the rainwater harvesting treatments were constructed by molding the soil into ridges and furrows across the length of the fields. The ridges were immediately covered with biodegradable film and secured beneath 3 cm of soil. In 2021, the procedure was repeated from March 20 to March 24. Before sowing, the field site was harrowed, and the furrows were leveled. The maize straw biochar was ground and sieved to 5 mm before it was amended to the soil. The biochar was mixed with the soil on April 14, 2020, using a hoe. On April 15, 2020, a native alfalfa variety (No. 3 Gannong) was sown 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 m^2 with 40 alfalfa-planted rows. The FP treatment field was 50.25 m^2 with 66 alfalfa sown rows. Approximately 2 months after seeding, the ties in tied-ridging treatments were manually banked and reinforced with soil. Before, during, or after alfalfa cultivation, neither fertilizer nor irrigation was used because alfalfa is a nitrogen-fixing legume and it is sensitive to excessive soil water.

2.4 Sampling and Measurements

2.4.1 Fodder Yield and Forage Quality

Alfalfa was manually harvested (first cutting) at the beginning of flowering (between the first bloom and when 25% of the plants were in bloom), 42 days after first cutting (second cutting), and at the end of senescence (third cutting). In 2020, alfalfa was harvested three times, whereas in 2021, it was harvested twice. Alfalfa was not harvested at the third cutting in 2021 because of weather and growth-related challenges. Alfalfa's actual fodder yield (AFY) was quantified from the samples collected on ridges and in furrows (including tied-ridge areas) while net fodder yield (NFY) was determined from the samples harvested in furrow areas (excluding tied-ridges) only. The harvested crop was weighed immediately after harvest. Leaf samples were dried at room temperature and ground into fine powder to estimate fodder yield. The Kjeldahl method was used to estimate total nitrogen (total N) (Sadeghpour et al. 2013), and crude protein (CP) was measured by multiplying the nitrogen content by the constant factor of 6.25 to convert nitrogen values to crude protein (CP) (Rodrigues et al. 2018) and determined by AOAC procedures (2005). Neutral detergent fiber (NDF) and acid detergent fiber (ADF) were evaluated using heat-stable amylase and VS-acid detergent fiber, respectively, as described by Grzegorczyk et al. (2017). Total digestible nutrients (TDN), relative feed value (RFV), digestible dry matter (DDM), and net energy for lactation (NE_l) were calculated following equations adapted from Sadeghpour et al. (2013), and Holman et al. (2016):

$$TDN = 4898 + ([1.044 - (0.119 \times \%ADF)] + (89.796) \quad (1)$$

$$RFV = \%DDM \times \%DMI \times 0.775, \quad (2)$$

$$DDM = 88.9 - (0.779 \times \%ADF;drymatterbasis), \quad (3)$$

$$Ne_1 = [1.044 - (0.0119 \times \%ADF)] \times 2.205 \quad (4)$$

2.5 Cost–Benefit Analysis

Total costs, revenue from hay sales, and net economic benefit (NEB) were considered in the cost–benefit analysis. The total production costs included seed and biodegradable film costs. The term "income" refers to the amount of money from the sale of fodder. The calculations, however, did not account for fixed costs such as land value, depreciation, or interest on capital. Labor was self-provided at zero cost for ridging, cross ties, weeding, application of biodegradable films, and other sampling operations. The major output considered in this analysis was alfalfa fodder yield. The net economic benefit was calculated as the difference between revenue from fodder yield and input costs (Guo et al. 2019). Total input (TI), total output (TO), and net profit (NP) were calculated using the following equations:

$$TI = PFI + SI \quad (5)$$

$$TO = AFY \times Pr \quad (6)$$

$$NP = TO - TI \quad (7)$$

where Y is the fodder yield; Pr is the local price of alfalfa fodder yield; PFI is the PF input and SI is the seed input.

2.6 Statistical Analysis

All statistical analyses were done with SPSS version 26 statistical software. Before statistical analyses, the data were statistically tested for normality using the Shapiro–Wilk test and variance homogeneity using the Levene test. Thereafter, a two-way analysis of variance (ANOVA) was used to examine variations between treatments. When the treatment effect was found to be significant, Tukey's pairwise comparison was performed to isolate which treatment means were significantly different at a 5% significance level.

3 Results

3.1 Fodder Yield and Crude Protein

Maize straw biochar addition led to considerably higher yield throughout alfalfa growing seasons in comparison with the no-biochar application (Table 2). The OR and TR significantly ($p < 0.05$) increased alfalfa fodder yield in biochar-amended plots as compared to the FP. Net fodder yield (NFY) in 2020 ranged from 806 to 4101 kg ha^{-1} for the no-biochar application, and from 907 to 4461 kg ha^{-1} for the biochar-amended plots. Annual total net fodder yield increased by 7.96% with biochar addition compared to the no-biochar application. Actual fodder yield (AFY) ranged from 545 to 2089 kg ha^{-1} for the no-biochar application, and from 552 to 2411 kg ha^{-1} for the biochar-amended treatment. Total annual yield for the OR and TR without biochar amendment increased by 38.63 and 34.06% compared to the FP, respectively, while for the OR and TR with biochar amendment, total annual fodder yield increased by 41.09 and 44.39%, respectively, compared to the FP. Overall, alfalfa fodder yield increased by 11.12% with biochar addition compared to the no-biochar application during the alfalfa growing season in 2020.

In 2021, alfalfa NFY largely ranged from 3101.87 to 6064.80 kg ha^{-1} with the no-biochar application, and from 5000 to 9490.73 kg ha^{-1} for the biochar-added plots (Table 2). Annual total net fodder yield increased by 51.10% with biochar addition compared to the no-biochar application. Alfalfa AFY ranged from 2155.9 to 3620.8 kg ha^{-1} with the no-biochar application, and from 3874 to 5666.1 kg ha^{-1} for the biochar-amended treatment. Total actual fodder yields were higher for the TR with no-biochar amendment compared to the counterpart FP treatment. Total annual AFY for the OR and TR increased by 9.80 and 11.62%, respectively, in the no-biochar-treated plots, while in the biochar-amended plots, AFY significantly ($p < 0.05$) increased by 16.00 and 21.09%, respectively. Overall, biochar application increased alfalfa fodder yield by 52.71% during the alfalfa growing season in 2021.

The OR and TR treatments with biochar increased the annual total CP concentration of alfalfa by 4.72 and 4.44%, respectively, compared with the OR and TR treatments with no-biochar addition. Overall, biochar addition in the FP

Table 2 Alfalfa fodder yield in ridge-furrow rainwater harvesting with biochar application

Biochar application	Rainwater harvesting method	Fodder yield (kg ha^{-1})							
		First cut		Second cut		Third cut		Annual total	
		NFY	AFY	NFY	AFY	NFY	AFY	NFY	AFY
2020									
No-biochar	Flat planting	1628 ± 39.7c	1628 ± 47.82c	1628 ± 40.74c	972 ± 6.9c	418 ± 9.32c	418 ± 24.5c	3018 ± 28.97c	3018 ± 37.42c
	Open-ridging	5289 ± 18.04b	2372 ± 43.97a	5289 ± 16.83a	1185 ± 34.49a	1013 ± 13.76a	627 ± 36.63a	8788 ± 21.56b	4184 ± 38.2a
	Tied-ridging	5387 ± 47.28a	2267 ± 46.52b	5387 ± 26.64a	1190 ± 26.77a	987 ± 21.08b	589 ± 22.17b	8855 ± 31.45a	4046 ± 9.73b
Biochar	Flat planting	1728 ± 14.09c	1728 ± 48.89c	1728 ± 30.75c	1027 ± 43.18c	487 ± 13.38c	487 ± 25.85c	3242 ± 32.4c	3242 ± 33.58c
	Open-ridging	5726 ± 32.7b	2679 ± 19.27b	5726 ± 26.66b	1298 ± 39.81a	1198 ± 5.99a	597 ± 28.52a	9451 ± 21.6b	4574 ± 27.5b
	Tied-ridging	5928 ± 43.98a	2826 ± 36.58a	5928 ± 29.88a	1283 ± 34a	1036 ± 35.58b	572 ± 12.12b	9612 ± 13.39a	4681 ± 39.17a
Mean	No-biochar	4101 ± 25.74	2089 ± 29.64	1980 ± 26.65	1116 ± 39.17	806 ± 44.2	545 ± 35.95	6887 ± 34.11	3749 ± 37.11
	Biochar	4461 ± 30.34	2411 ± 38.81	2067 ± 36.55	1203 ± 33.1	907 ± 39.04	552 ± 23.04	7435 ± 25.02	4166 ± 28.77
2021									
No-biochar	Flat planting	3101.85 ± 45.69e	3620.78 ± 39.83d	3240.74 ± 32.89d	2155.89 ± 19.54d	nd	nd	6342.59 ± 42.45e	5776.67 ± 34.46d
	Open-ridging	6064.81 ± 38.58c	3101.85 ± 34.13e	3611.11 ± 37.86d	3240.74 ± 20.81c	nd	nd	9675.93 ± 12.47d	6342.59 ± 41.94 cd
	Tied-ridging	5787.04 ± 42.33c	3316.75 ± 41.71e	5462.96 ± 36.67b	3131.01 ± 23.37c	nd	nd	11,250 ± 32.57c	6447.76 ± 48.1c
Biochar	Flat planting	5185.19 ± 42.16d	4537.31 ± 34.36c	5000 ± 14.93c	3873.96 ± 25.7b	nd	nd	10,185.19 ± 13.16d	8411.28 ± 47.71b
	Open-ridging	9490.74 ± 38.07a	5666.11 ± 16.45a	6851.85 ± 45.87a	4090.66 ± 21.34b	nd	nd	16,342.59 ± 44.45a	9756.77 ± 25a
	Tied-ridging	7916.67 ± 45.28b	5185.19 ± 31.47b	6759.26 ± 41.28a	5000 ± 38.16a	nd	nd	14,675.93 ± 38.65b	10,185.19 ± 34a
Mean	No-biochar	4985 ± 38.7	3346 ± 37.45	4105 ± 32.13	2843 ± 39.35	nd	nd	9090 ± 35.35	6189 ± 34.49
	Biochar	7531 ± 24.95	5130 ± 41.59	6204 ± 30.1	4322 ± 40.61	nd	nd	13,735 ± 39.76	9451 ± 45.66

The means (columns) labeled with the same letters within each group are not significantly different at the 5% level (Tukey's *b* test ANOVA) and ± indicates standard error of the mean. *NFY* net fodder yield, *AFY* actual fodder yield. The data were previously reported in Mak-Mensah et al. (under review). Alfalfa was not harvested at the third cutting in 2021 due to dry conditions and no regrowth. *nd* no data

slightly increased CP of alfalfa by 0.83% in 2020 compared with the FP with no biochar. In 2021, the biochar-amended plots tended to increase CP concentrations of alfalfa more than the no-biochar-treated plots irrespective of the rainwater harvesting method. As in 2020, there were significant variations in CP between the cuts. For first and second cuts, CP concentration of alfalfa significantly ($p < 0.05$) increased in biochar-amended plots by 10.55 and 8.75%, respectively, compared to the no-biochar-treated plots (Table 3).

3.2 Acid Detergent Fiber and Neutral Detergent Fiber

In 2020, acid detergent fiber (ADF) concentrations of alfalfa, on average, tended to increase in the biochar-amended plots than in the no-biochar-treated plots (Table 3). The TR treatment with maize straw biochar increased the annual total ADF concentration of alfalfa by 1.62% compared to the TR with the no-biochar application. The acid detergent fiber

Table 3 Seasonal crude protein concentrations and acid detergent fiber in alfalfa fodder yield in 2020 and 2021

Biochar application	Rainwater harvesting method	2020				2021			Average
		1st cut	2nd cut	3rd cut	Total	1st cut	2nd cut	Total	
Crude protein (g kg^{-1})									
No-biochar	Flat planting	20.48 ± 1.74a	20.74 ± 1.92a	21.84 ± 2.01ab	63.07 ± 1.38a	10.80 ± 0.52c	20.39 ± 0.88a	31.19 ± 1.96ab	47.13 ± 3.46a
	Open-ridging	19.42 ± 1.63ab	20.73 ± 1.46a	18.59 ± 1.61b	58.74 ± 2.94a	13.48 ± 0.59b	11.80 ± 0.90b	25.29 ± 1.31 cd	42.02 ± 1.30a
	Tied-ridging	18.61 ± 1.49ab	20.44 ± 1.51a	19.68 ± 0.32ab	58.72 ± 1.07a	13.96 ± 0.66b	13.53 ± 1.08b	27.49 ± 1.96bc	43.11 ± 3.62a
Biochar	Flat planting	18.12 ± 1.55ab	19.41 ± 0.44a	21.66 ± 1.35ab	59.18 ± 3.01a	8.67 ± 0.44d	13.57 ± 0.87b	22.24 ± 1.90d	40.71 ± 3.98a
	Open-ridging	16.52 ± 0.23b	21.47 ± 1.62a	23.52 ± 1.37a	61.52 ± 2.19a	12.50 ± 0.88b	22.30 ± 1.77a	34.80 ± 2.15a	48.16 ± 3.65a
	Tied-ridging	18.64 ± 0.87ab	21.70 ± 0.72a	21.00 ± 1.62ab	61.33 ± 2.87a	21.11 ± 0.35a	13.86 ± 0.64b	34.97 ± 1.99a	48.15 ± 2.23a
Mean	No-biochar	19.50 ± 1.60	20.64 ± 1.63	20.04 ± 1.15	60.18 ± 4.18	12.75 ± 0.36	15.24 ± 0.72	27.99 ± 1.17	44.09 ± 1.33
	Biochar	17.76 ± 1.33	20.86 ± 1.32	22.06 ± 1.49	60.68 ± 1.35	14.09 ± 0.61	16.58 ± 1.45	30.67 ± 1.51	45.68 ± 2.73
Acid detergent fiber (g kg^{-1})									
No-biochar	Flat planting	26.18 ± 1.80d	27.36 ± 0.80ab	15.95 ± 1.26bc	69.49 ± 3.78b	31.80 ± 2.33ab	27.70 ± 1.53ab	59.50 ± 2.59ab	64.5 ± 4.32a
	Open-ridging	30.48 ± 2.51 cd	28.75 ± 0.98a	19.22 ± 1.10a	78.45 ± 3.99ab	29.10 ± 1.11b	29.10 ± 2.18ab	58.20 ± 4.11ab	68.33 ± 4.13a
	Tied-ridging	35.96 ± 1.90abc	26.28 ± 1.24ab	16.92 ± 0.52ab	79.16 ± 4.42ab	31.90 ± 1.80ab	25.40 ± 2.09b	57.30 ± 1.20b	68.23 ± 1.79a
Biochar	Flat planting	34.21 ± 2.72bc	29.23 ± 0.52a	15.41 ± 0.62bc	78.85 ± 4.25ab	33.50 ± 2.67ab	31.00 ± 2.37a	64.50 ± 3.06ab	71.68 ± 1.78a
	Open-ridging	37.42 ± 1.88ab	26.48 ± 1.96ab	13.35 ± 1.09c	77.25 ± 1.48ab	33.80 ± 1.69ab	29.80 ± 0.86ab	63.60 ± 2.94ab	70.43 ± 3.89a
	Tied-ridging	42.08 ± 3.73a	24.59 ± 0.39b	13.77 ± 1.24c	80.44 ± 4.54a	34.90 ± 2.13a	30.80 ± 1.97a	65.70 ± 2.64a	73.07 ± 4.61a
Mean	No-biochar	30.87 ± 1.28	27.46 ± 1.42	17.36 ± 0.80	75.70 ± 1.52	30.93 ± 0.77	27.40 ± 0.95	58.33 ± 3.71	67.02 ± 4.17
	Biochar	37.90 ± 2.64	26.77 ± 1.71	14.18 ± 1.24	78.85 ± 0.90	34.07 ± 2.37	30.53 ± 0.80	64.60 ± 3.49	71.73 ± 4.66

Alfalfa was not harvested at the third cutting in 2021 due to dry conditions and no regrowth. ± indicates standard error of the mean

of alfalfa significantly ($p < 0.05$) increased by 4.16% in the FP with biochar compared to the FP without biochar. Contrary to the results in 2020, the maize straw biochar-amended plots, on average, marginally increased ADF concentrations of alfalfa compared to no-biochar-treated plots in 2021. Specifically, the FP, OR, and TR with maize straw biochar increased the annual total ADF concentration of alfalfa by 8.40, 9.28, and 14.66%, respectively, compared to the counterpart plots without biochar. In 2020, the neutral detergent fiber (NDF) concentration of alfalfa cultivated on the biochar-amended plots was slightly lower than the no-biochar-added plots for both first and second cuts. However, in 2021, biochar addition to FP and OR significantly ($p < 0.05$) increased the total annual NDF content of alfalfa cultivated on the FP and OR treatments by 7.46 and 6.04%, respectively, compared to the corresponding plots without biochar.

3.3 Total Digestible Nutrients

Total digestible nutrients (TDN) of alfalfa grown on the no-biochar-treated plots slightly increased in 2020 than in the biochar-amended plots (Table 4). The OR with biochar amendment increased the annual total TDN of alfalfa by 0.60% compared to the no-biochar application. However, in 2021, the TDN of alfalfa cultivated on the biochar-amended plots marginally increased compared with the no-biochar treatment. The TR with biochar amendment increased the annual total TDN of alfalfa by 18.51% compared to the no-biochar application.

Table 4 Seasonal neutral detergent fiber and total digestible nutrients in alfalfa fodder yield in 2020 and 2021

Biochar application	Rainwater harvesting method	2020				2021			
		1st cut	2nd cut	3rd cut	Total	1st cut	2nd cut	Total	Average
Neutral detergent fiber (g kg^{-1})									
No-biochar	Flat planting	37.13 ± 1.59b	50.88 ± 4.77a	25.74 ± 0.67abc	113.75 ± 3.69ab	39.50 ± 1.58bc	39.60 ± 2.44abc	79.10 ± 4.02b	96.43 ± 2.62a
	Open-ridging	42.10 ± 3.82ab	37.52 ± 1.08b	30.06 ± 2.36a	109.68 ± 4.52abc	43.80 ± 3.06ab	43.90 ± 1.70ab	87.70 ± 3.14ab	98.69 ± 3.26a
	Tied-ridging	50.67 ± 3.55a	37.13 ± 1.42b	27.86 ± 1.89ab	115.66 ± 4.15a	46.50 ± 2.01ab	41.40 ± 2.95abc	87.90 ± 2.98ab	101.78 ± 3.97a
Biochar	Flat planting	41.34 ± 3.03b	41.00 ± 3.81b	24.01 ± 1.89bc	106.35 ± 4.19abc	47.20 ± 3.77ab	37.80 ± 1.75bc	85.00 ± 1.96ab	95.68 ± 3.29a
	Open-ridging	42.15 ± 2.68ab	35.40 ± 2.62b	22.87 ± 0.76c	100.42 ± 3.98c	47.80 ± 3.72a	45.20 ± 3.34a	93.00 ± 3.17a	96.71 ± 1.79a
	Tied-ridging	44.02 ± 3.59ab	38.76 ± 2.04b	21.88 ± 1.98c	104.66 ± 2.66bc	34.60 ± 2.24c	35.40 ± 2.67c	70.00 ± 3.81c	87.33 ± 1.49b
Mean	No-biochar	43.30 ± 1.12	41.84 ± 2.78	27.89 ± 1.65	113.03 ± 3.69	43.27 ± 2.41	41.63 ± 2.27	84.90 ± 3.82	98.97 ± 1.56
	Biochar	42.50 ± 2.58	38.39 ± 2.66	22.92 ± 0.36	103.81 ± 3.71	43.20 ± 3.02	39.47 ± 2.16	82.67 ± 2.96	93.24 ± 4.12
Total digestible nutrients (g kg^{-1})									
No-biochar	Flat planting	70.67 ± 3.90a	69.41 ± 3.15a	81.60 ± 4.17a	221.68 ± 4.43a	56.44 ± 3.64ab	56.33 ± 3.73ab	112.77 ± 4.13ab	167.23 ± 4.07a
	Open-ridging	66.07 ± 2.76ab	67.92 ± 4.52a	78.11 ± 3.87a	212.11 ± 3.88ab	51.84 ± 3.57b	51.73 ± 3.48ab	103.58 ± 3.10bc	157.85 ± 3.57ab
	Tied-ridging	60.22 ± 3.81bc	70.56 ± 3.58a	80.56 ± 2.76a	211.35 ± 4.50ab	48.96 ± 2.08b	54.41 ± 3.43ab	103.36 ± 3.18bc	157.36 ± 3.66ab
Biochar	Flat planting	62.09 ± 4.57abc	67.41 ± 2.73a	82.18 ± 4.03a	211.68 ± 3.88ab	48.21 ± 2.91b	58.25 ± 2.40ab	106.46 ± 4.50bc	159.07 ± 3.32ab
	Open-ridging	58.66 ± 3.28bc	70.35 ± 3.58a	84.38 ± 3.52a	213.39 ± 4.01ab	47.57 ± 3.25b	50.35 ± 2.93b	97.91 ± 3.78c	155.65 ± 3.38b
	Tied-ridging	53.68 ± 3.12c	72.37 ± 2.68a	83.93 ± 3.03a	209.98 ± 4.41b	61.67 ± 4.20a	60.82 ± 4.29a	122.49 ± 4.60a	166.24 ± 4.39a
Mean	No-biochar	65.65 ± 4.19	69.30 ± 2.85	80.09 ± 3.23	215.05 ± 3.98	52.41 ± 3.69	54.16 ± 3.41	106.57 ± 4.10	160.81 ± 3.98
	Biochar	58.14 ± 3.82	70.04 ± 4.10	83.50 ± 2.87	211.68 ± 4.25	52.48 ± 2.12	56.47 ± 3.59	108.95 ± 3.62	160.32 ± 4.15

Alfalfa was not harvested at the third cutting in 2021 due to dry conditions and no regrowth. ± indicates standard error of the mean

3.4 Digestible Dry Matter and Net Energy for Lactation

In 2020, the digestible dry matter (DDM) concentrations of alfalfa cultivated on biochar-amended plots generally tended to decrease than that cultivated on the no-biochar-treated plots (Table 5). However, in 2021, a higher DDM of alfalfa was recorded in the biochar-amended plots, particularly towards the end of the growing season compared with the no-biochar-amended plots. Specifically, the DDM of alfalfa cultivated on the TR with biochar amendment increased by 12.75% compared to the counterpart plots with no-biochar addition.

In 2020, when averaged across the two growing seasons investigated, the net energy for lactation (NE_l) of alfalfa was slightly increased for the no-biochar-added plots than the biochar-amended plots in the 2020 growing season (Table 6). In terms of rainwater harvesting treatment and biochar application, the OR with maize straw biochar increased NE_l of alfalfa by 0.65% compared to the no-biochar application. On the contrary, in 2021, when averaged across the two growing seasons, NE_l increased for the biochar-amended plots more than the no-biochar-treated plots. Overall, the TR with biochar increased the annual total net energy for lactation of alfalfa by 20.44% compared with the no-biochar-amended plots.

3.5 Relative Feed Value and Economic Benefit

Results showed that in 2020, irrespective of the rainwater harvesting method, alfalfa relative feed value (RFV) marginally increased for the biochar-treated plots compared to

Table 5 Seasonal digestible dry matter of alfalfa fodder yield in 2020 and 2021

Biochar application	Rainwater harvesting method	2020				2021			
		1st cut	2nd cut	3rd cut	Total	1st cut	2nd cut	Total	Average
Digestible dry matter (g kg^{-1})									
No-biochar	Flat planting	68.51 ± 3.15a	67.59 ± 4.50a	76.47 ± 4.56a	212.57 ± 4.04a	58.13 ± 4.05ab	58.05 ± 3.61a	116.18 ± 3.50ab	164.38 ± 13.71a
	Open-ridging	65.16 ± 3.05ab	66.50 ± 2.78a	73.93 ± 3.72a	205.59 ± 4.49a	54.78 ± 4.44ab	54.70 ± 4.10a	109.48 ± 4.38b	157.54 ± 14.48a
	Tied-ridging	60.89 ± 3.59abc	68.43 ± 3.99a	75.72 ± 3.70a	205.03 ± 4.56a	52.68 ± 3.06ab	56.65 ± 4.09a	109.33 ± 4.55b	157.18 ± 12.45a
Biochar	Flat planting	62.25 ± 1.60abc	66.13 ± 4.00a	76.90 ± 4.53a	205.28 ± 3.17a	52.13 ± 3.66ab	59.45 ± 3.60a	111.59 ± 4.56b	158.44 ± 10.26a
	Open-ridging	59.75 ± 3.60bc	68.27 ± 2.21a	78.50 ± 3.21a	206.52 ± 3.80a	51.66 ± 2.43b	53.69 ± 2.59a	105.35 ± 4.09b	155.94 ± 12.36a
	Tied-ridging	56.12 ± 3.42c	69.74 ± 3.26a	78.17 ± 3.72a	204.04 ± 2.99a	61.95 ± 4.43a	61.32 ± 4.56a	123.27 ± 3.17a	163.66 ± 11.06a
Mean	No-biochar	64.85 ± 4.92	67.51 ± 3.19	75.37 ± 3.93	207.73 ± 3.29	55.20 ± 3.07	56.47 ± 3.61	111.66 ± 4.00	159.70 ± 13.35
	Biochar	59.37 ± 3.03	68.05 ± 2.77	77.86 ± 2.37	205.28 ± 3.02	55.25 ± 3.60	58.16 ± 2.95	113.40 ± 4.02	159.34 ± 12.57

Alfalfa was not harvested at the third cutting in 2021 due to dry conditions and no regrowth. ± indicate standard error of the mean

the no-biochar plots (Table 6). The OR and TR with biochar addition increased the annual total RFV of alfalfa by 17.29 and 15.35%, respectively, compared to the counterpart treatment with the no-biochar application. However, in 2021, alfalfa relative feed value tended to increase for the no-biochar-treated plots compared to the biochar-amended plots. The OR and TR with biochar addition decreased the annual total RFV of alfalfa by 24.80 and 7.55%, respectively, compared to the no-biochar application.

Because different rainwater harvesting methods were used during the investigation years, input costs varied. The average input cost for rainwater harvesting methods for the 2-year growing season was OR > TR > FP, with the output values in the order: TR > OR > FP. However, in 2020, the FP with biochar significantly ($p < 0.05$) increased the cost–benefit ratio (15) compared to 11 for the FP without biochar amendment. In terms of rainwater harvesting methods, the TR had a higher cost–benefit ratio of 37 compared to the OR treatment (22) in 2021 (Table 7).

4 Discussion

The study demonstrated that compared to the no-biochar treatment, tied-ridge-furrow rainwater harvesting (TR) with biochar amendment resulted in higher fodder yield during the 2-year alfalfa growing seasons investigated. High alfalfa fodder yield in the biochar-amended soil could be ascribed to biochar's ability to improve soil health for plant growth. For example, improve soil water retention due to the addition of maize straw biochar might have stimulated the release of nutrients from organic or insoluble forms to the root zone for alfalfa uptake. In other words, the findings suggest that the better soil condition induced by biochar addition might have improved the physical traits and physiological mechanisms of the alfalfa plant, e.g., the development of more resilient root architecture for better water and nutrient uptake under semi-arid conditions characterized by water deficit and poor soil quality. In China's Loess Plateau, Mak-Mensah et al. (2021) reported that combining biodegradable film with biochar in a ridge-furrow rainwater harvesting system increased maize yield by 23% compared to flat planting (FP). In areas with an annual rainfall total of 549 mm, soil water conservation technologies such as TR and mulching increased maize yield by 65% (Enfors et al. 2011). Conversely, Jensen et al. (2003) found that TR in a maize-cowpea intercropping system in a semi-arid climate was very beneficial when rainfall amounts were 500 to 600 mm. The authors attributed the lower yield recorded for the TR to waterlogging when rainfall amounts were 700 to 900 mm. Biochar applications to agricultural soils have been shown in several studies to significantly improve vegetative growth and crop productivity (E.gs., Liu et al. 2017; lulu et al. 2020; Nguyen et al. 2017; Sarfraz et al. 2020; Vaccari et al. 2011; Zhang et al. 2010, 2012). According to Liu et al. (2013), biochar soil applications of less than 30 t ha^{-1} increased crop productivity by 11% on average. However, it is important to mention that biochar amendment could lead to a decrease in plant yield due to for example soil toxicity caused by toxic elements and a high percentage of the volatile content of biochar, which reduces nutrient uptake by plants (Peiris et al. 2019).

Table 6 Seasonal net energy for lactation and relative feed value in alfalfa fodder yield in 2020 and 2021

Biochar application	Rainwater harvesting method	2020				2021			Average
		1st cut	2nd cut	3rd cut	Total	1st cut	2nd cut	Total	
Net energy for lactation (%)									
No-biochar	Flat planting	1.62 ± 0.13a	1.58 ± 0.05a	1.88 ± 0.04ab	5.08 ± 0.07a	1.27 ± 0.08ab	1.26 ± 0.08abc	2.53 ± 0.10ab	3.81 ± 0.06a
	Open-ridging	1.50 ± 0.01ab	1.55 ± 0.10a	1.80 ± 0.03b	4.85 ± 0.09ab	1.15 ± 0.10bc	1.15 ± 0.02c	2.30 ± 0.13bc	3.58 ± 0.07a
	Tied-ridging	1.36 ± 0.08bc	1.61 ± 0.09a	1.86 ± 0.07ab	4.83 ± 0.10ab	1.08 ± 0.07bc	1.22 ± 0.07bc	2.30 ± 0.13bc	3.57 ± 0.22a
Biochar	Flat planting	1.40 ± 0.10abc	1.54 ± 0.05a	1.90 ± 0.03ab	4.84 ± 0.05ab	1.06 ± 0.06c	1.31 ± 0.02ab	2.37 ± 0.08bc	3.61 ± 0.24a
	Open-ridging	1.32 ± 0.08bc	1.61 ± 0.07a	1.95 ± 0.09a	4.88 ± 0.12ab	1.05 ± 0.07c	1.12 ± 0.07c	2.16 ± 0.03c	3.52 ± 0.17a
	Tied-ridging	1.20 ± 0.06c	1.66 ± 0.04a	1.94 ± 0.02ab	4.80 ± 0.12b	1.39 ± 0.06a	1.37 ± 0.02a	2.77 ± 0.11a	3.79 ± 0.29a
Mean	No-biochar	1.49 ± 0.04	1.58 ± 0.08	1.85 ± 0.09	4.92 ± 0.10	1.17 ± 0.02	1.21 ± 0.03	2.38 ± 0.09	3.65 ± 0.26
	Biochar	1.31 ± 0.04	1.60 ± 0.10	1.93 ± 0.10	4.84 ± 0.12	1.17 ± 0.09	1.27 ± 0.08	2.43 ± 0.13	3.64 ± 0.14
Relative feed value (%)									
No-biochar	Flat planting	171.59 ± 15.25a	123.54 ± 9.13b	276.31 ± 16.00bc	571.43 ± 14.16 cd	500.56 ± 16.74b	264.72 ± 18.08b	765.28 ± 15.31bc	668.36 ± 40.71b
	Open-ridging	143.93 ± 6.55ab	164.84 ± 11.81a	228.72 ± 16.38d	537.49 ± 13.12d	377.84 ± 14.41c	431.03 ± 16.40a	808.87 ± 17.34b	673.18 ± 37.73ab
	Tied-ridging	111.75 ± 10.58c	171.39 ± 13.55a	252.76 ± 17.47 cd	535.90 ± 15.14d	350.93 ± 16.7c	389.31 ± 14.83a	740.23 ± 14.97c	638.07 ± 46.27b
Biochar	Flat planting	140.04 ± 7.28bc	150.00 ± 13.51ab	297.85 ± 13.95ab	587.89 ± 14.50bc	559.16 ± 13.23a	407.57 ± 17.12a	966.73 ± 19.17a	777.31 ± 36.03a
	Open-ridging	131.83 ± 11.43bc	179.36 ± 16.95a	319.22 ± 17.41ab	630.41 ± 14.96a	384.38 ± 15.16c	223.91 ± 17.05b	608.29 ± 15.46e	619.35 ± 40.34b
	Tied-ridging	118.56 ± 9.86bc	167.34 ± 13.63a	332.27 ± 15.64a	618.18 ± 13.62ab	272.96 ± 15.09d	411.37 ± 17.66a	684.34 ± 17.04d	651.26 ± 36.24b
Mean	No-biochar	142.42 ± 12.63	153.26 ± 11.38	252.60 ± 11.30	618.18 ± 15.83	409.77 ± 18.2	361.68 ± 18.42	771.46 ± 14.24	694.82 ± 37.84
	Biochar	130.15 ± 12.63	165.57 ± 12.55	316.45 ± 15.90	612.16 ± 17.14	405.5 ± 16.01	347.62 ± 17.01	753.12 ± 16.11	682.64 ± 25.80

Alfalfa was not harvested at the third cutting in 2021 due to dry conditions and no regrowth. ± indicates standard error of the mean

High-quality fodder is essential for high milk and meat production because the essential nutrient elements for animal daily nutrient requirements depend on the fodder quality (Sandhu et al. 2020). Information on fodder quality is useful for fodder processing and animal feeding (Farooq and Pisante 2019). Crude protein (CP) is generally regarded as a key factor affecting the quality of fodder (Abbasi et al. 2018). Forage quality is also determined by the presence of neutral detergent fiber (NDF) and acid detergent fiber (ADF) (Khatiwada et al. 2021). Results from the present study showed that biochar amendment tended to increase alfalfa CP and ADF concentrations, but slightly decreased NDF concentrations compared with the no-biochar application. According to Sadeghpour et al. (2013), legumes have higher crude protein levels than cereal crops. The authors reported that the concentration of CP is higher in the leaves of legumes than in stems, while the concentrations of ADF and NDF were higher in stems than in the leaves (Santos et al. 2021). However, it is worth noting that drought degrades fodder quality and accelerates the loss of CP (Kamely et al. 2020). The application of ridge-furrow rainwater harvesting with biochar can improve forage quality by reducing alfalfa cell wall component production (Xiao et al. 2016). High fodder digestible dry matter (DDM) improved livestock voluntary intake (feeding), leading to increased nutrient intake. According to Sadeghpour et al. (2013), legumes have a higher intake than non-legumes, and immature forage has a higher intake than mature forage. Unlike DDM yield, results from the present study showed neither maize straw biochar acting solely or in combination with rainwater harvesting methods significantly affected CP, NDF, and ADF of alfalfa during the 2-year experimental period. The

Table 7 Cost–benefit analysis of flat planting, open-ridging and tied-ridging in 2020 and 2021

Biochar application	Rainwater harvesting method	Seed (USD ha^{-1})	Plastic film (USD ha^{-1})	Total cost (USD ha^{-1})	Revenue (USD ha^{-1})	Net economic benefit (USD ha^{-1})	Benefit/cost ratio
2020							
No-biochar	Flat planting	81	0	81	960	879 ± 240.9d	11 ± 0.95b
	Open-ridging	65	27	91	1331	1239 ± 403.92bc	14 ± 0.87ab
	Tied-ridging	64	26	90	1287	1196 ± 199.00c	13 ± 1.16ab
Biochar	Flat planting	81	0	81	1031	950 ± 459.33d	12 ± 0.97b
	Open-ridging	65	27	91	1455	1363 ± 462.02ab	15 ± 1.19a
	Tied-ridging	64	26	90	1489	1398 ± 370.35a	15 ± 0.97a
Mean	No-biochar	70	18	87	1192	1105 ± 425.95	13 ± 1.10
	Biochar	70	18	87	1325	1237 ± 370.79	14 ± 1.05
2021							
No-biochar	Flat planting	109	0	109	2643	2534 ± 408.34e	23 ± 1.24b
	Open-ridging	99	28	127	2902	2775 ± 381.16d	22 ± 0.95b
	Tied-ridging	95	28	123	2950	2827 ± 233.52d	23 ± 1.40b
Biochar	Flat planting	109	0	109	3848	3739 ± 92.64c	34 ± 1.26a
	Open-ridging	99	28	127	4464	4337 ± 101.04b	34 ± 0.88a
	Tied-ridging	95	28	123	4660	4537 ± 352.62a	37 ± 1.15a
Mean	No-biochar	101	19	120	2832	2712 ± 408.73	23 ± 1.29
	Biochar	101	19	120	4324	4204 ± 341.18	35 ± 1.29

1 Chinese Yuan Renminbi equals 0.15 US Dollar. The net economic benefit was calculated as the difference between revenue from fodder yield and input costs

lack of significant effect is probably because of differences in response rate between DDM yield and the nutritional quality parameters. Improvement in alfalfa DDM yield is probably associated with soil moisture and nutrient availability in the biochar-amended soil, which might have enhanced chlorophyll fluorescence and the rate of photosynthesis of the alfalfa plant. Habermann et al. (2019) reported that water deficit under ambient temperature reduced photosynthesis rate, stomatal conductance, and maximum rate of carboxylation of Rubisco of forage grass *Panicum maximum* Jacq.

Regardless of whether alfalfa is used as pasture, hay, or silage, soil fertility has an impact on its quality. A forage farming system that supplies large quantities of adequate quality feed is required for profitable livestock production. However, the biggest challenge in recent years has been how to maximize profit from alfalfa production in semi-arid regions under rain-fed conditions (Mak-Mensah et al. 2022). Results of the present study showed that the highest net income throughout the 2 years of alfalfa cultivation was recorded in the TR with biochar amendment. Findings suggest that the integration of maize straw biochar and ridge-furrow rainwater harvesting method can provide additional benefits by increasing net economic returns to improve the income of farmers. The results are consistent with Zheng et al. (2019), who reported that plastic-mulched ridge plus bare furrow increased net income by 9.8% compared to plastic-mulched ridge plus straw-mulched furrow. Conversely, Mo et al. (2018) reported that mulched ridge-furrow rainwater harvesting increased net income for spring maize in Northwestern China. Furthermore, a study by Li et al. (2012) found that straw-mulched furrows had a higher net income than bare furrows. According to Fox et al. (2005) and Gang et al. (2019), a ridge-furrow rainwater harvesting system is economically viable when combined with mulching and improves soil nutrient management. The findings of the present study have practical relevance and lay a foundation for further research by showing TR with maize straw biochar amendment can be used to ameliorate the yield and quality of forage legumes, which are increasingly becoming key constraints to sustainable livestock production under arid and semi-arid conditions.

5 Conclusions

This study demonstrated that maize straw biochar amendment with a ridge-furrow rainwater harvesting method improved alfalfa fodder yield compared to the no-biochar application and flat planting. However, neither the individual effect of maize straw biochar and ridge-furrow rainwater harvesting methods nor their interactions significantly changed the nutritional quality of alfalfa fodder in terms of crude protein concentration, acid detergent fiber, and neutral detergent fiber contents. The insignificant treatment effect suggests that perhaps, the nutritional parameters of alfalfa responded slowly to the maize straw biochar amendment and/or with rainwater harvesting compared to fodder yield. Therefore, a longer time is probably required before any significant effect is observed. The highest net economic benefit during the 2 years of alfalfa cultivation was recorded in the tied-ridging with biochar amendment. Findings, thus, support the potential of adopting tied-ridging with maize straw biochar in smallholder agriculture to increase alfalfa fodder yield. Further studies investigating the long-term of tied-ridging methods with maize straw biochar amendment on the nutritional quality of alfalfa fodder are recommended to help make firm recommendations for farmers and ensure sustainable livestock production in semi-arid regions.

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Declarations

Competing Interests The authors declare no competing interests.

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