Paddy and Water Environment (2022) 20:287–302
https://doi.org/10.1007/s10333-022-00900-y

REVIEW

Integration of ridge and furrow rainwater harvesting systems and soil amendments improve crop yield under semi-arid conditions

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Received: 14 July 2021 / Revised: 30 March 2022 / Accepted: 11 April 2022 / Published online: 9 May 2022

Abstract

Low crop productivity due to prolonged droughts, inappropriate water saving practices, low soil fertility and soil erosion is a major threat to food security in semi-arid areas. In these areas, ridge and furrow rainwater harvesting (RFRH) technique is widely adopted to minimize water deficiency problems. Incorporating mulching in ridge and furrow rainwater harvesting (RFRH + M) is also being promoted to increase water storage and conservation for crop usage. Till date, evidence establishing the efficacy of incorporating mulching and biochar in ridge and furrow system, and modalities for improving crop yield has not been synthesized quantitatively to promote widespread adoption. The objective of this MA was to assess the whether the integration of ridge and furrow rainwater harvesting systems (RFRHs) with soil amendments, namely biochar or mulches affect crop yield and soil properties relative to traditional no-till flat planting. In addition, the MA investigated how factors such as such as precipitation moderate the performance of RFRHs with soil amendments in different regions in China was investigated. A meta-analysis (MA) of data from 42 published articles based on PRISMA guidelines was used to assess the impacts of ridge and furrow tillage with and without mulching on potato (*Solanum tuberosum*, L.), wheat (*Triticum aestivum*, L.), and maize (*Zea mays*, L.) yield relative to traditional no-till flat planting in the Loess Plateau of China. Mulch materials were plastic and straw in addition to biochar amendment. RFRH + M significantly affected crop yield in Gansu, Ningxia, Shanxi and Shaanxi regions of the Loess Plateau. Plastic film mulched ridge-furrow planting compared with flat planting without mulching increased potato yield by 34.01% in Gansu, 32.99% in Ningxia, and 12.78% in Shanxi. Maize yield increased by 33.10% in bare ridge-furrow planting with mean of 10,936.81 kg ha^{-1} compared with flat planting with a mean of 8217.07 kg ha^{-1}. Conversely, in areas where precipitation was higher than 500 mm, integrated plastic film with straw in ridge-furrow significantly ($p < 0.00001$) increased wheat yield by 60% compared to flat planting without mulching, which can be attributed to the soil alkalinity (pH > 7–8) of the soils in these areas. The observed differences in crop yield could also be ascribed to the influence of phosphorus availability. Results from the MA showed that the effect of straw mulched-ridge-furrow on crop yield was stronger in soils with higher available phosphorus at 20 mg kg^{-1} (5.31%; $p = 0.0003$) than flat planting without mulching. Findings of the MA suggest that the adoption of integrated plastic film mulch with straw in ridge and furrow system can improve soil properties and crop yield under rain-fed conditions. Compared with flat planting without mulching, incorporating plastic film mulch and straw in ridge and furrow systems averts residual plastic film accumulation on farmlands, which could impede plant growth, soil structure, water and nutrient uptake in rain-fed agriculture in semi-arid areas.

Keywords Rainwater harvesting · Ridge system · Tied ridge · Plastic film mulching · Biodegradable film mulching · Straw mulching

Introduction

Rainfall variability, extreme weather conditions, soil and nutrient losses in semi-arid areas are major limiting factors to crop production (Liu and Jin 2017). In addition to soil

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erosion, rain-fed agricultural production in semi-arid areas is constrained by declining plant water availability and poor soil fertility (Hakl et al. 2017; Li et al. 2020). This suggests the need for more sustainable and resilient techniques that improve soil water conservation and availability for crop production to meet global food demands. Evidence showed that increasing crop yield amidst environmental challenges such as climate change and soil degradation requires the adoption of smart and resilient agronomic practices. For example, by shifting from the traditional single farming technique, which has proven to be less effective and unsustainable (Durán-lara et al. 2020) to more robust agronomic practices like integrated farming methods. For rain-fed agriculture, an integrated approach that combines ridge and furrow rainwater harvesting with multiple mulch materials which considers productivity, economic, energy and environmental sustainability is necessary to address challenges associated with rain-fed agriculture such as crop water stress and soil erosion (Bhatt et al. 2021). Adoption of ridge-furrow rainwater harvesting techniques (RFRH) has been touted as an ideal technique for improving soil fertility and increasing crop yield in semi-arid areas (Bhatt et al. 2021).

Ridge-furrow rainwater harvesting technique involves concentration, collection, storage, and distribution of water that would have naturally exited a landscape through processes such as run-off and evaporation (Rango and Havst 2011). Longstanding evidence indicates that in semi-arid areas, adoption of RFRH on fields increased soil water and crop yield (Baig et al. 2013; Yin et al. 2015; Siderius et al. 2016; Mo et al. 2017). In recent years, farmers have used ridge-furrow mulching to improve the quality of agricultural soils by covering soil surface with various types of materials (Haapala et al. 2014). In northern China, straw mulches and plastic film have been used to improve crop yield (Zhu et al. 2018).

Mulches are essentially used to prevent soil water loss, improve soil water infiltration, and control soil erosion, particularly in arid and semi-arid regions (Mohammadi et al. 2012; Bhardwaj 2013). Mulched soils, especially on-ridge planting, improved soil fertility and microbial biomass than conventional flat planting with no mulch (Zhang et al. 2018). This could be attributed to the decomposition of the mulch (organic) material, moisture conservation and increase soil temperature under mulch compared to no mulch conditions (Moreno and Moreno 2008). Although, the effectiveness of single mulch in reducing runoff and water erosion have been widely reported, studies synthesizing evidence of co-application of mulch with ridge and furrow rainwater harvesting (RFRH + M) and modalities for improving crop yield are lacking. As mulching is an expensive agronomic practice for farmers, a meta-analysis of the impact of mulching with RFRH on soil properties and crop yield is necessary to establish scientific evidence to guide soil management practices and improve food production in semi-arid areas (Jafari et al. 2012). The objective of this MA was to assess the whether the integration of ridge and furrow rainwater harvesting systems (RFRHs) with soil amendments, namely biochar or mulches affect crop yield and soil properties relative to traditional no-till flat planting. Main crops investigated were maize, potato and wheat whereas mulch materials were plastic and straw in addition to biochar amendment. In addition, the MA investigated how factors such as such as precipitation moderate the performance of RFRHs with soil amendments in different regions in China was investigated.

Materials and methods

Scope of peer-reviewed papers

Different online databases (Google Scholar, Science Direct, Scopus (Elsevier), PubMed, JSTOR, and Web of Science) were explored for peer-reviewed articles published in English from 2000 to 2021 that investigated effects of RFRH and mulching on crops (Mak-Mensah et al. 2021a, b). The use of multiple academic databases ensured that selection bias was reduced.

Literature selection criteria and screening

The keywords used in the literature search for the meta-analysis (MA) were: "*mulching*", and/or "*rainwater harvesting*", and/or "*yield*" and/or "*ridge and furrow*". This yielded 121 articles, which were screened using the following inclusion criteria: (i) the experiment was conducted in a semi-arid region; (ii) field trials with at least ridge and furrow, plastic film mulched ridge, biochar or straw mulched furrow, compared with flat planting treatments (Fig. 1); (iii) mulched ridge and furrow; and flat planting plots were established within the same ecosystem and had similar environmental characteristics at the start of the study; (iv) data on maize, wheat or potato yield was reported; and (v) the experimental duration was clearly specified and the experiment was repeated, at least, two growing seasons.

We considered and extracted latitude, longitude, elevation, mean annual precipitation, soil organic carbon (SOC)/soil organic matter (SOM), texture, bulk density, and soil physico-chemical properties. The crops (maize, wheat and potato) in the various locations (Gansu, Shanxi, Shaanxi, Ningxia and Inner Mongolia) considered in this review were obtained using the stated inclusion and exclusion screening criteria. After the screening process, 42 articles were retained for the MA (Table 1). A flowchart depicting the screening procedure of articles, which was modified from the PRISMA guideline for meta-analysis (Moher et al. 2009) is shown in Fig. 2.

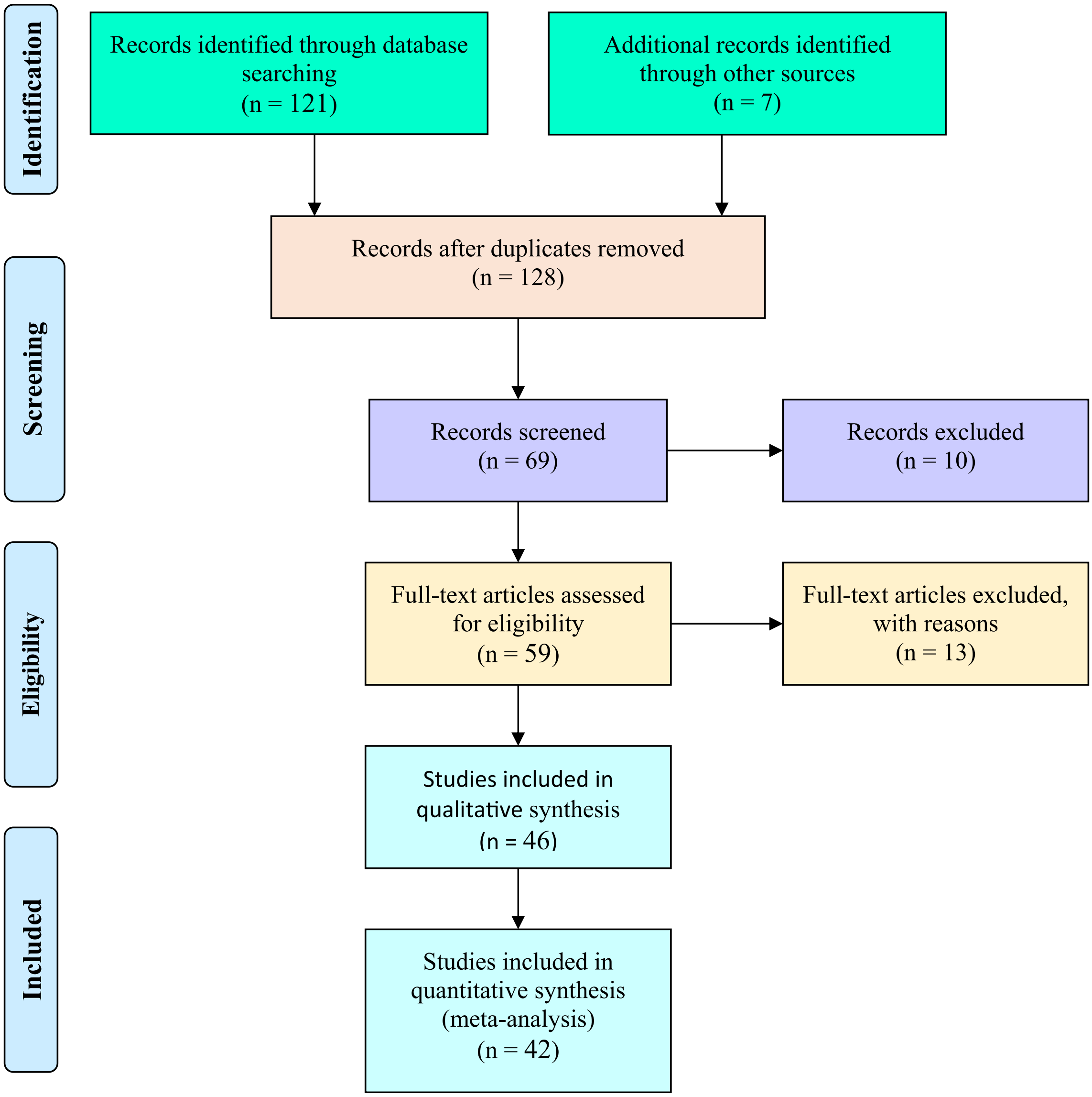

Fig. 1 Flowchart of literature identification, and screening for use in this study. Adapted from PRISMA (Moher et al. 2009)

Statistical analyses

The Newcastle Ottawa Scale (NOS) was used to determine the importance of articles examined in this MA (Zeng et al. 2015). High-quality articles were graded on a seven-point scale (papers). On a scale of one to ten, NOS scores ranged from six to nine (Table 1). Because additional detailed measurements have larger impact on overall sample (Yu et al. 2018), research articles with additional detailed measurements were assigned higher weight. Using SigmaPlot (version 14.0), descriptive statistics such as standard deviation (SD), mean, minimum, and maximum values of variables investigated (temperature, precipitation, available nitrogen, available phosphorus, available potassium, bulk density, SOC/SOM, total nitrogen, total phosphorus, total potassium, pH, soil texture, pan-evaporation, field capacity, permanent wilting point, sunshine hours and frost-free period) were computed. Subsequently, MA based on the response-ratio approach was conducted with a construction confidence interval analysis using the random-effect model of Nordic Cochrane Centre's Review Manager Software (Mak-Mensah et al. 2021a). In this MA, effect size was calculated as natural log (ln) of the response ratio (R), which is the ratio of mean crop yield in mulched ridges and furrows plots to mean crop yield in flat planting plots (Eze et al. 2018; Mak-Mensah et al. 2021b).

$$R = \theta_t / \theta_c, \tag{1}$$

Table 1 Overview of literature showing location of studies, included in the meta-analysis

References	Cardinal point (N, E, m a.s.l)	Location	NOS
Chen et al. (2015)	35°14′, 107°40′, 1230	Changwu County, Shaanxi Province	7
Chen et al. (2019)	35°11′, 105°19′, 1740	Dingxi City, Gansu	6
Cui et al. (2017)	42°14′, 123°48′	Liaoning Province	8
Dang et al. (2016)	114°93′, 36°7′	Quzhou county	6
Dong et al. (2017)	43°33′, 125°38′	Shuangyang, Inner Mongolia	9
Eldoma et al. (2016)	36°2′, 104°25′, 2400	Yuzhong County, Gansu Province	7
Gaimei et al. (2017)	37°54′, 113°09′, 1273	Shouyang, Shanxi	7
Gong et al. (2017)	37°45′58″, 113°12′9″, 1202	Shouyang, Shanxi	6
Han et al. (2013)	35°19′54.45″, 110°05′58.35″, 877	Heyang County, Shaanxi	8
Hu et al. (2019)	34°20′, 108°24′, 521	Yangling, Shaanxi	8
Huang et al. (2018)	29°48′, 106°24′, 266.3	Beibei District, Chongqing	9
Lan et al. (2020)	35°11′, 105°19′, 1740	Dingxi, Gansu	9
Li et al. (2001)	36°13′, 103°47′, 1780	Gaolan	6
Li et al. (2012)	35°150′, 110°18′, 910	Heyang County, Shaanxi	6
Li et al. (2013)	35°15′, 110°18′, 910	Heyang County, Shaanxi	7
Li et al. (2018)	34°17′, 108°04′, 520	Yangling	8
Liang et al. (2018)	26°5′, 104°4′, 1960	Xuanwei	7
Lin et al. (2019)	35°14′, 107°41′, 1200–1206	Changwu County, Shaanxi	9
Liu and Siddique (2015)	36°02′, 104°25′, 2400	Zhonglianchuan, Yuzhong County, Gansu	6
Lu et al. (2020)	34°59′, 107°38′, 1220	Changwu County of Shaanxi	6
Mak-Mensah et al. (2021a, b, c)	35°34′, 104°39′, 2075	Dingxi city, Gansu	8
Pan et al. (2019)	41°08′22.8″, 111°17′43.6″	Wuchuan County, Inner Mongolia	8
Qin et al. (2014)	35°33′, 104°35′, 1874	Dingxi city, Gansu	8
Qin et al. (2018)	35°14′, 107°42′	Changwu County of Shaanxi	9
Ren et al. (2016)	35°79′, 106°45′, 1800	Baiyang Town, Pengyang County, Ningxia	7
Ren et al. (2017)	35°15′, 110°18′, 850	Heyang County, Shaanxi	6
Song et al. (2013)	43°30′23″, 124°48′34″, 220	Gongzhuling, Jilin	6
Wang et al. (2005)	35°98′, 104°18′, 1800	Yuzhong County, Gansu	7
Wang et al. (2011)	113°39′, 34°43′, 111.3	Henan, Zhengzhou	9
Wu et al. (2017)	35°51′, 106°48′, 1658	Pengyang County, Ningxia	7
Xiao et al. (2016)	35°28′, 107°88′, 1200	Changwu county of Shaanxi	6
Xiukang et al. (2015)	35°12′, 107°40′, 1206	Changwu county of Shaanxi	8
Yin et al. (2019)	34°18′, 108°24′, 521	Yangling, Shaanxi	8
Zhang et al. (2011)	35°14′, 107°41′, 1206	Changwu county of Shaanxi	9
Zhang et al. (2017)	106°45′, 35°79′, 1800	Pengyang County, Ningxia	6
Zhang et al. (2019a)	35°51′, 106°47′, 1695	Pengyang County, Ningxia Hui	7
Zhang et al. (2019b)	35°51′, 106°48′, 1658	Pengyang county of Ningxia province	7
Zhang et al. (2019c)	35°51′, 106°47′, 1695	Pengyang County, Ningxia Hui	6
Zhao et al. (2012)	35°33′, 104°35′, 1896.7	Dingxi County in Gansu	6
Zhao et al. (2014)	35°33′, 104°35′, 1896.7	Dingxi County in Gansu	6
Zhou et al. (2009)	36°02′, 104°25′, 2400	Zhonglianchuan village, Yuzhong, Gansu	7
Zhou et al. (2015)	36°02′, 104°25′, 2400	Zhong-Lian-Chuan, Yuzhong County, Gansu	8

NOS refers to Newcastle Ottawa Scale

$$\text{Effect size} = \text{In}R = \text{In}\left(\theta_t/\theta_c\right) = \text{In}\theta_t - \text{In}\theta_c, \quad (2)$$

where θ_t is the mean crop yield of the ridge and furrow, and θ_c is the mean crop yield of the flat planting. Yield percentage effect size change (Z) was calculated to further substantiate outcomes from the MA (Eze et al. 2018; Mak-Mensah et al. 2021b):

$$Z = (\exp(\ln R) - 1) \times 100\%, \quad (3)$$

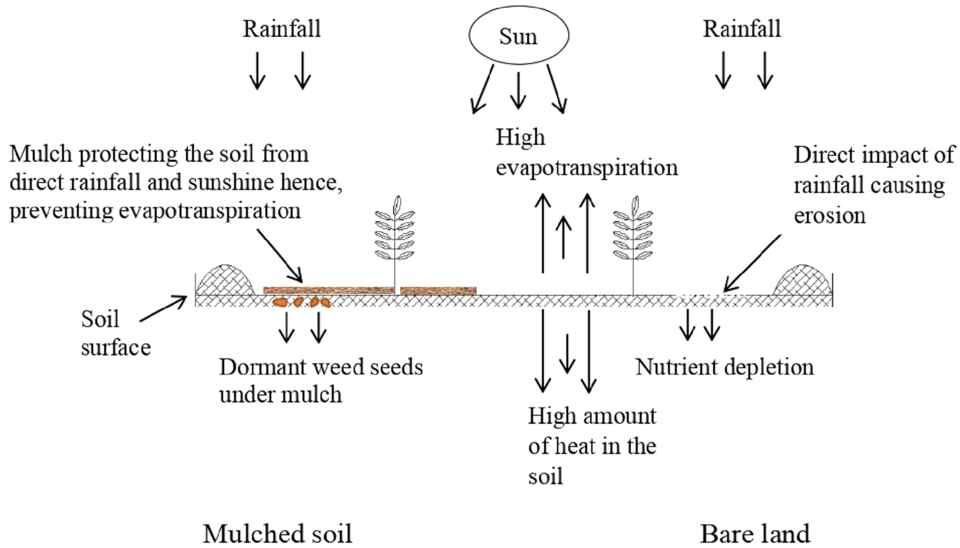

Fig. 2 Effects of mulching and no mulching in semi-arid areas

A positive percentage value indicated that the ridge and furrow treatment resulted in an increase in the metric of interest compared to the flat planting, while a negative percentage value showed that the ridge and furrow treatment resulted in a decrease compared to the flat planting. Following that, sample sizes, means and SDs for the ridge and furrow, and the flat planting variables were computed using the equation (Mak-Mensah et al. 2021a):

$$\mathrm{SD} = \mathrm{SE} \times \sqrt{n}, \quad (4)$$

For studies that did not report SD, average coefficient of variation (CV) was calculated from the screened data and then the SD was estimated using the equation (Gu et al. 2020):

$$\mathrm{SD} = \mathrm{CV} \times \theta, \quad (5)$$

where θ is the mean value of ridge and furrow planting or flat planting with or without mulching. The Nordic Cochrane Centre's Review Manager Software package (RevMan; version. 5.3, Denmark) was used to implement random-effects models to derive effect sizes of ridge and furrow treatment and flat planting with or without mulching for crop yields. Chi-square (χ^2) and I^2 tests were performed to determine heterogeneity between studies (Tables 2, 3, 4, 5 and 6). $I^2 < 25\%$ indicates low heterogeneity, 25–75% indicates medium heterogeneity, and $I^2 > 75\%$ indicates high heterogeneity (Higgins 2003; Huedo-Medina et al. 2006; Mak-Mensah et al. 2021b). The mean differences between ridge and furrow systems with biochar or mulches and flat planting were considered based on their standard errors, sample sizes, and confidence intervals (CI) which were calculated as continuous variables using weighted effect sizes. The 95% CIs for the effect size of a treatment were deemed significant if its CIs did not include zero. Similarly, a treatment was not significant when the 95% CIs included zero. The effect sizes (Odds ratio) frequency distribution was computed in Excel 2019 spreadsheet to validate distribution symmetries of individual studies.

Results

Influence of bare ridge-furrow rainwater harvesting system on soil properties and maize yield

Bare ridge-furrow significantly improved soil available potassium (51.55%; $p=0.04$) at >100 mg kg^{-1} quantity with effect size of 1139.66 and the 95% confidence intervals ranging from 50.42 to 2228.90 compared to the flat planting. Results showed that the effect of bare ridge-furrow rainwater harvesting on soil potassium content was moderated by precipitation amount. Thus, it was found that increase in soil available potassium was significant ($p=0.01$) in areas with precipitation higher than 500 mm. Twenty of the studies included in the MA reported that areas with precipitation higher than 500 mm had an effect size of 1058.03 and 95% confidence intervals ranging from 234.50 to 1881.56. I^2 test performed indicated low heterogeneity between studies (Table 2). Maize yields in Shaanxi ranged from 19,043.50 to 30,188.10 kg ha^{-1} in bare ridge-furrow treatment compared to the flat planting which ranged from 353 to 29,582.55 kg ha^{-1}. This indicates 33.10% increase in maize yield for the bare ridge-furrow as compared with the flat planting treatment in Shaanxi. On the contrary, potato and wheat yields in Gansu province did not significantly differ ($p=0.48$) between the bare ridge-furrow rainwater harvesting system and the flat planting.

Table 2 Heterogeneity analysis on crop yield in ridge-furrow rainwater harvesting system with mulching using random-effects models

Treatment combinations	Variables	*n*	Heterogeneity			Test for overall effect		
			χ^2	df	*P*	I^2	Z	*P*
Flat planting vs. ridge furrow	Gansu	14	5.04	5	0.41	1	0.71	0.48
	Shaanxi	9	4.32	2	0.12	54	1.68	0.09
	Maize	21	13.35	7	0.06	48	1.45	0.15
	Potato	6	0.01	2	0.99	0	1.86	0.06
	Wheat	7	0.02	1	0.9	0	0.5	0.62
	Temperature < 10 °C	20	9.88	7	0.2	29	0.61	0.54
	Temperature < 10–20 °C	8	0.48	2	0.79	0	1.86	0.06
	Precipitation ≤ 500 mm	12	5.03	4	0.28	21	0.59	0.56
	Precipitation > 500 mm	20	5.19	6	0.52	0	2.52	0.01
	Available nitrogen < 50 mg kg^{-1}	4	5.86	1	0.02	83	1	0.32
	Available nitrogen > 50 mg kg^{-1}	9	0.43	2	0.81	0	1.82	0.07
	Available phosphorus < 20 mg kg^{-1}	4	5.86	1	0.02	83	1	0.32
	Available phosphorus > 20 mg kg^{-1}	9	0.43	2	0.81	0	1.82	0.07
	Available potassium > 100 mg kg^{-1}	14	4.94	4	0.29	19	2.05	0.04
	Total nitrogen < 1 g kg^{-1}	9	4.84	2	0.09	59	0.48	0.63
	Total phosphorus > 0.5 g kg^{-1}	7	0.64	1	0.43	0	1.69	0.09
	Total potassium < 10 g kg^{-1}	7	0.64	1	0.43	0	1.69	0.09
	Soil organic carbon ≤ 10 g kg^{-1}	7	2.08	2	0.35	4	0.59	0.55
	Soil organic matter > 10 g kg^{-1}	9	3.44	2	0.18	42	1.92	0.05
	pH > 7–8	13	6.11	4	0.19	35	0.56	0.58
	Soil texture (Light)	4	0.01	1	0.9	0	0.89	0.37
	Bulk density > 1.3 g cm^{-3}	12	1.03	3	0.79	0	1.18	0.24
	Pan Evaporation ≤ 1500	10	0.08	3	0.99	0	1.81	0.07
	Pan Evaporation > 1500	6	1.67	1	0.2	40	1.31	0.19
	FC ≤ 25%	11	0.96	3	0.81	0	1.11	0.27
	FC > 25%	5	0.02	1	0.88	0	0.36	0.72
	PWP < 10	13	1.24	4	0.87	0	1.03	0.3
	Sunshine hours > 1300 h	11	5.97	4	0.2	33	1.45	0.15
	Frost-free period > 140 days	10	7.49	3	0.06	60	1.73	0.08

Influence of biochar amended ridge-furrow rainwater harvesting system on soil properties and maize yield

Results from this MA showed that biochar increased available potassium (24.26%) at < 100 mg kg^{-1}, SOC (39.10%) at > 10 g kg^{-1}, total potassium (17.61%) at > 10 g kg^{-1} and in alkaline soils (4.99%; pH > 7–8). Consequently, the responses of yield to biochar amended ridge-furrow treatments from four study observations in the MA averaged 7600.71 kg ha^{-1} with an effect size of 905.03 (Fig. 3). The 95% confidence intervals ranged from 414.73 to 1395.32 compared with the flat planting. However, there was no significant difference in maize yield ($p > 0.05$) with biochar amendment ridge-furrow compared to the flat planting. Also, there was no moderating effect of precipitation and soil properties, namely soil organic carbon (SOC), available nitrogen and phosphorus, total phosphorus, and total nitrogen maize yield. The I^2 test indicated no heterogeneity between the studies considered in this MA (Table 5).

Influence of plastic film mulched ridge-furrow on soil properties and potato and maize yield

Soil bulk density increased with plastic film mulch application by 37.11% compared to the flat planting (Fig. 3). In addition, compared to flat planting, total phosphorus, SOC, total nitrogen, and total potassium for the plastic film mulching increased by 76.03, 45.80, 39.17 and 24.78%, respectively. Specifically, there was a significant increase in soil available nitrogen (63.60%; $p = 0.02$) at < 50 mg kg^{-1} quantity with effect size of 1051.16

Table 3 Heterogeneity analysis on crop yield in plastic film mulched ridges compared to flat planting using random-effects models

Treatment combinations	Variables	*n*	Heterogeneity				Test for overall effect	
			χ^2	df	*P*	I^2	Z	*P*
Flat planting vs. plastic film	Gansu	20	77.65	8	< 0.00001	90	3.63	0.0003
	Shaanxi	37	318.47	10	< 0.00001	97	2.62	0.009
	Shanxi	6	0	1	0.98	0	2.99	0.003
	Inner Mongolia	6	0.66	1	0.42	0	1.11	0.27
	Ningxia	14	19.46	5	0.002	74	4.44	< 0.00001
	Maize	67	836.17	22	< 0.00001	97	5.24	< 0.00001
	Potato	10	53.7	4	< 0.00001	93	2.21	0.03
	Wheat	8	1.53	2	0.46	0	1.51	0.13
	Temperature < 10 °C	59	813.56	21	< 0.00001	97	4.58	< 0.00001
	Temperature < 10–20 °C	17	56.41	5	< 0.00001	91	3.42	0.0006
	Precipitation ≤ 500 mm	39	160.69	16	< 0.00001	90	5.4	< 0.00001
	Precipitation > 500 mm	43	323.36	12	< 0.00001	96	2.95	0.003
	Available nitrogen < 50 mg kg^{-1}	10	7.62	3	0.05	61	2.41	0.02
	Available nitrogen > 50 mg kg^{-1}	16	4.28	4	0.37	7	6.1	< 0.00001
	Available phosphorus < 20 mg kg^{-1}	35	592.42	13	< 0.00001	98	3.92	< 0.0001
	Available phosphorus > 20 mg kg^{-1}	14	3.85	3	0.28	22	4.65	< 0.00001
	Available potassium > 100 mg kg^{-1}	45	676.85	16	< 0.00001	98	5.09	< 0.00001
	Total nitrogen < 1 g kg^{-1}	37	867.79	14	< 0.00001	98	4.81	< 0.00001
	Total nitrogen > 1 g kg^{-1}	87	907.14	31	< 0.00001	97	6.08	< 0.00001
	Total phosphorus > 0.5 g kg^{-1}	16	57.77	4	< 0.00001	93	2.82	0.005
	Total potassium < 10 g kg^{-1}	13	6.08	3	0.11	51	2.8	0.005
	Soil organic carbon ≤ 10 g kg^{-1}	18	137	6	< 0.00001	96	3.65	0.0003
	Soil organic carbon > 10 g kg^{-1}	7	17.04	2	0.0002	88	2.12	0.03
	Soil organic matter < 10 g kg^{-1}	8	2.86	2	0.24	30	1.82	0.07
	Soil organic matter > 10 g kg^{-1}	25	101.21	8	< 0.00001	92	3.38	0.0007
	pH > 7–8	42	628.49	14	< 0.00001	98	3.54	0.0004
	Soil texture (Light)	13	55.81	4	< 0.00001	93	2.99	0.003
	Soil texture (Heavy)	17	20.02	3	0.0002	85	1.27	0.21
	Bulk density ≤ 1.3 g cm^{-3}	18	88.84	4	< 0.00001	95	2.4	0.02
	Bulk density > 1.3 g cm^{-3}	33	144.97	12	< 0.00001	92	5.34	< 0.00001
	Pan Evaporation ≤ 1500	12	3.13	5	0.68	0	3.41	0.0006
	Pan Evaporation > 1500	17	20.23	5	0.001	75	3.85	0.0001
	FC ≤ 25%	25	311.24	8	< 0.00001	97	1.9	0.06
	FC > 25%	9	6.12	3	0.11	51	3.43	0.0006
	PWP < 10	24	88.15	8	< 0.00001	91	2.68	0.007
	Sunshine hours > 1300 h	28	144.84	10	< 0.00001	93	4.1	< 0.0001
	Frost-free period > 140 days	24	73.26	8	< 0.00001	89	2.84	0.005

[CI: 194.86, 1907.45] and SOM (33.24%; $p = 0.0007$) at > 10 g kg^{-1}. In terms of crop yield, results showed the moderating effect of soil texture on wheat yield. For example, there was no significant difference in wheat yield ($p = 0.46$) between the plastic film mulch application and the flat planting in heavy textured (clay loam, silt clay, and clay) soils in Inner Mongolia. The I^2 test showed no heterogeneity between studies considered in the MA (Table 3). Plastic film mulching, however, increased potato and maize yield by 34.01 and 33.26%, respectively, compared to the flat planting.

Influence of straw mulched ridge-furrow on soil properties and maize yield in Shaanxi province

Straw mulching increased total nitrogen (90.11% at < 1 g kg^{-1}), available phosphorus (78.48% at < 20 mg kg^{-1}), SOC (62.04% at ≤ 10 g kg^{-1}) and

Table 4 Heterogeneity analysis on crop yield in straw mulching compared with flat planting using random-effects models

Treatment combinations	Variables	*n*	Heterogeneity			Test for overall effect		
			χ^2	df	*P*	I^2	Z	*P*
Flat planting vs. straw	Shaanxi	6	0.24	1	0.63	0	1.89	0.06
	Maize	10	1.27	3	0.74	0	2.1	0.04
	Temperature < 10 °C	8	113.96	2	< 0.00001	98	0.98	0.33
	Temperature < 10–20 °C	6	2.98	2	0.22	33	0.09	0.93
	Precipitation > 500 mm	12	13.21	4	0.01	70	0.21	0.83
	Available nitrogen > 50 mg kg^{-1}	6	2.98	2	0.22	33	0.09	0.93
	Available phosphorus < 20 mg kg^{-1}	7	113.26	2	< 0.00001	98	0.98	0.33
	Available phosphorus > 20 mg kg^{-1}	7	2.98	2	0.23	33	0.15	0.88
	Available potassium < 100 mg kg^{-1}	5	0.01	1	0.93	0	2.96	0.003
	Available potassium > 100 mg kg^{-1}	9	113.57	3	< 0.00001	97	1.18	0.24
	Total nitrogen < 1 g kg^{-1}	5	33.01	1	< 0.00001	97	0.95	0.34
	Soil organic carbon ≤ 10 g kg^{-1}	7	34.54	2	< 0.00001	94	0.87	0.39
	pH > 6–7	4	0.01	1	0.91	0	2.95	0.003
	pH > 7–8	7	113.55	2	< 0.00001	98	1.24	0.21
	Bulk density ≤ 1.3 g cm^{-3}	5	1.04	1	0.31	4	0.89	0.37
	Sunshine hours > 1300 h	9	145.3	3	< 0.00001	98	2.37	0.02
	Frost-free period > 140 days	7	113.55	2	< 0.00001	98	1.24	0.21

Table 5 Heterogeneity analysis on crop yield in biochar amendment compared with flat planting using random-effects models

Treatment combinations	Variables	*n*	Heterogeneity			Test for overall effect		
			χ^2	df	*P*	I^2	Z	*P*
Flat planting vs. biochar	Maize	4	0.03	1	0.87	0	3.62	0.0003
	Temperature < 10 °C	3	2.08	1	0.15	52	1.53	0.13
	Temperature < 10–20 °C	4	0	1	0.98	0	0.26	0.79
	Precipitation > 500 mm	6	9.14	2	0.01	78	1.08	0.28
	Available nitrogen > 50 mg kg^{-1}	4	0	1	0.98	0	0.26	0.79
	Available phosphorus < 20 mg kg^{-1}	4	0.03	1	0.87	0	3.62	0.0003
	Available potassium < 100 mg kg^{-1}	3	4.12	1	0.04	76	0.81	0.42
	Available potassium > 100 mg kg^{-1}	4	0.03	1	0.87	0	3.62	0.0003
	Total nitrogen < 1 g kg^{-1}	3	2.08	1	0.15	52	1.53	0.13
	Total phosphorus > 0.5 g kg^{-1}	3	4.12	1	0.04	76	0.81	0.42
	Total potassium > 10 g kg^{-1}	3	4.12	1	0.04	76	0.81	0.42
	Soil organic carbon > 10 g kg^{-1}	4	9.14	1	0.003	89	1.03	0.3
	pH > 6–7	4	0	1	0.98	0	0.26	0.79
	pH > 7–8	3	2.08	1	0.15	52	1.53	0.13
	Bulk density > 1.3 g cm^{-3}	3	2.08	1	0.15	52	1.53	0.13

available potassium (29.23% at < 100 mg kg^{-1}; 32.69% at > 100 mg kg^{-1}). This could be attributed to longer sunshine hours per growing season. In areas with sunshine hours longer than 1300 h, straw mulched ridge and furrow rainwater harvesting system had an overall significant effect ($p = 0.04$) on maize as compared with the flat planting without mulching. Maize yields in Shaanxi province increased by 13.93% and ranged from 5247–10,264.85 kg ha^{-1} in straw mulched fields compared to the flat planting without mulching. The effect size was 2179.22 and the 95% confidence interval ranged from 373.60 to 3984.84. However, in terms of climatic variables like air temperature and precipitation, the MA demonstrated that in maize cultivation, air temperature and precipitation had no significant moderating effect ($p > 0.05$) on maize with straw applied as mulch compared with flat planting without mulching (Fig. 3).

Table 6 Heterogeneity analysis on crop yield in plastic film with straw compared to flat planting using random-effects models

Treatment combinations	Variables	*n*	Heterogeneity			Test for overall effect		
			χ^2	df	*P*	I^2	Z	*P*
Flat planting vs. plastic film with straw	Shaanxi	13	4.3	3	0.23	30	3.95	< 0.0001
	Maize	13	1.53	3	0.68	0	7.15	< 0.00001
	Wheat	5	0.4	1	0.52	0	0.92	0.36
	Temperature < 10 °C	10	6.41	3	0.09	53	2.46	0.01
	Temperature < 10–20 °C	8	0.1	1	0.75	0	5.62	< 0.00001
	Precipitation > 500 mm	16	4.3	4	0.37	7	5.25	< 0.00001
	Available phosphorus > 20 mg kg^{-1}	8	0.1	1	0.75	0	5.62	< 0.00001
	Available potassium > 100 mg kg^{-1}	14	3.7	3	0.3	19	4.67	< 0.00001
	Total nitrogen < 1 g kg^{-1}	10	3.11	2	0.21	36	2.82	0.005
	Total phosphorus > 0.5 g kg^{-1}	11	3.7	2	0.16	46	3.36	0.0008
	Total potassium < 10 g kg^{-1}	7	3.33	1	0.07	70	1.3	0.19
	Soil organic carbon ≤ 10 g kg^{-1}	7	3.08	1	0.08	68	1.45	0.15
	Soil organic matter > 10 g kg^{-1}	6	1.11	1	0.29	10	3.23	0.001
	pH > 7–8	14	3.7	3	0.3	19	4.67	< 0.00001
	Soil texture (Heavy)	10	1.14	2	0.56	0	5.63	< 0.00001
	Bulk density ≤ 1.3 g cm^{-3}	5	0.32	1	0.57	0	2.03	0.04
	Bulk density > 1.3 g cm^{-3}	7	3.08	1	0.08	68	1.45	0.15
	FC > 25%	7	3.08	1	0.08	68	1.45	0.15

Influence of co-application of plastic film and straw in ridge-furrow on soil properties and wheat and maize yield

Average maize yield in Shaanxi was 9412.22 kg ha^{-1} ($p < 0.00001$) and ranged from 7167.5–12,122.67 kg ha^{-1}, with an effect size of 2599.44 compared with wheat yield which on average was 3862.17 kg ha^{-1} and ranged from 2972.33–4752 kg ha^{-1}. The observed trend is probably because of the significant (20.48%; $p < 0.00001$) increase in soil available phosphorus at > 20 mg kg^{-1}, with an effect size of 2423.80 [CI: 1578.54, 3269.07]. Conversely, air temperature at 10–20 °C with an effect size of 2423.80 significantly ($p < 0.00001$) increased wheat yield (by 60%) in areas with precipitation greater than 500 mm. The MA demonstrated that wheat and maize yield was significantly ($p = 0.01$) increased with co-application of plastic film and straw mulching in ridge-furrow compared with flat planting without mulching (Fig. 3).

Discussion

Effect of integrating mulching in ridge and furrow rainwater harvesting systems on soil properties

Inappropriate land use and management practices pose threats to soil sustainability because it can lead to soil organic matter (SOM) depletion, soil compaction, water and wind erosion, and decreased N use efficiency (Koch et al. 2015; Kassawmar et al. 2018). The impacts of climate change, particularly global warming and rainfall variability is projected to heighten management-induced threats on soil sustainability (Lal et al. 2011; El-Khoury et al. 2015). Therefore, improving soil nutrients is a necessity to increase crop production in modern agriculture (Wichelns 2016; Mak-Mensah et al. 2021c). The MA showed that the addition of crop residues as biochar and/or mulch to soil improves soil quality by releasing organic carbon, and essential macro and micronutrients to the soil for plant use. The results from the MA showing increased SOC in the biochar amended soil is consistent with the previous findings that soil amendment with biochar increases soil carbon (Liu et al. 2016; Blanco-Canqui 2017; Razzaghi et al. 2020). Biochar is regularly inhabited by *actinomycetes* bacteria, and *arbuscular mycorrhizal* fungi, so increased SOM following biochar application could be a reflection of microbial C responses (Verheijen et al. 2019; Cooper et al. 2020). Through surface catalytic activity, biochar adsorbs soil organic molecules and stimulates organic molecule polymerization to form SOM (Zhang et al. 2016; Gaimei et al. 2017).

Huo et al. (2017) reported that straw mulch with plastic film mulching increased SOC in dry saline soils compared with the control without mulch and plastic film (Huo et al. 2017). In this MA, co-application of plastic film and straw or biochar on ridges and in furrows increased available potassium, available phosphorus, SOM, total phosphorus, and total nitrogen (Fig. 4). The MA also showed that biochar

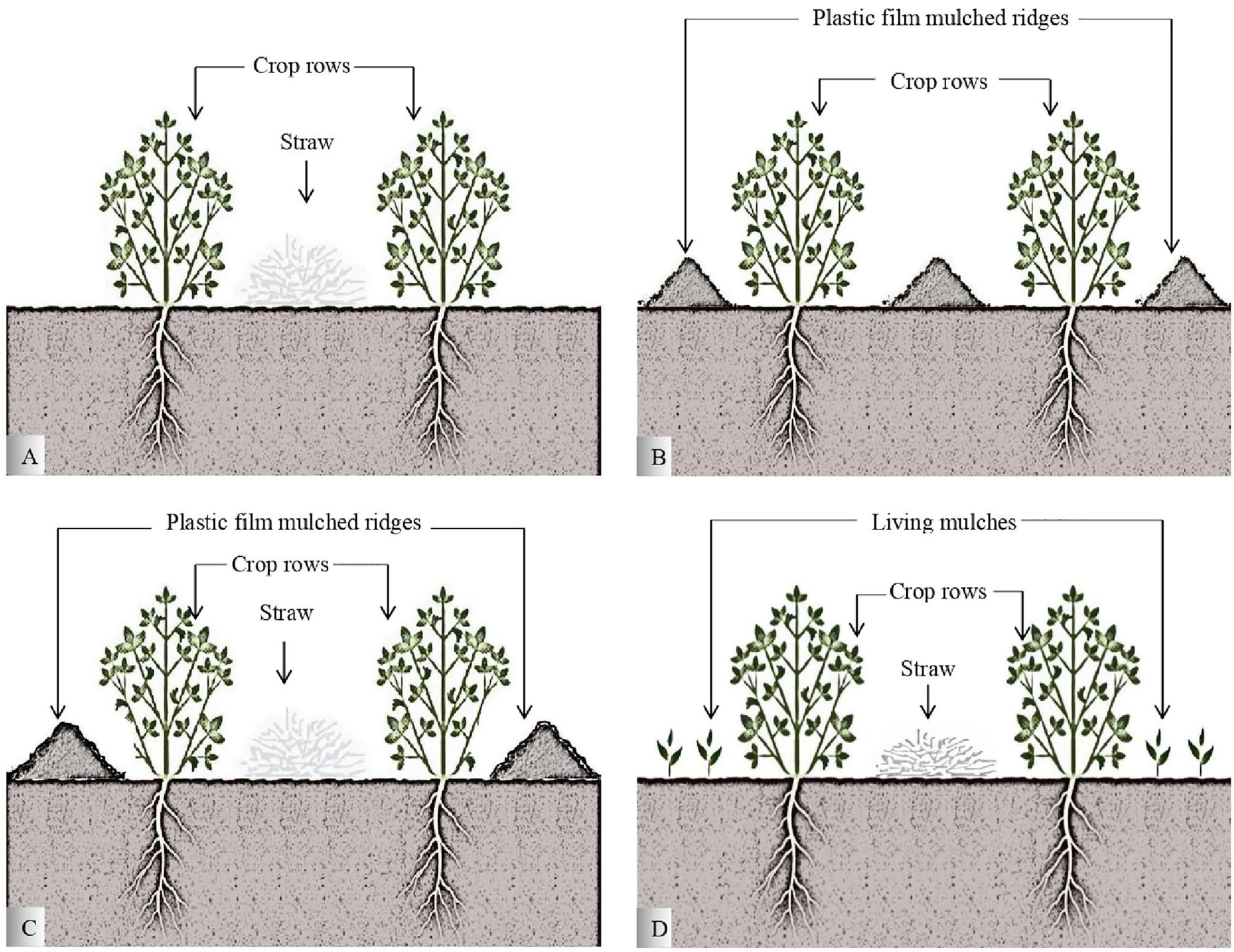

Fig. 3 Common ridge-furrow rainwater harvesting with mulching practices in semi-arid areas

amendment led to increase soil pH (Fig. 4). The ability of biochar to increase soil pH is generally attributed to (i) its alkalinity and release of base cations, particularly K^+ and Ca^{2+}, as well as the replenishment of soil Al^{3+} and H^+ on negatively charged soils (Masud et al. 2014), (ii) the negatively charged functional groups (e.g., phenolic, carboxylic, and hydroxyl) present in biochar binds excess H^+ ions in the soil solution (Gul et al. 2015), and (iii) increase organic anions decarboxylation as a result of increased attack of organic anions by microbes, which may consume surplus H^+ from soil solution (Wang et al. 2014).

An increase in pH can improve soil quality by decreasing harmful elements like Al availability and improving plant nutrient availability (Bedassa 2020). Also due to its alkalinity, application of biochar to acidic soils increases the soil pH, which boosts readily available soil nutrients for to promote crop growth (Lourembam et al. 2018). Wang et al. (2012) revealed soil pH increased after maize straw was co-applied with urea in a paddy flooded silt loam soil. The authors attributed the increase in soil pH to the release of base cations. Further, given its high specific surface area and porosity, biochar improves soil nutrient retention and soil permeability for crop growth (Glaser et al. 2002; Blanco-Canqui 2017). High porosity of biochar decreases soil bulk density to promote root growth and increase soil water retention for plant uptake (Blanco-Canqui 2017).

Results of the MA indicating increased soil total nitrogen for the biochar amended soils are consistent with previous findings by Spokas et al. (2012) and Huang et al. (2013) who reported that biochar can preserve nitrogen due to its porosity and large surface area. Furthermore, biochar has been shown to improve nitrogen adsorption and retention, reduce soil nitrogen loss, improve nitrite to ammonia oxidation, and increase soil nitrogen availability by increasing NO_3-N quantity (Nelissen et al. 2013; Case et al. 2015).

Biochar typically has high potassium (K), content which increases soil K status by enriching K-containing salts (e.g., $KHCO_3$) (Karim et al. 2017). According to Karimi et al.

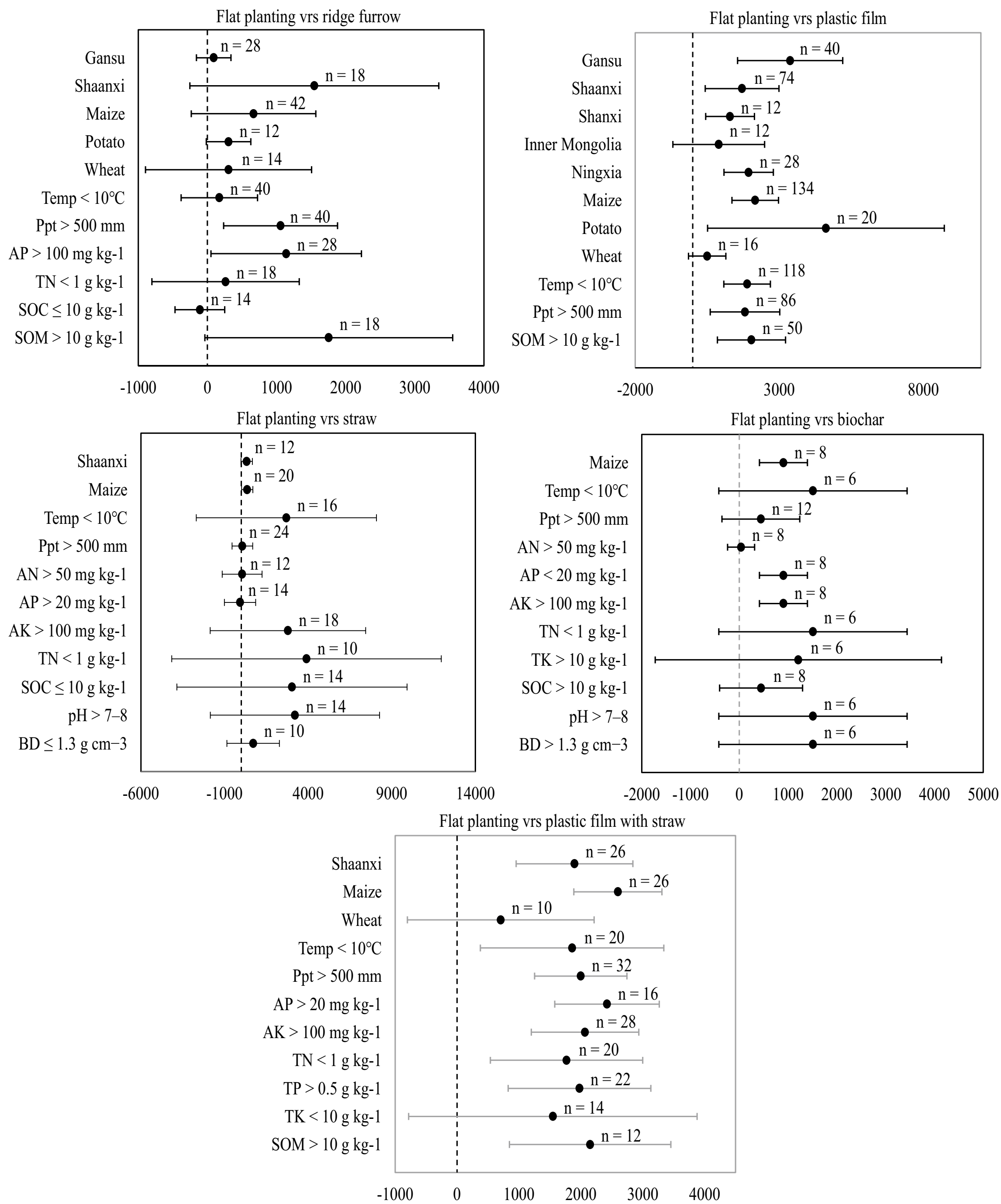

Fig. 4 Odds ratios of crop yields in ridge-furrow rainwater harvesting systems with mulching. The error bars signify 95% confidence intervals, and the values above the bars indicate the number of observations (*n*)

(2020), corn residue biochar produced at higher temperatures (200–600 °C) increased calcareous soil K status by 1.52 to 2.59 folds. Khadem et al. (2021) found a 12.41 percent increase in available K after corn biochar amendment in two calcareous soils. Naeem et al. (2017) found that K increased (32–415 mg kg^{-1}) in calcareous soil after wheat residue biochar produced at 300–500 °C amendment. It important to point out that the effect of biochar on soil K is moderated by other soil properties such as clay mineralogy and innate K contributing capability (Li et al. 2009).

Increase in phosphorus in the biochar amended soil could be explained as biochar liming effect on acid soil which precipitates Al and Fe as $Fe(OH)_3$ and $Al(OH)_3$ thereby increasing phosphorus availability (Bedassa 2020). The pH range of 6.0 to 7.0 is where the most phosphorus is available (Bedassa 2020). For mineral soils, however, phosphorus is readily available at pH 6.5 (Bedassa 2020). Another reason for increase phosphorus in the biochar amended soil is the presence of available phosphorus in biochar. In other words, biochar contains high soluble phosphorus salt content resulting from pyrolyzing organic materials (DeLuca et al., 2012).

Effect of integrating mulching in ridge and furrow rainwater harvesting systems on crop yield

Mulching practice in rain-fed agriculture is gaining prominence in recent years due to its beneficial effect on soil quality and crop productivity (Mondal et al. 2020). This is particularly so in semi-arid areas where annual precipitation is rarely more than 250–600 mm (Cao et al. 2021; Mak-Mensah et al. 2022). In semi-arid areas, prolonged drought and erratic rainfall are major constraints to rain-fed agriculture contributing to crop failures. Thus, saving water in crop fields is an integral part of sustainable agricultural intensification approaches (Yuge and Anan 2011). In the present MA, the application of bare ridge-furrow rainwater harvesting technique increased maize yield by 33.10% compared to flat planting. According to Zhang et al. (2011), ridge-furrow rainwater harvesting technique increased rainwater collection and infiltration which can lead to improved crop yield. The effect of ridge-furrow rainwater harvesting on soil moisture and crop yield is moderated by factors such as soil bulk density and field capacity (Daryanto et al. 2016). According to Wang et al. (2020), ridge-furrow rainwater harvesting is most beneficial in regions with low field capacity and low soil bulk density.

In the semi-arid region of Eastern Kenya, Miriti et al. (2012) reported that yield of maize cultivated in tied-ridging rainwater harvesting system was higher compared with the flat planting. Tied-ridging rainwater harvesting system with minimal irrigation increased sorghum and maize yield in semi-arid China and central Tanzania (Dong et al. 2017; Habtemariam et al. 2019). Jensen et al. (2003) found that maize yield increased by 42% in tied-ridging with normal rainfall amounts, without any nutrient inputs. Conservation treatments such as mulching and tied-ridging increased maize yield by 65% under rainfall conditions of 549 mm (Enfors et al. 2011). Mak-Mensah et al. (2021a) found that combining biodegradable film mulch with biochar increased maize yield by 23% when compared to farmers' bare flat planting practices. Results of the MA showing increased crop yield in the mulch or biochar and tied-ridging compared to the flat planting is could be attributed to improved soil properties and soil moisture conservation leading to good soil quality for plant development and growth.

Tied ridging can be used to conserve rainwater for crops in regions where seasonal rainfall is insufficient to meet crop water needs. Tied-ridges keep water between the ties in the furrows through runoff reduction and increasing infiltration, which is especially important when rainfall is insufficient to support crop growth. However, Ndlangamandla et al. (2016) found no significant difference in sorghum yield between the mulching in tied-ridge-furrow system and the flat planting methods. The lack of significant difference could probably be due to high soil temperatures under the ridges, which may be undesirable for seed germination, and infiltration compared with flat planting (Mak-Mensah et al. 2021b). In this MA, plastic film mulch application increased potato and maize yields in Gansu, Shaanxi, Ningxia, and Shanxi all located in semi-arid areas compared to flat planting (Fig. 4). This might be due to the ability of plastic film to keep topsoil moisture stable and minimize evaporation (Zhou et al. 2009). The increased yield could also be due to the ability of plastic film to move groundwater to the topsoil via vapor transfer and capillary action (Tian et al. 2003). The stomata of plants grown in plastic film mulched fields were reported to be more opened than that in flat planting fields, which may have increased available soil water, accelerated plant development, increased shoot biomass and leaf area index in the former than the latter (Qin et al. 2014). Liu et al. (2014) reported that double mulching in ridge-furrow rainwater harvesting system with plastic film preserved soil moisture throughout the growing season and increased maize yield compared with flat planting. Results from this MA highlight the potentials of integrated ridge-furrow systems to improve soil quality and increase crop production in semi-arid regions.

Conclusions and perspectives

The complexity of factors limiting agricultural productivity, including poor soil quality and water stress suggest that a single soil and water conservation intervention may not be sufficient to effectively address crop productivity challenges in semi-arid regions. Integrated mulched ridge-furrow rainwater harvesting systems (RFRHs) could improve crop growth and yields. The MA demonstrated even though that biochar amendment increased organic carbon, soil pH, available potassium and phosphorus, the integration of biochar with RFRHs did not significantly change maize yield compared to the flat planting. RFRHs with plastic film mulching increased potato and maize yields in Gansu, Shaanxi, Shanxi, and Ningxia provinces all located in semi-arid areas compared to the flat planting. We conclude that the integration of RFRHs with soil amendments could thus, be an optimal agronomic practice for smallholder farmers to maximize yield under rain-fed conditions. The findings of this MA provide useful information on optimizing RFRHs and soil amendments to improve soil quality and crop production especially in semi-arid areas.

References

Baig MB, Shahid SA, Straquadine GS (2013) Making rainfed agriculture sustainable through environmental friendly technologies in Pakistan: a review. Int Soil Water Conserv Res 1:36–52. https://doi.org/10.1016/S2095-6339(15)30038-1

Bedassa M (2020) Soil acid Management using Biochar: review. Int J Agric Sci Food Technol 6:211–217. https://doi.org/10.17352/ijasft

Bhardwaj RL (2013) Effect of mulching on crop production under rainfed condition—a review Organic mulches: organic mulches are derived. Agri Rev 34:188–197. https://doi.org/10.5958/j.0976-0741.34.3.003

Bhatt R, Singh P, Hossain A, Timsina J (2021) Rice–wheat system in the northwest Indo-Gangetic plains of South Asia: issues and technological interventions for increasing productivity and sustainability. Paddy Water Environ 19:345–365. https://doi.org/10.1007/s10333-021-00846-7

Blanco-Canqui H (2017) Biochar and soil physical properties. Soil Sci Soc Am J 81:687–711. https://doi.org/10.2136/sssaj2017.01.0017

Cao D, Zhu H, Guo C et al (2021) Passive distributed temperature sensing (PDTS)-based moisture content estimation in agricultural soils under different vegetative canopies. Paddy Water Environ 19:383–393. https://doi.org/10.1007/s10333-021-00839-6

Case SDC, McNamara NP, Reay DS et al (2015) Biochar suppresses N2O emissions while maintaining N availability in a sandy loam soil. Soil Biol Biochem 81:178–185. https://doi.org/10.1016/j.soilbio.2014.11.012

Chen Y, Chai S, Tian H et al (2019) Straw strips mulch on furrows improves water use efficiency and yield of potato in a rainfed semiarid area. Agric Water Manag 211. https://doi.org/10.1016/j.agwat.2018.09.048

Chen Y, Liu T, Tian X et al (2015) Effects of plastic film combined with straw mulch on grain yield and water use efficiency of winter wheat in Loess Plateau. F Crop Res 172:53–58. https://doi.org/10.1016/j.fcr.2014.11.016

Cooper J, Greenberg I, Ludwig B et al (2020) Effect of biochar and compost on soil properties and organic matter in aggregate size fractions under field conditions. Agric Ecosyst Environ 295:106882. https://doi.org/10.1016/j.agee.2020.106882

Cui Y, feng, Meng J, Wang Q xiang, et al (2017) Effects of straw and biochar addition on soil nitrogen, carbon, and super rice yield in cold waterlogged paddy soils of North China. J Integr Agric 16:1064–1074. https://doi.org/10.1016/S2095-3119(16)61578-2

Dang J, Liang W, Wang G et al (2016) A preliminary study of the effects of plastic film-mulched raised beds on soil temperature and crop performance of early-sown short-season spring maize (Zea mays L.) in the North China Plain. Crop J 4:331–337. https://doi.org/10.1016/j.cj.2016.02.002

Daryanto S, Wang L, Jacinthe PA (2016) Global synthesis of drought effects on maize and wheat production. PLoS ONE 11:1–15. https://doi.org/10.1371/journal.pone.0156362

DeLuca TH, MacKenzie MD, Gundale MJ (2012) Biochar effects on soil nutrient transformations. Biochar Environ Manag Sci Technol 251–270. https://doi.org/10.4324/9781849770552

Dong W, Zhang L, Duan Y et al (2017) Ridge and furrow systems with film cover increase maize yields and mitigate climate risks of cold and drought stress in continental climates. F Crop Res 207:71–78. https://doi.org/10.1016/j.fcr.2017.03.003

Durán-lara EF, Valderrama A, Marican A (2020) Natural organic compounds for application in organic farming. Agriculture 10(2):41 https://doi.org/10.3390/agriculture10020041

El-Khoury A, Seidou O, Lapen DRL et al (2015) Combined impacts of future climate and land use changes on discharge, nitrogen and phosphorus loads for a Canadian river basin. J Environ Manage 151:76–86. https://doi.org/10.1016/j.jenvman.2014.12.012

Eldoma IM, Li M, Zhang F, Li F-MM (2016) Alternate or equal ridge–furrow pattern: which is better for maize production in the rainfed semi-arid Loess Plateau of China? F Crop Res 191:131–138. https://doi.org/10.1016/j.fcr.2016.02.024

Enfors E, Barron J, Makurira H et al (2011) Yield and soil system changes from conservation tillage in dryland farming: a case study from North Eastern Tanzania. Agric Water Manag. https://doi.org/10.1016/j.agwat.2010.02.013

Eze S, Palmer SM, Chapman PJ (2018) Soil organic carbon stock in grasslands: effects of inorganic fertilizers, liming and grazing in different climate settings. 223:74–84. https://doi.org/10.1016/j.jenvman.2018.06.013

Gaimei L, Yuguo W, Baoliang C, et al (2017) Exploring optimal soil mulching to enhance maize yield and water use efficiency in dryland areas in China. Acta Agric Scand Sect B Soil Plant Sci 1–10. https://doi.org/10.1080/09064710.2017.1394486

Glaser B, Lehmann J, Zech W (2002) Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal—a review. Biol Fertil Soils

Gong D, Mei X, Hao W et al (2017) Comparison of ET partitioning and crop coefficients between partial plastic mulched and non-mulched maize fields. Agric Water Manag 181:23–34. https://doi.org/10.1016/j.agwat.2016.11.016

Gu X, Cai H, Fang H et al (2020) Effects of degradable film mulching on crop yield and water use efficiency in China: A meta-analysis. Soil Tillage Res 202:104676. https://doi.org/10.1016/j.still.2020.104676

Gul S, Whalen JK, Thomas BW et al (2015) Physico-chemical properties and microbial responses in biochar-amended soils: mechanisms and future directions. Agric Ecosyst Environ 206:46–59. https://doi.org/10.1016/j.agee.2015.03.015

Haapala T, Palonen P, Korpela A, Ahokas J (2014) Feasibility of paper mulches in crop production—a review. Agric Food Sci 23:60–79. https://doi.org/10.23986/afsci.8542

Habtemariam LT, Mgeni CP, Mutabazi KD, Sieber S (2019) The farm income and food security implications of adopting fertilizer micro-dosing and tied-ridge technologies under semi-arid environments in central Tanzania. J Arid Environ 166:60–67. https://doi.org/10.1016/j.jaridenv.2019.02.011

Hakl J, Šantrůček J, Pisarčik M, Dindová A (2017) Agronomic factors affecting productivity and nutritive value of perennial fodder crops: a review. Slovak J Anim Sci 50(1):33–41

Han J, Jia Z, Han Q, Zhang J (2013) Application of Mulching Materials of Rainfall Harvesting System for Improving Soil Water and Corn Growth in Northwest of China. J Integr Agric 12:1712–1721. https://doi.org/10.1016/S2095-3119(13)60342-1

Higgins JPT (2003) Measuring inconsistency in meta-analyses. BMJ 327:557–560. https://doi.org/10.1136/bmj.327.7414.557

Hu Y, Ma P, Zhang B et al (2019) Exploring optimal soil mulching for the wheat-maize cropping system in sub-humid drought-prone regions in China. Agric Water Manag 219:59–71. https://doi.org/10.1016/j.agwat.2019.04.004

Huang M, Barbour SL, Elshorbagy A et al (2013) Effects of variably layered coarse textured soils on plant available water and forest productivity. Procedia Environ Sci 19:148–157. https://doi.org/10.1016/j.proenv.2013.06.017

Huang R, Tian D, Liu J et al (2018) Responses of soil carbon pool and soil aggregates associated organic carbon to straw and straw-derived biochar addition in a dryland cropping mesocosm system. Agric Ecosyst Environ 265:576–586. https://doi.org/10.1016/j.agee.2018.07.013

Huedo-Medina TB, Sánchez-Meca J, Marín-Martínez F, Botella J (2006) Assessing heterogeneity in meta-analysis: Q statistic or I 2 Index? Psychol Methods 11:193–206. https://doi.org/10.1037/1082-989X.11.2.193

Huo L, Pang H, Zhao Y, et al (2017) Buried straw layer plus plastic mulching improves soil organic carbon fractions in an arid saline soil from Northwest China. Soil Tillage Res 165. https://doi.org/10.1016/j.still.2016.09.006

Jafari M, Haghighi JAP, Zare H (2012) Mulching impact on plant growth and production of rainfed fig orchards under drought conditions. J Food, Agric Environ 10:428–433

Jensen J, Bernhard R, Hansen S et al (2003) Productivity in maize based cropping systems under various soil–water–nutrient management strategies in a semi-arid, alfisol environment in East Africa. Agric Water Manag 59:217–237. https://doi.org/10.1016/S0378-3774(02)00151-8

Karim AA, Kumar M, Singh SK et al (2017) Potassium enriched biochar production by thermal plasma processing of banana peduncle for soil application. Elsevier B.V

Karimi A, Moezzi A, Chorom M, Enayatizamir N (2020) Application of biochar changed the status of nutrients and biological activity in a calcareous soil. J Soil Sci Plant Nutr 20:450–459. https://doi.org/10.1007/s42729-019-00129-5

Kassawmar T, Gessesse GD, Zeleke G, Subhatu A (2018) Assessing the soil erosion control efficiency of land management practices implemented through free community labor mobilization in Ethiopia. Int Soil Water Conserv Res 6:87–98. https://doi.org/10.1016/j.iswcr.2018.02.001

Khadem A, Raiesi F, Besharati H, Khalaj MA (2021) The effects of biochar on soil nutrients status, microbial activity and carbon sequestration potential in two calcareous soils. Biochar 3:105–116. https://doi.org/10.1007/s42773-020-00076-w

Koch A, Chappell A, Eyres M, Scott E (2015) Monitor soil degradation or triage for soil security? An Australian challenge. Sustain 7:4870–4892

Lal R, Delgado JA, Groffman PM et al (2011) Management to mitigate and adapt to climate change. J Soil Water Conserv 66:276–282

Lan X, Chai S, Coulter JA et al (2020) Maize straw strip mulching as a replacement for plastic film mulching in maize production in a semiarid region. Sustain 12. https://doi.org/10.3390/SU12156273

Li N, Zhou C, Sun X et al (2018) Effects of ridge tillage and mulching on water availability, grain yield, and water use efficiency in rain-fed winter wheat under different rainfall and nitrogen conditions. Soil Tillage Res 179:86–95. https://doi.org/10.1016/j.still.2018.01.003

Li R, Hou X, Jia Z et al (2012) Effects of rainfall harvesting and mulching technologies on soil water, temperature, and maize yield in Loess Plateau region of China. Soil Res 50:105. https://doi.org/10.1071/SR11331

Li R, Hou X, Jia Z et al (2013) Effects on soil temperature, moisture, and maize yield of cultivation with ridge and furrow mulching in the rainfed area of the Loess Plateau, China. Agric Water Manag 116:101–109. https://doi.org/10.1016/j.agwat.2012.10.001

Li R, Li Q, Pan L (2020) Review of organic mulching effects on soil and water loss. Arch Agron Soil Sci 00:1–16. https://doi.org/10.1080/03650340.2020.1718111

Li X-YY, Gong J-DD, Gao Q-ZZ, Li F-RR (2001) Incorporation of ridge and furrow method of rainfall harvesting with mulching for crop production under semiarid conditions. Agric Water Manag 50:173–183. https://doi.org/10.1016/S0378-3774(01)00105-6

Li X, Lu J, Wu L, Chen F (2009) The difference of potassium dynamics between yellowish red soil and yellow cinnamon soil under rapeseed (Brassica napus L.)-rice (Oryza sativa L.) rotation. Plant Soil 320:141–151. https://doi.org/10.1007/s11104-008-9879-7

Liang S, Ren C, Wang P et al (2018) Improvements of emergence and tuber yield of potato in a seasonal spring arid region using plastic film mulching only on the ridge. F Crop Res 223:57–65. https://doi.org/10.1016/j.fcr.2018.03.012

Lin W, Liu W, Zhou S, Liu C (2019) Influence of plastic film mulch on maize water use efficiency in the Loess Plateau of China. Agric Water Manag 224:105710. https://doi.org/10.1016/j.agwat.2019.105710

Liu C-A, Siddique KHM (2015) Does plastic mulch improve crop yield in semiarid farmland at high altitude? Agron J 107:1724–1732. https://doi.org/10.2134/agronj15.0052

Liu S, Zhang Y, Zong Y et al (2016) Response of soil carbon dioxide fluxes, soil organic carbon and microbial biomass carbon to biochar amendment: a meta-analysis. GCB Bioenergy 8:392–406. https://doi.org/10.1111/gcbb.12265

Liu Z, Chen X, Jing Y et al (2014) Effects of biochar amendment on rapeseed and sweet potato yields and water stable aggregate in upland red soil. CATENA 123:45–51. https://doi.org/10.1016/j.catena.2014.07.005

Liu Z, Jin J (2017) Review on rainfed agriculture and rainwater harvesting techniques. In: Proceedings of the 2016 international conference on biological engineering and pharmacy (BEP 2016). Atlantis Press, Paris, France, pp 329–331

Lourembam D, Laskar S, Mukherjee S (2018) Framework for an optical sensor system for monitoring of soil nitrogen and tailoring soil pH. J Opt 47:180–194. https://doi.org/10.1007/s12596-017-0434-x

Lu H, Xia Z, Fu Y et al (2020) Response of soil temperature, moisture, and spring maize (Zea mays L.) root/shoot growth to different mulching materials in semi-arid areas of Northwest China. Agronomy 10:453. https://doi.org/10.3390/agronomy10040453

Mak-Mensah E, Obour PB, Essel E et al (2021a) Influence of plastic film mulch with biochar application on crop yield, evapotranspiration, and water use efficiency in northern China: a meta-analysis. PeerJ 9:e10967. https://doi.org/10.7717/peerj.10967

Mak-Mensah E, Obour PB, Wang Q (2021b) Influence of tied-ridge-furrow with inorganic fertilizer on grain yield across semiarid regions of Asia and Africa: a meta-analysis. PeerJ 9:e11904. https://doi.org/10.7717/peerj.11904

Mak-Mensah E, Sam FE, Safnat Kaito IOI et al (2021c) Influence of tied-ridge with biochar amendment on runoff, sediment losses, and alfalfa yield in northwestern China. PeerJ 9:e11889. https://doi.org/10.7717/peerj.11889

Mak-Mensah E, Zhang D, Zhou X et al (2022) Effect of co-application of ridge-furrow rainwater harvesting and mulching on fodder yield, quality, and soil desiccation in Alfalfa (Medicago sativa) production. J Soil Sci Plant Nutr. https://doi.org/10.1007/s42729-022-00829-5

Masud MM, Li JY, Xu RK (2014) Use of alkaline slag and crop residue biochars to promote base saturation and reduce acidity of an acidic ultisol. Pedosphere 24:791–798. https://doi.org/10.1016/S1002-0160(14)60066-7

Miriti JM, Kironchi G, Esilaba AO et al (2012) Yield and water use efficiencies of maize and cowpea as affected by tillage and cropping systems in semi-arid Eastern Kenya. Agric Water Manag 115:148–155. https://doi.org/10.1016/j.agwat.2012.09.002

Mo F, Wang JY, Zhou H et al (2017) Ridge-furrow plastic-mulching with balanced fertilization in rainfed maize (Zea mays L.): an adaptive management in east African Plateau. Agric for Meteorol 236:100–112. https://doi.org/10.1016/j.agrformet.2017.01.014

Mohammadi GR, Mozafaril S, Najaphy A, Ghobadi ME (2012) Corn (Zea mays L.) seed vigour and quality as influenced by weed interference and living mulch. Adv Environ Biol 6:1026–1031

Moher D, Liberati A, Tetzlaff J, Altman DG (2009) Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. PLoS Med 6:e1000097. https://doi.org/10.1371/journal.pmed.1000097

Mondal S, Naik SK, Haris AA et al (2020) Effect of conservation tillage and rice-based cropping systems on soil aggregation characteristics and carbon dynamics in Eastern Indo-Gangetic Plain. Paddy Water Environ 18:573–586. https://doi.org/10.1007/s10333-020-00802-x

Moreno MM, Moreno A (2008) Effect of different biodegradable and polyethylene mulches on soil properties and production in a tomato crop. Sci Hortic (amsterdam) 116:256–263. https://doi.org/10.1016/j.scienta.2008.01.007

Naeem MA, Khalid M, Aon M et al (2017) Effect of wheat and rice straw biochar produced at different temperatures on maize growth and nutrient dynamics of a calcareous soil. Arch Agron Soil Sci 63:2048–2061. https://doi.org/10.1080/03650340.2017.1325468

Ndlangamandla MT, Ndlela ZP, Manyatsi AM (2016) Mulching and tied ridges as a moisture conservation strategy to improve the yield of sorghum (Sorghum Bicolor) in semi-arid parts of Swaziland. Int J Environ Agric Res 2:2012–2015

Nelissen V, Rütting T, Huygens D et al (2013) Temporal evolution of biochar's impact on soil nitrogen processes—a 15N tracing study. GCB Bioenergy 7:172–177. https://doi.org/10.1016/j.fcr.2013.08.010

Pan Y, Pan X, Zi T et al (2019) Optimal ridge-furrow ratio for maximum drought resilience of sunflower in semi-arid region of China. Sustainability 11:4047. https://doi.org/10.3390/su11154047

Qin S, Zhang J, Dai H et al (2014) Effect of ridge-furrow and plastic-mulching planting patterns on yield formation and water movement of potato in a semi-arid area. Agric Water Manag. https://doi.org/10.1016/j.agwat.2013.09.015

Qin X, Li Y, Han Y et al (2018) Ridge-furrow mulching with black plastic film improves maize yield more than white plastic film in dry areas with adequate accumulated temperature. Agric for Meteorol 262:206–214. https://doi.org/10.1016/j.agrformet.2018.07.018

Rango A, Havst K (2011) Review of water-harvesting techniques to benefit forage growth and livestock on arid and Semiarid Rangelands. Water Conserv 1–19. https://doi.org/10.5772/29857

Razzaghi F, Obour PB, Arthur E (2020) Does biochar improve soil water retention? A systematic review and meta-analysis. Geoderma 361:114055. https://doi.org/10.1016/j.geoderma.2019.114055

Ren X, Cai T, Chen X et al (2016) Effect of rainfall concentration with different ridge widths on winter wheat production under semi-arid climate. Eur J Agron 77:20–27. https://doi.org/10.1016/j.eja.2016.03.008

Ren X, Chen X, Cai T et al (2017) Effects of ridge-furrow system combined with different degradable mulching materials on soil water conservation and crop production in semi-humid areas of China. Front Plant Sci 8. https://doi.org/10.3389/fpls.2017.01877

Siderius C, Van Walsum PEV, Roest CWJ et al (2016) The role of rainfed agriculture in securing food production in the Nile Basin. Environ Sci Policy 61:14–23. https://doi.org/10.1016/j.envsci.2016.03.007

Song Z, Guo J, Zhang Z et al (2013) Impacts of planting systems on soil moisture, soil temperature and corn yield in rainfed area of Northeast China. Eur J Agron 50:66–74. https://doi.org/10.1016/j.eja.2013.05.008

Spokas KA, Novak JM, Venterea RT (2012) Biochar's role as an alternative N-fertilizer: Ammonia capture. Plant Soil 350:35–42. https://doi.org/10.1007/s11104-011-0930-8

Tian Y, Su D, Li F, Li X (2003) Effect of rainwater harvesting with ridge and furrow on yield of potato in semiarid areas. F Crop Res 84:385–391. https://doi.org/10.1016/S0378-4290(03)00118-7

Verheijen FGA, Zhuravel A, Silva FC et al (2019) The influence of biochar particle size and concentration on bulk density and maximum water holding capacity of sandy vs sandy loam soil in a column experiment. Geoderma 347:194–202. https://doi.org/10.1016/j.geoderma.2019.03.044

Wang G, Wu B, Zhang L et al (2014) Role of soil erodibility in affecting available nitrogen and phosphorus losses under simulated rainfall. J Hydrol 514:180–191. https://doi.org/10.1016/j.jhydrol.2014.04.028

Wang J, Wang D, Zhang G, Wang C (2012) Effect of wheat straw application on ammonia volatilization from urea applied to a paddy field. Nutr Cycl Agroecosystems. https://doi.org/10.1007/s10705-012-9527-8

Wang TC, Wei L, Wang HZ et al (2011) Responses of rainwater conservation, precipitation-use efficiency and grain yield of summer maize to a furrow-planting and straw-mulching system in northern China. F Crop Res 124:223–230. https://doi.org/10.1016/j.fcr.2011.06.014

Wang X-L, Li F-M, Jia Y, Shi W-Q (2005) Increasing potato yields with additional water and increased soil temperature. Agric Water Manag 78:181–194. https://doi.org/10.1016/j.agwat.2005.02.006

Wang Y, Guo T, Qi L et al (2020) Meta-analysis of ridge-furrow cultivation effects on maize production and water use efficiency. Agric Water Manag 234. https://doi.org/10.1016/j.agwat.2020.106144

Wichelns D (2016) Managing water and soils to achieve adaptation and reduce methane emissions and arsenic contamination in Asian rice production. Water (Switzerland) 8. https://doi.org/10.3390/w8040141

Wu Y, Huang F, Jia Z et al (2017) Response of soil water, temperature, and maize (Zea may L.) production to different plastic film mulching patterns in semi-arid areas of northwest China. Soil Tillage Res. https://doi.org/10.1016/j.still.2016.10.012

Xiao Q, Zhu L-X, Zhang H-P et al (2016) Soil amendment with biochar increases maize yields in a semi-arid region by improving soil quality and root growth. Crop Pasture Sci 67:495. https://doi.org/10.1071/CP15351

Xiukang W, Zhanbin L, Yingying X (2015) Effects of mulching and nitrogen on soil temperature, water content, nitrate-N content and maize yield in the Loess Plateau of China. Agric Water Manag 161:53–64. https://doi.org/10.1016/j.agwat.2015.07.019

Yin M, Li Y, Fang H, Chen P (2019) Biodegradable mulching film with an optimum degradation rate improves soil environment and enhances maize growth. Agric Water Manag 216:127–137. https://doi.org/10.1016/j.agwat.2019.02.004

Yin M, Li Y, Li H et al (2015) Ridge-furrow planting with black film mulching over ridge and corn straw mulching over furrow enhancing summer maize's growth and nutrient absorption. Nongye Gongcheng Xuebao/Transactions Chinese Soc Agric Eng. https://doi.org/10.11975/j.issn.1002-6819.2015.22.017

Yu Y, Tao H, Yao H, Zhao C (2018) Assessment of the effect of plastic mulching on soil respiration in the arid agricultural region of China under future climate scenarios. Agric For Meteorol 256–257. https://doi.org/10.1016/j.agrformet.2018.02.025

Yuge K, Anan M (2011) Quantification of the crop stem flow in the sprinkler irrigated field. Paddy Water Environ 9:229–236. https://doi.org/10.1007/s10333-010-0222-6

Zeng X, Zhang Y, Kwong JSW et al (2015) The methodological quality assessment tools for preclinical and clinical studies, systematic review and meta-analysis, and clinical practice guideline: a systematic review. J Evid Based Med 8:2–10. https://doi.org/10.1111/jebm.12141

Zerihun A, Sharma JJ, Nigussie D et al (2013) The effect of integrated organic and inorganic fertilizer rates on performances of soybean and maize component crops of a soybean/maize mixture at Bako, Western Ethiopia. African J Agric Res 8:3921–3929. https://doi.org/10.5897/AJAR12.1044
Zhang D, Yan M, Niu Y et al (2016) Is current biochar research addressing global soil constraints for sustainable agriculture? Agric Ecosyst Environ 226:25–32. https://doi.org/10.1016/j.agee.2016.04.010
Zhang P, Wei T, Cai T et al (2017) Plastic-film mulching for enhanced water-use efficiency and economic returns from maize fields in semiarid China. Front Plant Sci 8. https://doi.org/10.3389/fpls.2017.00512
Zhang S, Li P, Yang X et al (2011) Effects of tillage and plastic mulch on soil water, growth and yield of spring-sown maize. Soil Tillage Res 112:92–97. https://doi.org/10.1016/j.still.2010.11.006
Zhang W, Qin S, Xu X et al (2018) Soil bacterial biomass and diversity are affected by different furrow-ridge mulched management systems during potato continuous cropping. bioRxiv 394551. https://doi.org/10.1101/394551
Zhang X, Kamran M, Xue X et al (2019a) Ridge-furrow mulching system drives the efficient utilization of key production resources and the improvement of maize productivity in the Loess Plateau of China. Soil Tillage Res 190:10–21. https://doi.org/10.1016/j.still.2019.02.015
Zhang X, Yang L, Xue X et al (2019b) Plastic film mulching stimulates soil wet-dry alternation and stomatal behavior to improve maize yield and resource use efficiency in a semi-arid region. F Crop Res 233:101–113. https://doi.org/10.1016/j.fcr.2019.01.002
Zhang X, Zhao J, Yang L et al (2019c) Ridge-furrow mulching system regulates diurnal temperature amplitude and wetting-drying alternation behavior in soil to promote maize growth and water use in a semiarid region. F Crop Res 233:121–130. https://doi.org/10.1016/j.fcr.2019.01.009
Zhao H, Wang R-YY, Ma B-LL et al (2014) Ridge-furrow with full plastic film mulching improves water use efficiency and tuber yields of potato in a semiarid rainfed ecosystem. F Crop Res 161:137–148. https://doi.org/10.1016/j.fcr.2014.02.013
Zhao H, Xiong Y-CC, Li F-MM et al (2012) Plastic film mulch for half growing-season maximized WUE and yield of potato via moisture-temperature improvement in a semi-arid agroecosystem. Agric Water Manag 104:68–78. https://doi.org/10.1016/j.agwat.2011.11.016
Zhou L-M, Li F-M, Jin S-L, Song Y (2009) How two ridges and the furrow mulched with plastic film affect soil water, soil temperature and yield of maize on the semiarid Loess Plateau of China. F Crop Res 113:41–47. https://doi.org/10.1016/j.fcr.2009.04.005
Zhou L-M, Zhang F, Liu C-A (2015) Improved yield by harvesting water with ridges and subgrooves using buried and surface plastic mulchs in a semiarid area of China. Soil Tillage Res 150:21–29. https://doi.org/10.1016/j.still.2015.01.006
Zhu Y, Chen Y, Gong X et al (2018) Plastic film mulching improved rhizosphere microbes and yield of rainfed spring wheat. Agric for Meteorol 263:130–136. https://doi.org/10.1016/j.agrformet.2018.08.015

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