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Combining biochar with cotton-sugarbeet intercropping increased water-fertilizer productivity and economic benefits under plastic mulched drip irrigation in Xinjiang, China

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ABSTRACT

Intercropping and biochar application are two main practices that can conserve land, improve water and fertilizer use efficiency and crop yields. However, the performance of the combination of different biochar application amounts and intercropping system is not clear. The objectives of this study were to determine how biochar and intercropping affected soil water, soil pH and nutrients, plant growth, yield, irrigation water - fertilizer use efficiency, and economic benefits for cotton monoculture and cotton-sugarbeet intercropping system, and find the optimal biochar application amount and application years. A three-year cotton-sugarbeet intercropping with biochar application experiment were conducted compared with cotton monoculture. The biochar was continuously applied to the field at the rates of 0, 10, 50 and 100 t ha^{-1} in 2018, 0, 10, 25, 50 and100 t ha^{-1} in 2019 and 0, 10, 25 and 30 t ha^{-1} in 2020. The soil water, nutrients, cotton growth, cotton and sugarbeet yields, water and fertilizer use efficiency and economic benefits were studied. The combination of biochar and cotton-sugarbeet intercropping has several positive effects compared to the cotton monoculture system. The soil water condition was improved. The comprehensive fertility of soil was increased by 3.9–28.3%. The cotton yields, water and fertilizer use efficiency and economic benefits were increased by 0.5–43.8%, 43.3–135.3% and 11.5–65.6%, respectively. The multicriteria assessment showed that the biochar application amount at 10 t ha^{-1} treatment performed the best with the highest scale every year. The multivariate nonlinearity equation implicated that three years of a continuous biochar application amount of 16.6 t ha^{-1} was an efficient mode to improve IWUE. The research provides a new insight for agricultural production in the arid and semi-arid.

1. Introduction

Cotton is the most extensively cultivated fiber crop in the world, and its yield directly affects the development of fiber, food, and rural economy (Thorp et al., 2014; Yang et al., 2016). With a strong salt tolerance, cotton has been widely grown in Xinjiang Uyghur Autonomous Region, China, where about 1/3 of the arable land is threatened by salinization (Günther et al., 2017; Li et al., 2015). In addition, sugarbeet (*Beta vulgaris L.*) has become the other major economic crop in Xinjiang (Hong et al., 2017). With high annual pan evapotranspiration, low

Abbreviations: LAI, Leaf area index; SWC, Soil water content; EC, Electrical conductivity; SSC, soil salt content; DAS, Days after sowing; NO_3^-, Nitrate nitrogen; K, potassium; P, Phosphorus; WPSWS, Weighted planar soil water storage; IWUE, Irrigation water use efficiency; PFP, Partial factor productivity; LSD, Least significant differences.

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precipitation and minimal water resources, improving irrigation water use efficiency (IWUE) is imperative in this region for local agriculture sustainability. The practice to improve IWUE are to improve crop yields or to reduce irrigation water amounts according to the calculation of IWUE (Howell, 1994). Since 1996, under plastic mulched drip irrigation has been widely used in Xinjiang, and it is playing an important role in promoting agricultural production and in saving water resources (Ning et al., 2021). Various strategies including farm management and soil amendments application have been applied to increase crop yields.

As a prevalent agricultural practice, intercropping systems cultivate two or more plants in the same field at the same time (Willey, 1979). Intercropping systems can increase resource use efficiency such as land, light, water and nutrient (Gou et al., 2016), reduce soil erosion (Hu et al., 2016), alleviate drought risk (Ren et al., 2019), strengthen pest management (Li et al., 2017), therefore increase yield and farmers' income (Zhang et al., 2018). The main intercropping systems that have been studied extensively are maize-wheat, maize-peanut and maize-soybean (Gou et al., 2016; Zhang et al., 2020; Xu et al., 2022). Recently, jujube-cotton intercropping systems have been developed to improve yield and enhance farmers' income in arid areas including Xinjiang. Whereas, the intercropping system of agroforestry is more complex than that of agriculture (Wang et al., 2021a). It was hypothesized the cotton-sugarbeet intercropping system (intercropping system of agriculture) was more suitable for Xinjiang region. However, the performance of intercropping system depends on environmental conditions, crop management and the level of competition between species (Corre-Hellou et al., 2006). The advantages of cotton-sugarbeet intercropping system over cotton monoculture system need to be further investigated.

Biochar (solid carbonaceous residue, produced under oxygen-free or oxygen-limited conditions at temperatures ranging from 300° to 1000°C) has been widely used for soil remediation and soil quality improvement (Abrol et al., 2016). The advantages of biochar include: (1) improving soil physical and chemical properties. Biochar decreases soil bulk density and increases soil porosity by promoting a rich pore structure (Burrell et al., 2016). The effect of biochar on soil pH (increasing or decreasing) varies with the biochar types and the soil properties (Wang et al., 2017); (2) enhancing soil nutrients. The application of biochar increases soil organic matter, available nitrogen, available phosphorus and available potassium (Laghari et al., 2015); (3) promoting plant growth. The effects of biochar on growth in corn, wheat, and soybean have been investigated extensively (Mehdizadeh et al., 2020; Qayyum et al., 2017). The application of biochar improved soil conditions, promoted plant growth, improved photosynthetic properties and increased yield (Huang et al., 2019; Zhao et al., 2020).

The effects of biochar on soil and plant growth are influenced by biochar application amounts (He et al., 2020; Zhu et al., 2020). An appropriate biochar application amount is essential for soil improvement and economic benefit (Saifullah et al., 2018). To avoid the adverse effects of biochar on soil and plant growth, the appropriate range of biochar application amount was 10–80 t ha^{-1} (Lehmann, 2007). Laghari et al. (2015) applied biochar at 0, 15, 22 and 45 t ha^{-1} to study the effects of biochar on sorghum yield. The results showed that the 22 t ha^{-1} was the most appropriate biochar application amount to increase yield. Fu et al. (2019) evaluated the effects of different biochar application amounts (0, 30, 60, 90 and 120 t·ha^{-1}) on soil water retention curves and hydraulic characteristics including field capacity, permanent wilting point and available water content. The application amount at 60 t ha^{-1} induced the most relative change in field capacity. Zhao et al. (2020) applied biochar at rates of 0, 5, 10, 15, 20, 25 and 30 t ha^{-1} to saline-alkali soil; the results of soil nutrient, soil salt content, and corn yield indicated that the best rate was 20 t ha^{-1}. When the cumulative amount of applied biochar was the same, multiple applications were better than a one-time- approach for soil improvement (Wu et al., 2019).

The combination of farm management practice of intercropping with biochar application is seldomly studied. The application amounts and applied-time of biochar are also need to be determined. In this study, biochar was applied continuously in different amounts in a cotton-sugarbeet intercropping system and compared to that of cotton monoculture treatment under plastic mulched drip irrigation in Xinjiang. The objectives of this study were: (1) to determine how the application of biochar affected soil water, soil pH and nutrients, plant growth, yield, irrigation water and fertilizer use efficiency, and economic benefits; (2) to find the optimal amounts and applied-time of biochar application manner for sustainable agricultural development in Xinjiang.

2. Materials and methods

2.1. Experimental site

A three-year field experiments was conducted at Bayingol Mongolian Autonomous Prefecture in the Xinjiang Uyghur Autonomous Region of Northwest China (86°56′ E, 40°53′ N). With a mean annual temperature of 10.9 °C, annual mean precipitation of 34.1 mm, and annual mean pan evapotranspiration of 2417 mm, this is a representative temperate continental desert climate. High annual pan evapotranspiration and low precipitation indicate that irrigation is imperative for local agriculture.

Before the experiment began in 2018, soil samples at 0–100 cm soil layers were collected to analyze soil properties. Soil particle composition was determined with the Malvern laser particle size analyzer (Mastersizer 2000). Soil textures at 0–50 cm were silt clay loam, and 50–100 cm depths were sand (Wrb, 2006) (Table 1). The soil pH values and electrical conductivity (EC) were measured with a pH meter and a DDS-303 conductivity meter at 25 °C. The soil salt content (SSC) was obtained by EC with SSC= 3.4328$EC_{1:5}$ + 1.0513 (R^2 =0.95) (Liang et al., 2021b). Averaged soil salt content for the 0–60 cm depth varied from 0.1%–0.2%, which indicated that the soil belonged to a light salinized level (Xu, 1980). The basic soil properties are given in Table 1.

2.2. Experiments design

2.2.1. Biochar properties

The commercial biochar was provided by Zhengzhou Yongbang New Energy Equipment Technology Co., Ltd. The raw material for the biochar used in this experiment was empty fruit bunch, which were the processing residue of palm (*Trachycarpus fortunei*) oil. After crushing, impurity removal and screening, the empty fruit bunch was oven dried at 105 ℃ for 5 h to a constant mass. The biochar was produced by slow pyrolysis at 600℃under anaerobic conditions with a covered stainless container in a muffle furnace. To improve the contacting area between biochar and soil, the cooled biochar was milled to the powdery biochar. According to the biochar product information, the biochar particle size was smaller than 2 mm and bulk density was 0.5 g cm^{-3}. The specific surface area was 217 m^2 g^{-1}. The initial electrical conductivity ($EC_{1:5}$) of the biochar was 11.02 mS cm^{-1}. The total and dissolved organic carbon content were 472.2 g kg^{-1} and 143.5 mg kg^{-1}, respectively. The cation

Table 1
Physical and chemical properties of the tested soils at the depth range of 0–100 cm.

Soil depth (cm)	Bulk density (g cm^{-3})	Particle content (%)			Soil texture	Soil salt content (g kg^{-1})	pH
		Clay	Silt	Sand			
0–20	1.54	19.09	55.26	25.65	Silt clay loam	1.84	8.9
20–40	1.55	19.06	54.92	26.02	Silt clay loam	1.70	8.5
40–50	1.52	15.51	46.68	37.81	Silt clay loam	1.66	8.6
50–60	1.56	1.55	2.43	96.02	Sand	1.71	8.4
60–80	1.62	1.38	1.63	96.99	Sand	1.33	8.4
80–100	1.59	1.37	1.42	97.21	Sand	1.47	8.3

exchange capacity was 12.2 cmol kg^{-1}. The total nitrogen and phosphorus were 2.30 and 0.39 g kg^{-1}. The available phosphorus and potassium were 91.1 and 2575 mg kg^{-1}. The nitrate and ammonia nitrogen were 2.54 and 1.15 mg kg^{-1}. The biochar was acidified by ferrous sulfate, resulting in a biochar pH of 6.7. This relatively lower pH value of biochar avoids increasing the pH value of the saline-alkaline soils after application.

2.2.2. Field planting and irrigation systems

The varieties of cotton (*Gossypium hirsutum L.*) and sugarbeet (*Beta vulgaris L.*) were Xinluzhong 66 and Detian II, respectively. The intercropping system was comprised of every 4 rows of cotton were intercropped with 1 row of sugarbeet. The irrigation pattern was "one plastic film, two drip lines, and four rows of cotton plants". Two drip lines were located beneath one plastic mulch, and four rows of cotton plants were covered by a plastic mulch. The one row of sugarbeet was intercropped in the no-mulched zone. The narrow row spacing between the two cotton plants, the wide row spacing and inter-mulch spacing were 10, 66 and 30 cm, respectively (Fig. 1). Each drip line consisted of emitters spaced 30 cm apart, and the discharge rate for each emitter was 2.0 L h^{-1}. The cotton monoculture system was not intercropped sugarbeet.

2.2.3. The biochar application, irrigation and fertilization treatments

The biochar was mixed into the soil at depths of 0–30 cm before sowing. The initial biochar application amounts were 0, 10, 50 and 100 t• ha^{-1} in 2018. Then, the biochar application amounts in 2019 were adjusted according to the results of soil water, salt, temperature and crop growth and yield in 2018. A biochar application amount at 25 t• ha^{-1} was added in 2019, i.e. 0, 10, 25, 50 and 100 t• ha^{-1}. As the soil in the study area was light salinized and the salt content in the used biochar, the application amount of biochar in the 3rd year was adjusted to avoid aggravating soil salinization. In addition, considering both crop growth and the economic cost of the biochar, 0, 10, 25 and 30 t• ha^{-1} of biochar were adopted in 2020. Each treatment was replicated three times. Therefore, the field had 15, 18, and 15 experimental plots in 2018, 2019 and 2020, respectively. Each plot area was 36 m^2 (6 m × 6 m), designed in a randomized block way. The experiments lasted from April, 11 to September, 24 both in 2018 and 2019 and April 15 to September 20 in 2020. Corresponding to the application amount of biochar, the treatments were named as the B0, B10, B25, B30, B50 and B100. The details of experiments during 2018, 2019 and 2020 are given in Table 2. Treatments with the same color represented that the field was the same. The cotton monoculture treatment was named as the CK.

The irrigation and fertilization application schedules were the same for all the treatments during 2018, 2019 and 2020. Soil salt was leached with a 300 mm-flood-irrigation in November. The irrigation quota was 260 mm for all of three years. The fertilization applications with urea (N ≥ 46%), diammonium phosphate (P_2O_5 ≥ 46%, N ≥ 12%) and potassium sulfate (K_2O≥ 52%) were 450, 265, and 100 kg ha^{-1}. The irrigation and fertilization schedules are presented in Table 3.

2.3. Observation and data analysis

2.3.1. Meteorological data

A portable small automatic weather station (HOBO U30, USA) was used to observe the meteorological data for the experimental field. The mean air temperatures were 23.5 °C, 24.1 °C, and 24.1 °C. The precipitation was 22.1 mm, 20 mm, and 32.4 mm. The average wind speeds were 1.32, 0.81, and 0.91 m s^{-1}, and the average solar radiations were 217.1, 235.2 and 253.6 MJ m^{-2} d^{-1} in 2018, 2019 and 2020 respectively (Fig. 2).

2.3.2. Soil water content (SWC) and pH

Soil samples were collected with a steel auger on different days after sowing (DAS) at 0, 10, 20, 30, 40, 60, 80, 100 cm in no mulch, narrow row, and wide row zones during 2018–2020. Then the oven drying method was used to obtain SWC. The soil pH values were measured with a pH meter (PHS-3 C).

The concept of weighted planar soil water storage (WPSWS) at root zone (40 cm with the measuring interval at 10 cm) was proposed to describe the soil water distribution in a 2-D plane of XOZ (See Fig. 1) (Liang et al., 2021b; Wang et al., 2022). WPSWS synthesized soil water information not only for the wide rows, narrow rows and no mulch zones but also for soil depths. The WPSWS (cm^3 cm^{-3}) is calculated by:

$$WPSWS = \frac{HL_w\overline{\theta}_w + HL_N\overline{\theta}_N + HL_{NM}\overline{\theta}_{NM}}{H(L_w + L_N + L_{NM})} \tag{1}$$

where L_w, L_N, and L_{NM} are the half-width of wide row zone, narrow row zone, and no mulched zone, which equal to 33, 20 and 15 cm, respectively; H is set to be 40 cm; $\overline{\theta}_W$, $\overline{\theta}_N$, and $\overline{\theta}_{NM}$ are averaged soil water content (cm^3 cm^{-3}) in the wide row, narrow row, and no mulch zones at the depth of 40 cm with a measuring interval at 10 cm, respectively.

2.3.3. Soil nutrients

Soil samples at the depth of 0–40 cm were collected before sowing and after harvest. Soil organic carbon was measured with $K_2Cr_2O_7$ volumetric method-external heating method. Soil nitrate nitrogen (NO_3^-), available potassium (K) and available phosphorus (P) were measured with the ultraviolet spectrophotometry method, NH_4OAC extraction-flame photometry, and $NaHCO_3$ extraction-Mo-Sb colorimetry method (Gautheyrou, 2006). Finally, the comprehensive fertility of the soil was calculated with the following equation (Bao et al., 2012):

$$IFI_i = \begin{cases} \dfrac{x}{x_a}, x \le x_a \\ 1 + \dfrac{x - x_a}{x_c - x_a}, x_a < x \le x_c \\ 2 + \dfrac{x - x_c}{x_p - x_c}, x_c < x \le x_p \\ 3, x > x_p \end{cases} \tag{2}$$

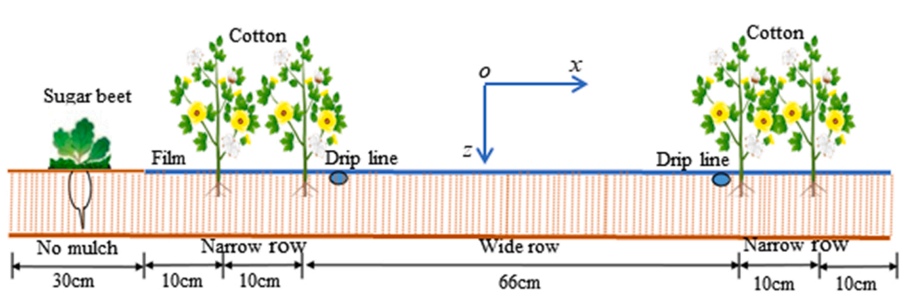

Fig. 1. Schematic diagram of cotton-sugarbeet system planting pattern, drip-line arrangements (one mulch, two drip lines, and four rows of cotton plants intercropped one row of sugarbeet).

Table 2
The details of biochar treatments.

Year	Biochar amount ($t{\cdot}ha^{-1}$)	Treatment	Year	Biochar amount ($t{\cdot}ha^{-1}$)	Treatment	Year	Biochar amount ($t{\cdot}ha^{-1}$)	Treatment
	0	CK		0	CK		0	CK
	0	B0		0	B0		0	B0
	10	B10		10	B10		10	B10
2018	50	B50	2019	25	B25	2020	25	B25
	100	B100		50	B50		30	B30
	--			100	B100		--	

$$IFI = \sqrt{\frac{\overline{IFI_i}^2 + (\min IFI_i)^2}{2}} \times \left(\frac{n-1}{n}\right) \tag{3}$$

where IFI_i is the sub-fertility index of the i_{th} nutrient index; x is the observed value of the i_{th} nutrient index; x_a, x_p and x_c are the lower limits, upper limit and threshold of the grading criteria for the i_{th} nutrient index. The specific values are referred to Table S1; IFI is soil comprehensive fertility index; and $\min IFI_i$ are the average and minimum soil comprehensive fertility index, respectively; n is the number of reference indicators ($n = 5$, i.e. pH, soil organic carbon, NO_3^-, available P and available K).

2.3.4. Cotton-sugarbeet growth and yields

(1) Cotton height and LAI

After emergence, the cotton plant height, leaf area, and dry matter accumulation were measured every 10–15 days. Cotton plant height was measured with a tape. Leaf area was the product of the largest length and the largest width. The LAI (García-Vila et al., 2009) was calculated with:

$$LAI = 0.84 \times \varepsilon \sum_{i}^{m} \sum_{j}^{n} \frac{L_{ij} \times W_{ij}}{m \times 10^4} \tag{4}$$

where ε was actual cotton planting density (plant/m^2); m is the total number of measured plants; n is the total leaves number of the single plant; L and W are leaf length and width (cm), respectively; I and j are the j_{th} leaf on the i_{th} plant. 0.84 is the conversion coefficient (Zong et al., 2021).

(2) Cotton root shoot ratio and cotton-sugarbeet yield

Three representative cotton plants were selected for each plot to measure the dry matter of root, stem, leaf, bud, flower and boll. Each part of the cotton was cut and oven dried at 105 ℃ for one hour and 75 ℃ for 48 h to a constant weight. The root shoot ratio was calculated as follows:

$$\text{Root shoot ratio} = \text{Biomass}_{root}/\text{Aboveground biomass} \tag{5}$$

where Biomass_{root} is the root biomass, and Aboveground biomass is aboveground biomass. In this experiment, the Root shoot ratio was obtained at the sowing stage, squaring stage, bolling stage and boll-opening stage in 2018, 2019 and 2020.

Three strips with an area of 6.67 m^2 were randomly selected in each plot. The cotton bolls with a diameter greater than 2 cm and sugarbeet plants were recorded. 20 bolls, 20 bolls and 20 bolls were respectively picked from in the lower third, middle third or upper third of cotton plants to calculate the yield. The sugarbeet plants were dug out to weigh roots and calculate the yield.

(3) Irrigation water and fertilizer use efficiency and economic benefits

The IWUE and partial factor productivity (PFP) were calculated as follows:

$$IWUE = \frac{P_c Y_c + P_s Y_s}{IRR} \tag{6}$$

$$PFP_x = \frac{P_c Y_c + P_s Y_s}{F_x} \tag{7}$$

where P_c and P_s are the planting proportion for cotton and sugar beet in the intercropping system; Y_c and Y_s are the yields of cotton

Table 3
Irrigation and fertilizer schedules of plastic-film mulched trickle irrigation for all treatments in 2018–2020. DAS represents days after sowing.

Year	DAS (d)	Irrigation amount (mm)	Urea (kg ha^{-1})	Diammonium phosphate (kg ha^{-1})	Potassium sulfate (kg ha^{-1})
2018	65	25	——	——	——
	72	20	22.8	9.6	3.6
	80	25	22.8	19.2	7.2
	88	20	28.5	24.0	9.0
	94	30	34.2	24.0	9.0
	100	30	68.4	28.8	10.8
	107	30	68.4	28.8	10.8
	115	20	68.4	43.2	16.2
	123	20	68.4	43.2	16.2
	131	20	68.4	43.2	16.2
	139	20	——	——	——
2019	65	22	——	——	——
	73	23	22.8	9.6	3.6
	82	25	22.8	19.2	7.2
	90	30	28.5	24.0	9.0
	98	30	34.2	24.0	9.0
	106	30	68.4	28.8	10.8
	114	30	68.4	28.8	10.8
	122	30	68.4	43.2	16.2
	129	20	68.4	43.2	16.2
	137	20	68.4	43.2	16.2
2020	65	22	——	——	——
	71	23	22.8	9.6	3.6
	80	25	22.8	19.2	7.2
	91	30	28.5	24.0	9.0
	101	20	34.2	24.0	9.0
	108	30	68.4	28.8	10.8
	116	30	68.4	28.8	10.8
	123	30	68.4	43.2	16.2
	130	30	68.4	43.2	16.2
	135	20	68.4	43.2	16.2
Total		260	450.3	264	99

and sugarbeet, kg ha^{-1}; IRR is the irrigation amount, mm; PFP_x is the partial factor productivity; F_x is application amount of the N, P and K; x is the fertilizer type, N, P and K.

Compared to irrigation water use efficiency and partial factor productivity, the economic benefits are of great concern to growers. We conducted an economic benefit analysis for cotton-sugarbeet intercropping with different biochar application amounts. The benefit was the sale of cotton and sugarbeet after subtracting the costs including agricultural machinery for plowing, fertilizer and irrigation, labor, field management and biochar. Finally, the economic benefit was calculated using the following equations (Li et al., 2022):

$$\text{Production costs} = C_s + C_b + C_f + C_p + C_i + C_l + Cm \tag{8}$$

$$\text{Total income} = \text{Crop yield} \times \text{Crop price} \tag{9}$$

$$\text{Economic benefits} = \text{Total income} - \text{Production costs} \tag{10}$$

where C_s, C_b, C_f, C_p, C_i, C_l and C_m are the cost of seeds, biochar, fertilizers, pesticides, irrigation water, labor and machinery.

(4) Multicriteria assessment

To evaluate the overall performance of different treatments, the minimum average values (Min) and maximum average values (Max) of each index including comprehensive fertility of soil at the boll-opening stage, aboveground biomass, yield, economic benefits and IWUE were used to obtain 0–10 scale:

$$Scale = 10 \times \frac{Value - Min}{Max - Min} \tag{11}$$

The scale of 0 was the worst performance and 10 was the best performance (Pelzer et al., 2016; Xu et al., 2022).

2.4. Statistical analysis

Statistical analysis was conducted with the SPSS software package (version 23.0) (IBM Corporation, Armonk, NY). The least significant differences (LSD) ($P < 0.05$) were used to analyze the significant differences among the treatments.

The general framework of the study is shown in Fig. 3.

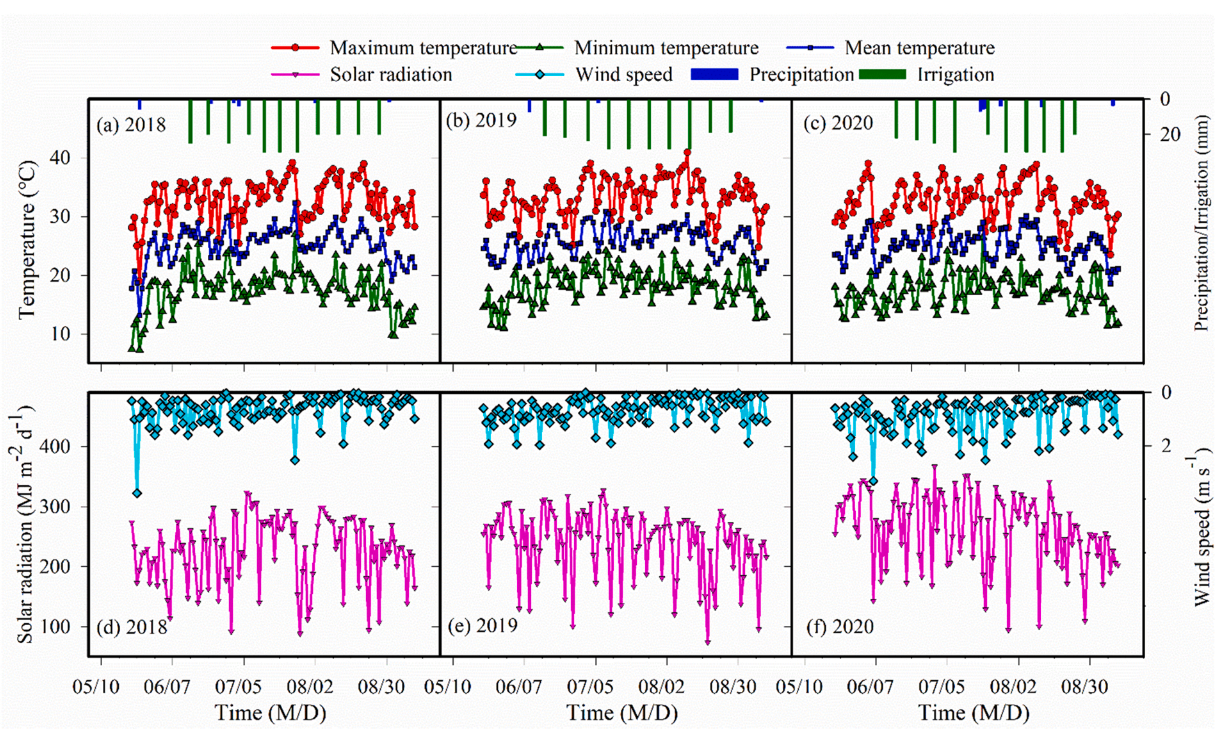

Fig. 2. Daily variations of precipitation, irrigation, air temperature, solar radiation, and wind speed during crop growing seasons in 2018, 2019, and 2020.

3. Results

3.1. Effects of biochar applications on soil water and nutrition properties

3.1.1. Weighted planar soil water storage (WPSWS)

The average WPSWS during the growth periods at 0–40 cm in 2018, 2019, and 2020 are presented in Table 4. Compared to the CK treatment, the intercropping treatments increased the average WPSWS, except for the B100 treatment in 2019. For intercropping treatments, compared to the B0 treatment, the increases in average WPSWS were 15.0%, 10% and 5% for the B10, B50 and B100 treatments in 2018, 9.1%, 0.5%, − 4.5% and − 22.7% for the B10, B25, B50 and B100 treatment inn 2019, 8.7%, 4.3% and 4.1% for the B10, B25 and B30 treatment in 2020, respectively. The highest average WPSWS was all obtained from the B10 treatment in three experimental years.

3.1.2. Soil pH and nutrients

Soil pH, organic carbon, NO_3^-, available P and available K at the depth of 0–40 cm soil depth during 2018–2020 were affected by different biochar application amounts (Fig. 4). Soil pH and nutrients decreased at the boll-opening stage compared to the sowing stage. There was no significant difference between the CK and the B0 treatments. The application of biochar slightly decreased soil pH (Fig. 4(a-c)). The soil pH ranged 8.52–8.75, 8.11–8.29 and 7.67–7.77 at the sowing stage, 7.96–8.15, 7.62–7.95 and 7.58–7.66 at the boll-opening stage in 2018, 2019 and 2020, respectively. The pH was decreased by 5.4–7.8%, 4.1–7.5% and 1.2–4.9% during three experimental years. Due to the rich organic carbon content, biochar application amounts significantly increased the soil organic carbon content (Fig. 4d-f). The application of biochar at 100 t ha^{-1} increased soil organic carbon by two times compared to the no biochar application treatment in 2018. Content of NO_3^-, available P and available K were increased at first and then decreased with the increase in the application amount of biochar. The continuous application of biochar at 10 t ha^{-1} for three years and 25 t ha^{-1} for 2 years increased NO_3^-, available P and available K compared to other treatments.

Table 4
The average WPSWS (cm^3 cm^{-3}) at the depth of 0–40 cm during growth period for the CK, B0, B10, B25, B30, B50 and B100 treatments in 2018, 2019, and 2020.

Treatment	2018	2019	2020
CK	0.19b	0.21b	0.21c
B0	0.20b	0.22ab	0.23b
B10	0.23a	0.24a	0.25a
B25	–	0.22ab	0.22c
B30	–	–	0.22c
B50	0.22a	0.21b	–
B100	0.21a	0.17c	–

To reflect the comprehensive influence of each nutrient index, the comprehensive fertility of the soil is presented in Table 5.

The comprehensive fertility of soil in the boll-opening stage was lower than that in the sowing stage during three experimental years. The comprehensive fertility of the soil of the B0 treatment was slightly higher than that of the CK treatment at the sowing stage and smaller at the boll-open stage. With increasing biochar application amounts, the comprehensive fertility of soil in the intercropping system was increased at first and then decreased during 2018–2020. The comprehensive fertility of soil ranged 1.378–1.711, 1.280–1.562 and 1.218–1.535 at the sowing stage, 1.202–1.567, 1.007–1.354 and 1.181–1.289 at the boll-opening stage in 2018, 2019 and 2020, respectively. Correspondingly, the relative changes of comprehensive fertility of soil were 5.8%–

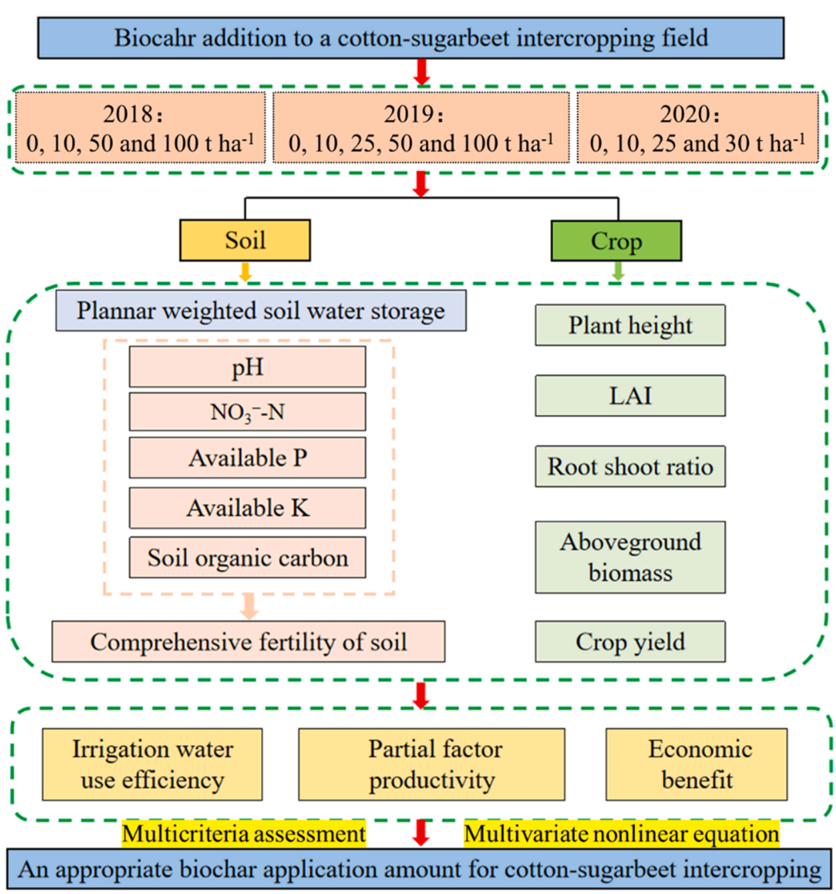

Fig. 3. The main research route of this study.

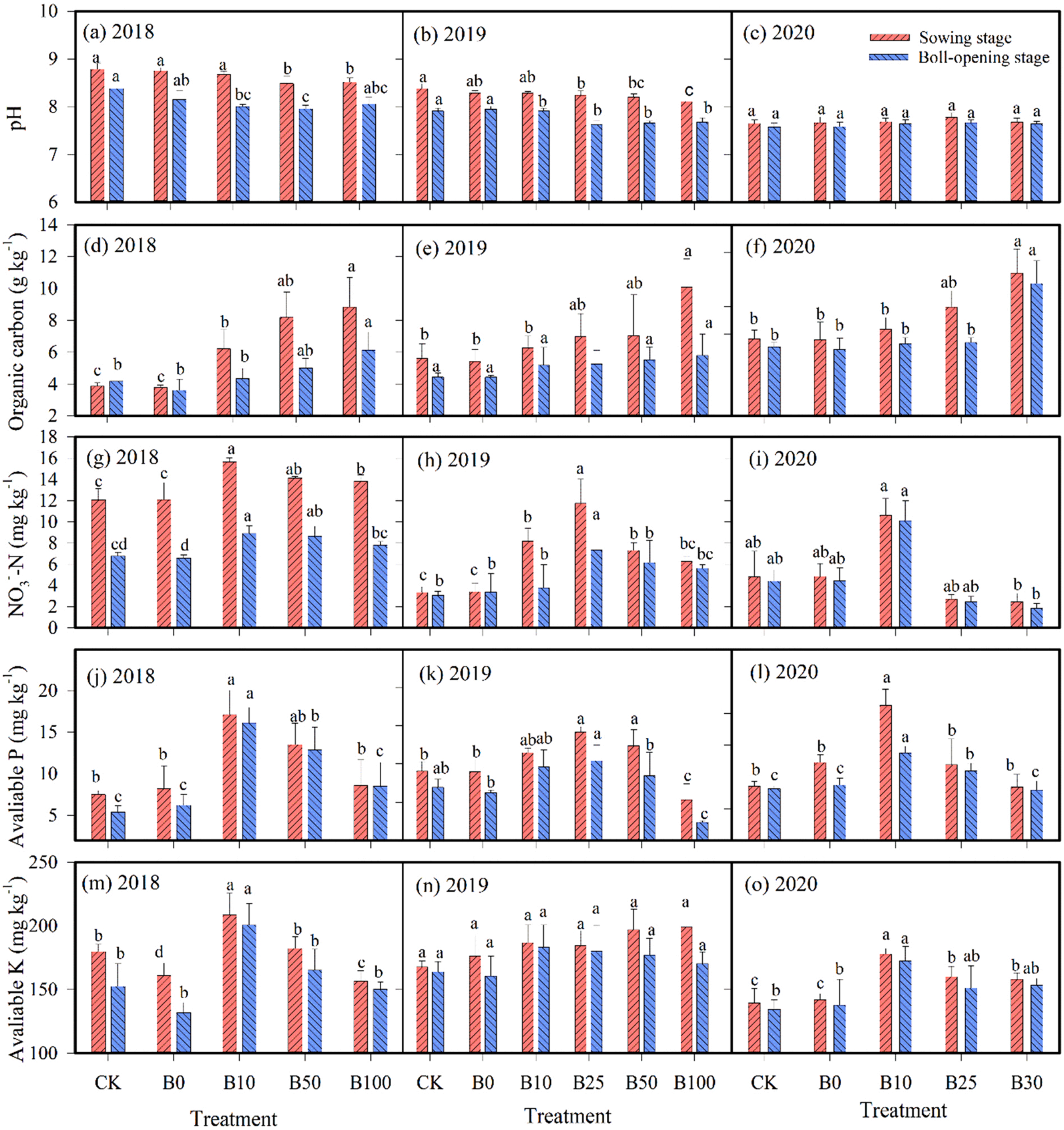

Fig. 4. Effects of different biochar application amounts on soil pH, organic matter, NO_3^-, available P and available K for 0–40 cm soil depth during 2018, 2019 and 2020. Error bars represent standard errors. Different letters above the bars indicate statistical differences among treatments at the significance level $P < 0.05$ with an LSD test.

Table 5
Effects of different biochar application amounts on comprehensive fertility of soil during 2018–2020.

Year	Stage	Treatment						
		CK	B0	B10	B25	B30	B50	B100
2018	Sowing	1.425	1.378	1.711	–	–	1.583	1.432
	Boll-openning	1.202	1.211	1.567	–	–	1.423	1.292
2019	Sowing	1.384	1.379	1.496	1.549	–	1.562	1.280
	Boll-openning	1.167	1.172	1.354	1.333	–	1.254	1.007
2020	Sowing	1.175	1.284	1.535	1.332	1.218	–	–
	Boll-openning	1.132	1.164	1.389	1.264	1.181	–	–

28.3%, − 14.1%− 15.5% and − 8.0%− 8.2% at the sowing stage, 3.9%− 24.1%, − 7.2%− 13.3% and − 5.1%− 19.5% at boll-opening stage in 2018, 2019 and 2020, respectively. The continuous application of biochar at 10 t ha^{-1} for 3 years and 25 t ha^{-1} for 2 years had an advantage over other treatments in increasing the comprehensive soil fertility.

3.2. Effects of biochar applications on cotton-sugarbeet growth and yields

3.2.1. Cotton plant height

An appropriate biochar addition effectively increased the plant height of cotton, while excessive biochar addition stunted plant height (Fig. 5(a-c)). The plant height for all treatments showed a consistent trend of increasing at first and then stabilizing. Tip pruning was conducted on 120 DAS to limit plant height and promote reproductive growth. In general, the effect of biochar on plant height was obvious after 80 DAS. In 2018, the maximum plant height values of CK, B0, B10, B50 and B100 were 71.3, 73.5, 88.3, 67.8 and 75.1 cm, respectively. In 2019, the maximum plant height values of CK, B0, B10, B25, B50 and B100 treatments were 84.6, 79.8, 94.8, 96.7, 75.8 and 74.5 cm, respectively. The maximum values of plant height in 2020 were 82.5, 87.4, 97.6, 96.7 and 93.7 cm for the CK, B0, B10, B25 and B30 treatments (Table 5). Compared with the B0 treatment for the intercropping system, the relative changes of maximum plant height ranged − 7.4%− 20.6% in 2018, − 6.7%− 21.1% in 2019, and 7.2%− 11.7% in 2020, respectively. The maximum plant height of the B10 treatment was higher than that of the other treatments during three experimental years.

3.2.2. LAI of cotton

The LAI of cotton increased at first, then tended to be stable and decreased slightly during the growth period for the three experimental years (Fig. 5(d-f)). The application of biochar generally increased LAI except for the B100 treatment in 2018. The maximum LAI values were 3.9, 3.9, 4.7, 4.5 and 3.9 in 2018, 3.4, 3.3, 4.4, 4.1, 4.0 and 3.1 in 2019, 3.5, 3.4, 4.1, 4.1 and 4.0 in 2020, respectively. The maximum LAI values between the CK and the B0 treatment were closed. For the intercropping system, compared to the B0 treatment, the relative changes of LAI were 20.3%, 13.2% and − 1.8% in 2018 for B10, B50 and B100 treatments, 41.7%, 34.4%, 31.9% and 6.5% in 2019 for B10, B25, B50 and B100 treatments, 19.0%, 19.6% and 17.8% in 2020 for B10, B25 and B30 treatments, respectively.

3.2.3. Aboveground biomass of cotton

Fig. 5(g-i) presents the aboveground biomass of cotton for different application amounts of biochar during 2018, 2019 and 2020. Overall, an appropriate biochar addition effectively increased the aboveground biomass of cotton. The aboveground biomasses of cotton consistently first increased and then decreased, reaching the maximum value between 10 and 25 t ha^{-1} in three experimental years. The application of biochar increased aboveground biomass by 51.7%, 32.5% and 0.2% in 2018, 44.1%, 66.1%, 38.1% and 0.4% in 2019, 37.2%, 18.0% and 8.1% treatments in 2020, respectively.

3.2.4. Root shoot ratio of cotton

The root shoot ratio of different treatments at seedling, squaring, bolling and boll-opening stage during 2018–2020 is presented in Fig. 6. As plants grew, the root shoot ratio was gradually decreased for all treatments. In general, the root shoot ratio of the CK is slightly smaller than that of the B0 treatment. The application of biochar decreased the root shoot ratio for the intercropping system. However, the decreases in root shoot ratio were not directly proportional to the application amount of biochar. The decreases in root shoot ratio ranged 4.0%− 28.3%, 19.5%− 20.2%, 20.4%− 26.5% and 4.3%− 20.1% in 2018, 20.7%−

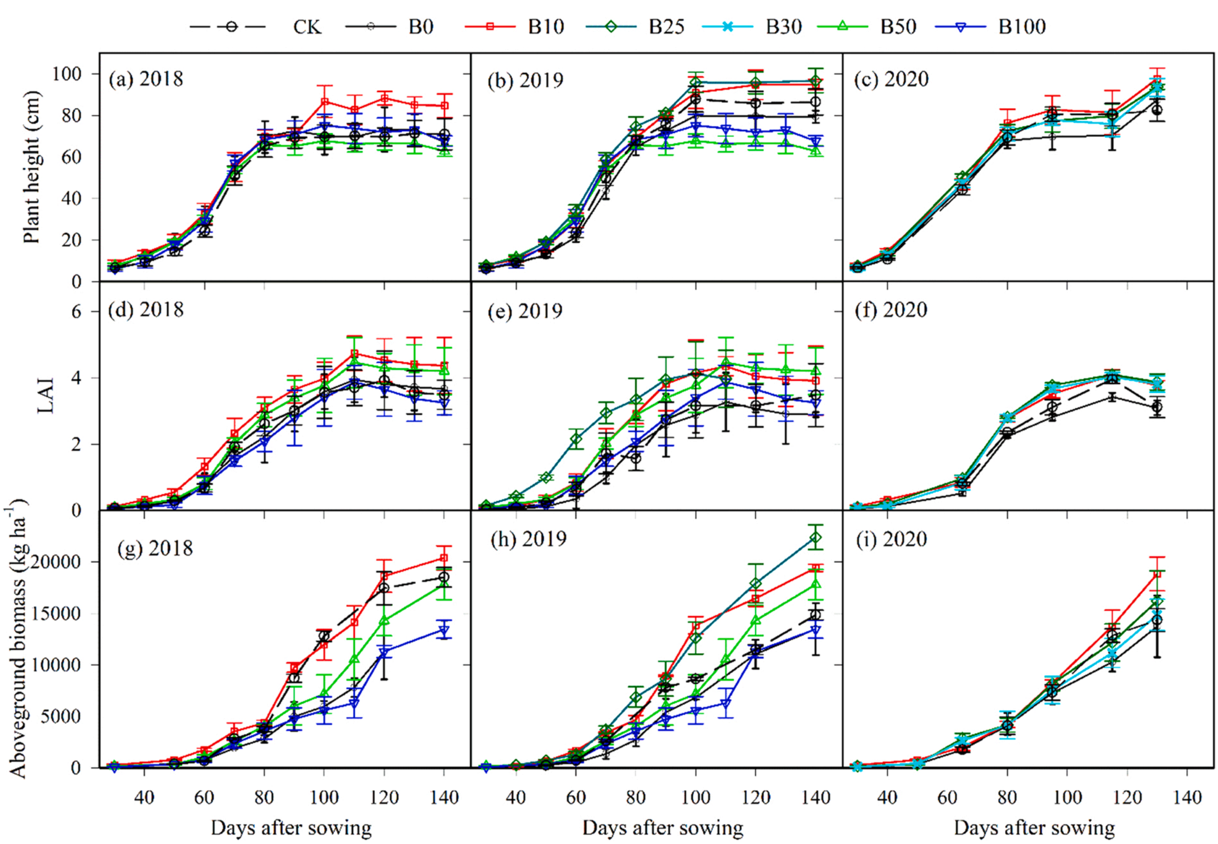

Fig. 5. Effects of different biochar application amounts on plant height, LAI and aboveground biomass of cotton during 2018, 2019 and 2020. Error bars represent standard errors.

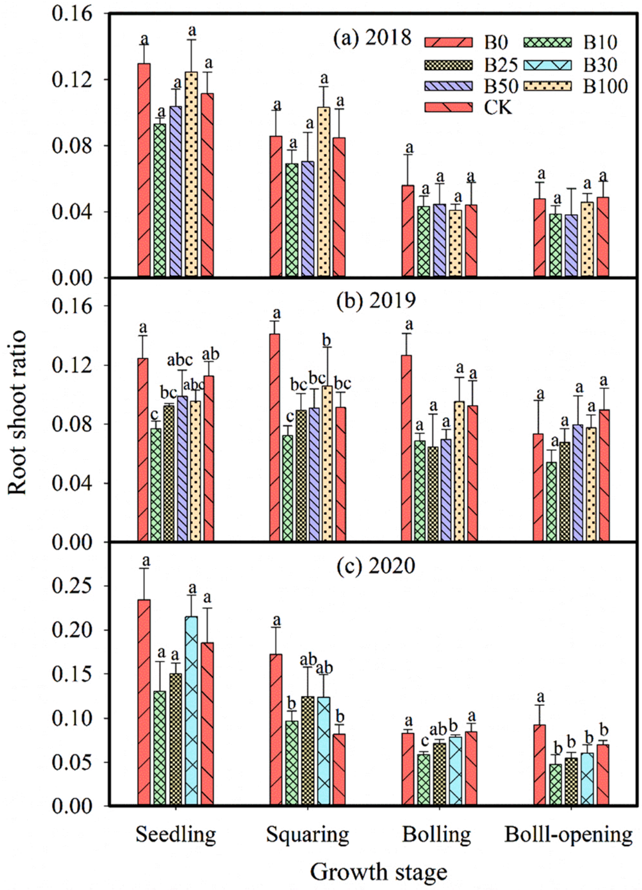

Fig. 6. Effects of different biochar application amounts on root shoot ratio during 2018, 2019 and 2020. Error bars represent standard errors. Different letters above the bars indicate statistical differences among treatments at the significance level $P < 0.05$ with an LSD test.

38.3%, 25.1%– 48.8%, 24.8%– 49.1% and 7.2%– 26.5% in 2019, 8.2%– 44.1%, 27.8%– 43.7%, 5.4%– 29.3% and 34.6%– 48.0% in 2020 at seedling, squaring, bolling and boll-opening stage, respectively. The greatest reduction in root shoot ratio was found in the B10 treatment for three experimental years.

3.2.5. *Yields of cotton and sugarbeet*

The effects of different application amounts of biochar on yields of cotton and sugarbeet in the intercropping system are presented in Fig. 7. In general, an appropriate amount (<25 t ha^{-1} year^{-1}) of biochar significantly increased cotton yield, while an excessive amount (>50 t ha^{-1} year^{-1}) of biochar decreased cotton yield. Compared to the CK treatment, the cotton yield was increased by 0.5–43.8% for the intercropping treatments. Specifically, in 2018, compared with the B0 treatment, the B10 treatment significantly increased the cotton yield at a rate of 16.5%, while the B100 treatment significantly decreased cotton yield by 6.31%. The cotton yield of the B50 treatment slightly decreased, but there was no significant difference between the B50 and B0 treatments. In 2019, the yields of B10 and B25 treatments were significantly increased by 22.5% and 24.9%, while that of the B50 and B100 treatments were decreased by 1.4% and 8.0%. In 2020, the application of biochar at 10 and 25 t ha^{-1} increased cotton yield significantly (25.0% and 34.4%) compared with other treatments, but there was no significant difference between these two treatments. The B30 and B50 treatments had no significant effects on cotton yield, while the B100 treatment significantly reduced cotton yield ($P < 0.05$). The application of biochar increased sugarbeet yield during 2018, 2019 and 2020 (Fig. S1). Specifically, the application of biochar increased sugarbeet

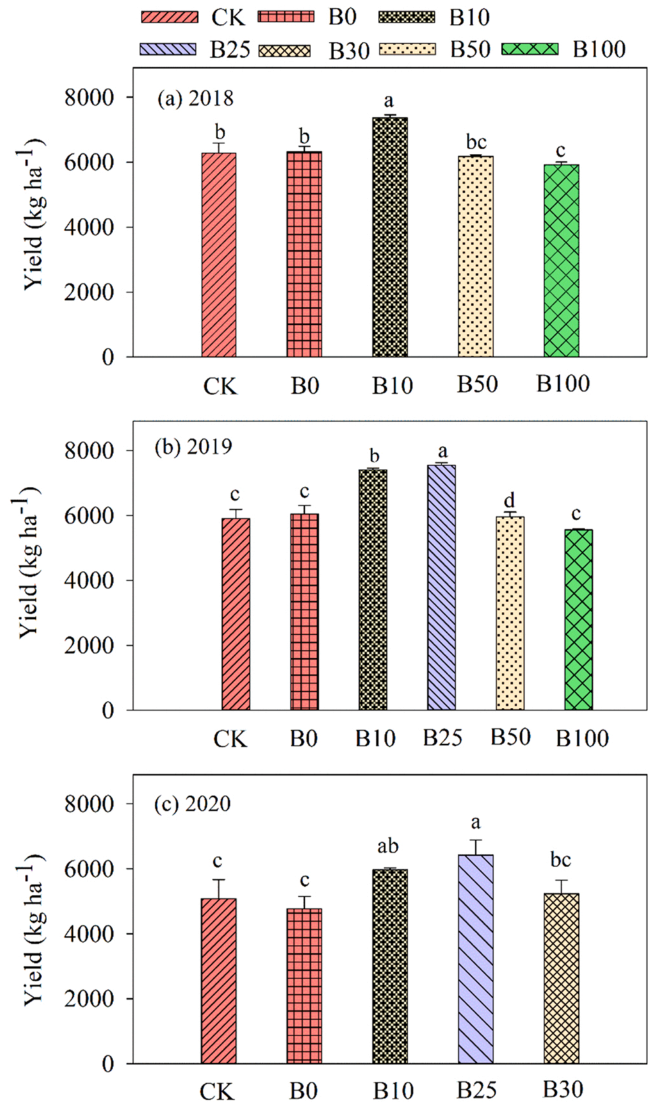

Fig. 7. The cotton yields of monoculture and intercropping system during 2018, 2019 and 2020.

yield by 31.6%, 15.8% and 3.7% in 2018, 38.3%, 40.9%, 25.3% and 1.3%in 2019, 79.9%, 32.2% and 24.9% in 2020, respectively. Overall, the B10 treatment significantly increased sugarbeet yield in the three experimental years.

3.3. *The IWUE, PFP, economic benefits and multicriteria assessment*

The yields of cotton, IWUE, PFP and economic benefits of the intercropping system were higher than the cotton monoculture system (Table 6). The IWUE of intercropping system ranged from 3.48 to 4.37 kg ha^{-1} mm^{-1}, 3.25–4.47 kg ha^{-1} mm^{-1} and 2.92–4.45 kg ha^{-1} mm^{-1} for 2018, 2019 and 2020.

With the increase in the application amount of biochar, the IWUE first increased and then decreased. The rank of the IWUE was B10 > B50 > B0 > B100 in 2018, B25 > B10 > B50 > B0 > B100 in 2019, B10 > B25 > B30 > B0 in 2020, respectively.

The application of biochar significantly ($P < 0.05$) affected PFP during 2018, 2019 and 2020. The maximum PFP for N, P and K was 47.7, 93.7, and 220.8 kg kg^{-1} in 2018, 48.7, 95.7 and 225.8 kg kg^{-1} in 2019 and 48.5, 95.2 and 224.4 kg kg^{-1} in 2020 obtained with the B10, B25 and B10 treatments, respectively. From Eqs. (6) and (7), the changes of IWUE and PFP for biochar application treatments relative to the CK

Table 6
Effects of biochar application amounts on irrigation water use efficiency (IWUE), partial factor productivity and economic benefit.

Year	Treatment	IUWE (kg ha^{-1} mm^{-1})	Partial factor productivity (kg kg^{-1})			Economic benefit (Yuan ha^{-1})
			N	P	K	
2018	CK	2.41d	26.2d	51.7d	121.9d	30,142b
	B0	3.55c	38.7c	78.9c	179.0c	42,906a
	B10	4.37a	47.7a	93.7a	220.8a	44,633a
	B50	3.76b	40.9b	80.4b	189.6b	-6791c
	B100	3.48c	37.9c	74.6c	176.0c	- 60,090d
2019	CK	2.27e	24.7e	48.7e	114.8e	28,207c
	B0	3.38d	36.8d	72.4d	171.0d	40,151a
	B10	4.38b	47.7b	93.9b	221.5b	41,859a
	B25	4.47a	48.7a	95.7a	225.8a	31,447b
	B50	3.74c	40.8c	80.2c	189.0c	-8282d
	B100	3.25d	34.5d	69.6d	164.2d	- 63,812e
2020	CK	1.95e	21.3e	41.7e	98.7e	21,673c
	B0	2.92d	31.7d	62.6d	147.5d	29,075b
	B10	4.45a	48.5a	95.2a	224.4a	35,894a
	B25	3.89b	42.5b	83.3b	196.5b	20,615c
	B30	3.42c	37.4c	73.3c	172.7c	5032d

treatment were equivalent. The IWUE and PFP were increased by 43.3–135.3%. Application of biochar at 100 t ha^{-1} $year^{-1}$ significantly decreased water and fertilizer productivity.

The economic benefit analysis indicated that the application amounts of biochar significantly affected economic benefit ($P < 0.05$). The average economic benefit during experimental years of the cotton monoculture (0 t ha^{-1}), no biochar-applied intercropping system (0 t ha^{-1}), continuous application of 10 t ha^{-1} for three years (30 t ha^{-1}), continuous application of 25 t ha^{-1} for two years(50 t ha^{-1}), continuous application of 50 t ha^{-1} for two years plus 30 t ha^{-1} for one year (130 t ha^{-1}) and continuous application of 100 t ha^{-1} (200 t ha^{-1}) for 2 years were 26,674, 37,377, 40,795, 26,031, − 3347 and − 61,951 Yuan ha^{-1}, respectively. The combination of applying biochar at the rate of 10 t ha^{-1} for continuous three years with cotton-sugarbeet intercropping system has an advantage in increasing economic benefit with the highest change of 65.6% compared to the cotton monoculture.

The multicriteria assessment of the 5 indexes for all treatments in 2019 is presented in Fig. 8. The B10 and B25 treatments performed better compared to other treatments, while the B100 treatment performed the worst. Combining the results in 2018 and 2020 (Fig. S2), the application of biochar at the rate of 10 t ha^{-1} $year^{-1}$ performed the best with the highest average scale (9.8) for 5 indexes.

4. Discussion

4.1. Advantages of the combination of biochar with intercropping system

The results of crop yields, water and fertilizer use efficiency and economic confirmed the combination of biochar with cotton-sugarbeet intercropping system had advantages over cotton monoculture (Fig. 7 and Table 6). Comparing the CK to the B0 treatment (no biochar applied treatment for cotton monoculture and cotton-sugarbeet intercropping), the cotton yield of the B0 treatment was higher than the CK treatment, which may be attributed to the absorption of salt by the intercropped sugarbeet according to the results of Liang (2021a). With the same planting area, irrigation and fertilizer amounts, the increasing cotton yield coupled with sugarbeet yield resulted in increasing water and fertilizer use efficiency and economic benefits for B0 treatment compares with the CK treatment.

For biochar-applied intercropping system, the increases in cotton and sugarbeet yields were ascribed to the beneficial effects of biochar on the interaction of soil water, nutrient conditions and growth index (Devereux et al., 2012). The WPSWS at the root zone of the B10 treatment was higher than the other treatments under the identical irrigation schedule during the three experimental years (Table 4). It was reported that, soil water was reduced as a result of hydrophobicity in biochar (Gray et al., 2014). Applying biochar (with initial water droplet penetration time at 8 s, (Wang et al., 2022)) at a large amount altered soil wettability and lead to uneven soil water distribution in the root zone, thus affecting crop yields (Wang et al., 2021b). The low pH of the biochar applied in this study also influence the cotton and sugarbeet growth and yields. The soil in this study was slightly salt-affected and biochar was acidified by ferrous sulfate, which decreased the soil pH in the sowing and boll-opening stages at the depth of 0–40 cm (Fig. 4). In addition, biochar contained rich C to increase soil organic carbon content and could absorb the soil organic molecules, promote the small organic molecules aggregation, and form organic matter (Yuan et al., 2019). Therefore, biochar significantly increased soil organic carbon (Fig. 4). Biochar also increased soil nutrients such as N, P and K (Pandit et al., 2018a; Zhao et al., 2020). The relative changes of the application of biochar at 10 t ha^{-1} and 25 t ha^{-1} increased NO_3^-, available P,

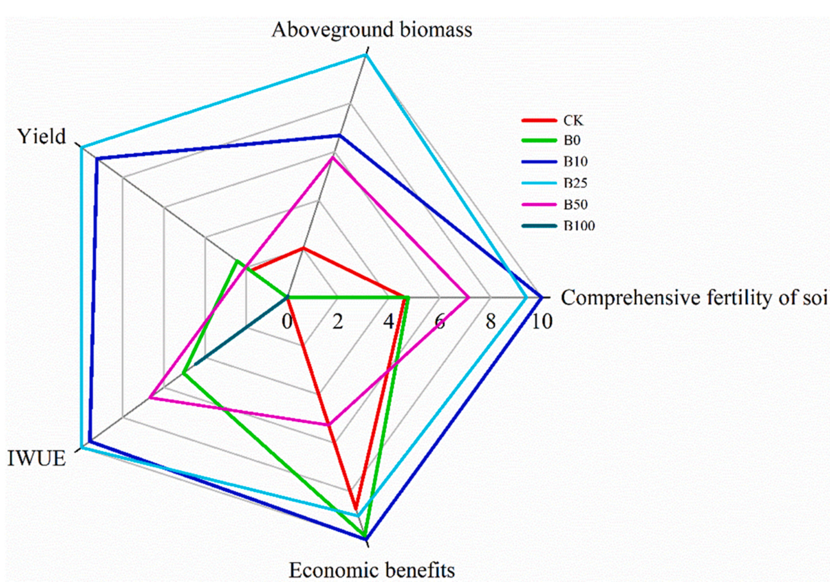

Fig. 8. The multicriteria assessment for comprehensive fertility of soil at the boll-opening stage, aboveground biomass, yield, IWUE and economic benefits of all treatments in 2019.

available K and the comprehensive fertility of soil were higher than other application amounts of biochar. For crop growth index, the effects of biochar on plant height, LAI, aboveground biomass, and yields were consistent with the comprehensive fertility of soil. The increases in yields also influenced by the root shoot ratio, which reflected the co-ordination of root and shoot growth (Lloret et al., 1999). Wang et al. (2020) showed that the root shoot ratio was negatively related to cotton biomass and yield. Similarly, the highest yield was obtained from the treatment that the root shoot ratio was the lowest during three experimental years in this study. The water and fertilizer use efficiency was increased following the increased cotton and sugarbeet yields, which further increase the economic benefits.

4.2. The most appropriate biochar application rate

This study showed that the effects of biochar on crop yield, water and fertilizer production and economic benefits varied non-linearly (having a peak) with the increased biochar application amounts. The B10 treatment has many advantages in increasing water and fertilizer use efficiency and economic benefits over other treatments. This is consistent with previous studies (Laghari et al., 2015; Zhao et al., 2020). It implies that excessive biochar application amounts do not only have negative effects on crop growth but also result in high economic costs (Table 6) (Pandit et al., 2018b). Li et al. (2018) conducted tomato growth experiments with five biochar application amounts (0, 10, 20, 40 and 60 t ha^{-1}). Considering plant growth, water use efficiency and net profits, they proposed an appropriate biochar application rate of 40 t ha^{-1}. Pandit et al. (2018b) applied biochar at rates of 0, 5, 10, 15, 25 and 40 t ha^{-1} to acidic silty loam soil grown with maize and found that the optimal amount was 15 t ha^{-1} from an agronomic and economic perspective. Yan et al. (2019) reported that biochar enhanced the SWC with a maximum effect achieved at 40 t ha^{-1} among 0, 20, 40 and 60 t ha^{-1}. Zhao et al. (2020) showed that the 20 t ha^{-1} was the optimal biochar application rate among 0, 5, 10, 15, 20, 25 and 30 t ha^{-1} based on the soil properties and crop yield. Fu et al. (2019) revealed that biochar applied at an excessive amount resulted in an imbalance between the liquid and gas phases in soil. Furthermore, excessive biochar also increased the soil salt content, thus, threatening crop growth, which was mainly induced by the ash content in biochar (Li et al., 2018; Nigussie et al., 2011). Ash contained a large number of carbonates such as alkali and alkaline earth metals, heavy metals, and sesquioxides (Raison, 1979). The 3-year experiments showed that the application amount biochar at 10 t ha^{-1} year^{-1} was beneficial to soil nutrients, crop yield increases and economic benefits.

To obtain the optimal biochar application amount and application years, the relationship between IWUE and biochar application features were described with a multivariate nonlinear equation (Wu et al., 2019):

$$\mathrm{IWUE}= a+b\,x_1+c\,x_2+d\,x_1\,x_2+e\,x_1^2+f\,x_2^2 \tag{12}$$

where x_1 is biochar application amount, t ha^{-1}; x_2 is biochar application year; a, b, c, d, e and f are fit coefficients. The programming solve was applied to obtain x_1 and x_2 for the maximum IWUE.

The fitted a, b, c, d, e and f values in Eq. 12 were 3.871, − 0.448, 0.163, 0.066, − 0.065 and 0.001, respectively. When x_1 and x_2 were 16.6 and 3.0, the IWUE was the maximum, i.e. three years of continuous biochar application at the amount of 16.6 t ha^{-1} was beneficial to save water.

5. Conclusions

The combination of farm management of cotton-sugarbeet intercropping with appropriate biochar application was an effective practice to increase crop yields, water and fertilizer use efficiency and economic benefits in Xinjiang. It has several positive effects compared to the cotton monoculture system (CK). Firstly, the soil water condition was improved. Secondly, the comprehensive fertility of soil was increased by 3.9–28.3%. Thirdly, the cotton yields, water and fertilizer use efficiency and economic benefits were increased by 0.5–43.8%, 43.3–135.3% and 11.5–65.6%, respectively. The multicriteria assessment showed that the application of biochar at the rate of 10 t ha^{-1} performed the best with the highest scale every year. The multivariate nonlinearity equation implicated that three years of a continuous biochar application amount of 16.6 t ha^{-1} with an intercropping system was an efficient mode to improve IWUE. The research provides a new insight for agricultural production in the arid and semi-arid region. The soil water, salt transport and crop yield of this mode need to be studied with field experiments or crop models in the future.

CRediT authorship contribution statement

Xiaofang Wang: Investigation, Formal analysis, Conceptualization, Methodology, Writing – original draft. **Yi Li**: Conceptualization, Methodology, Project administration, Writing – review & editing, Supervision. **Hao Feng**: Project administration, Writing – review & editing, Supervision. **Qiang Yu**: Conceptualization, Supervision, Writing – review & editing. **Xiangyang Fan**: Conceptualization, Methodology, Project administration, Resources. **Chuncheng Liu**: Conceptualization, Project administration, Resources, Curation. **Junying Chen**: Conceptualization. **Zhe Yang**: Writing – review & editing. **Asim Biswas**: Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.indcrop.2022.116060.

References

Abrol, V., Ben-Hur, M., Verheijen, F.G.A., Keizer, J.J., Martins, M.A.S., Tenaw, H., Tchehansky, L., Graber, E.R., 2016. Biochar effects on soil water infiltration and erosion under seal formation conditions: rainfall simulation experiment. J. Soil. Sediment. 16, 2709–2719.
Bao, Y., Xu, M., Lv, F., Huang, Q., Nie, J., Zhang, H., Yu, H., 2012. Evaluation method on soil fertility Under long-term fertilization. Sci. Agric. Sin. 45 (20), 4197–4204.
Burrell, L.D., Zehetner, F., Rampazzo, N., Wimmer, B., Soja, G., 2016. Long-term effects of biochar on soil physical properties. Geoderma 282, 96–102.
Corre-Hellou, G., Fustec, J., Crozat, Y., 2006. Interspecific competition for soil N and its interactions with N2 fixation, leaf expansion and crop growth in pea–barley intercrops. Plant Soil 282, 195–208.
Devereux, R.C., Sturrock, C.J., Mooney, S.J., 2012. The effects of biochar on soil physical properties and winter wheat growth. Earth Environ. Sci. Trans. R. Soc. 103, 13–18.
Fu, Q., Zhao, H., Li, T., Hou, R., Liu, D., Ji, Y., Zhou, Z., Yang, L., 2019. Effects of biochar addition on soil hydraulic properties before and after freezing-thawing. Catena 176, 112–124.
García-Vila, M., Fereres, E., Mateos, L., Orgaz, F., Steduto, P., 2009. Deficit irrigation optimization of cotton with aquaCrop. Agron. J. 101 (3), 477–487.
Gautheyrou, P.A., 2006. Handbook of Soil Analysis.
Gou, F., van Ittersum, M.K., Wang, G., van der Putten, P.E.L., van der Werf, W., 2016. Yield and yield components of wheat and maize in wheat–maize intercropping in the Netherlands. Eur. J. Agron. 76, 17–27.

Gray, M., Johnson, M.G., Dragila, M.I., Kleber, M., 2014. Water uptake in biochars: the roles of porosity and hydrophobicity. Biomass Bioenergy 61, 196–205.

Günther, J., Thevs, N., Gusovius, H.-J., Sigmund, I., Brückner, T., Beckmann, V., Abdusalik, N., 2017. Carbon and phosphorus footprint of the cotton production in Xinjiang, China, in comparison to an alternative fibre (Apocynum) from Central Asia. J. Clean. Prod. 148, 490–497.

He, K., He, G., Wang, C., Zhang, H., Xu, Y., Wang, S., Kong, Y., Zhou, G., Hu, R., 2020. Biochar amendment ameliorates soil properties and promotes Miscanthus growth in a coastal saline-alkali soil. Appl. Soil Ecol. 155, 103674.

Hong, Y., Heerink, N., Jin, S., Berentsen, P., Zhang, L., van der Werf, W., 2017. Intercropping and agroforestry in China – current state and trends. Agric. Ecosyst. Environ. 244, 52–61.

Howell, T., 1994. Irrigation engineering, evapotranspiration. In: Arntzem, C.J., Ritter, E. M. (Eds.), Encyclopedia of Agricultural Science, 2, pp. 591–600.

Hu, F., Gan, Y., Cui, H., Zhao, C., Feng, F., Yin, W., Chai, Q., 2016. Intercropping maize and wheat with conservation agriculture principles improves water harvesting and reduces carbon emissions in dry areas. Eur. J. Agron. 74, 9–17.

Huang, M., Zhang, Z., Zhu, C., Zhai, Y., Lu, P., 2019. Effect of biochar on sweet corn and soil salinity under conjunctive irrigation with brackish water in coastal saline soil. Sci. Hortic. 250, 405–413.

Laghari, M., Mirjat, M.S., Hu, Z., Fazal, S., Xiao, B., Hu, M., Chen, Z., Guo, D., 2015. Effects of biochar application rate on sandy desert soil properties and sorghum growth. Catena 135, 313–320.

Lehmann, J., 2007. A handful of carbon. Nature 447, 143–144.

Li, C., Xiong, Y., Qu, Z., Xu, X., Huang, Q., Huang, G., 2018. Impact of biochar addition on soil properties and water-fertilizer productivity of tomato in semi-arid region of Inner Mongolia, China. Geoderma 331, 100–108.

Li, X., Jin, M., Huang, J., Yuan, J., 2015. The soil–water flow system beneath a cotton field in arid north-west China, serviced by mulched drip irrigation using brackish water. Hydrogeol. J. 23, 35–46.

Li, X., Šimůnek, J., Shi, H., Yan, J., Peng, Z., Gong, X., 2017. Spatial distribution of soil water, soil temperature, and plant roots in a drip-irrigated intercropping field with plastic mulch. Eur. J. Agron. 83, 47–56.

Li, Y., Yao, N., Liang, J., Wang, X., Jia, Y., Jiang, F., Liu, D.L., Hu, W., He, H., Javed, T., 2022. Optimum biochar application rate for peak economic benefit of sugar beet in Xinjiang, China. Agric. Water Manag. 272, 107880.

Liang, J., 2021a. Improvement Mechanism of Biochar on Saline-alkali Soil in Cotton and Sygarbeet Field Under Mulched Drip Irrigation in Arid Area of Xinjiang (Ph.D. thesis). Northwest A&F University (in Chinese with English abstract).

Liang, J., Li, Y., Si, B., Wang, Y., Chen, X., Wang, X., Chen, H., Wang, H., Zhang, F., Bai, Y., Biswas, A., 2021b. Optimizing biochar application to improve soil physical and hydraulic properties in saline-alkali soils. Sci. Total Environ. 771, 144802.

Lloret, F., Casanovas, C., Penuelas, J., 1999. Seedling survival of Mediterranean shrubland species in relation to root: shoot ratio, seed size and water and nitrogen use. Funct. Ecol. 13, 210–216.

Mehdizadeh, L., Moghaddam, M., Lakzian, A., 2020. Amelioration of soil properties, growth and leaf mineral elements of summer savory under salt stress and biochar application in alkaline soil. Sci. Hortic. 267, 109319.

Nigussie, A., K, E., M, M., A, G., 2011. Effect of biochar application on soil properties and nutrient uptake of lettuces (Lactuca sativa) grown in chromium polluted soils. Am.-Eurasian J. Agric. Environ. Sci. 12 (3), 369–376.

Ning, S., Zhou, B., Shi, J., Wang, Q., 2021. Soil water/salt balance and water productivity of typical irrigation schedules for cotton under film mulched drip irrigation in northern Xinjiang. Agric. Water Manag. 245, 106651.

Pandit, N.R., Mulder, J., Hale, S.E., Martinsen, V., Schmidt, H.P., Cornelissen, G., 2018a. Biochar improves maize growth by alleviation of nutrient stress in a moderately acidic low-input Nepalese soil. Sci. Total Environ. 625, 1380–1389.

Pandit, N.R., Mulder, J., Hale, S.E., Zimmerman, A.R., Pandit, B.H., Cornelissen, G., 2018b. Multi-year double cropping biochar field trials in Nepal: finding the optimal biochar dose through agronomic trials and cost-benefit analysis. Sci. Total Environ. 637–638, 1333–1341.

Pelzer, E., Bazot, M., Guichard, L., Jeuffroy, M.H., 2016. Crop management affects the performance of a winter pea–wheat intercrop. Agron. J. 108, 1089–1100.

Qayyum, M.F., Liaquat, F., Rehman, R.A., Gul, M., ul Hye, M.Z., Rizwan, M., Rehaman, M.Zu, 2017. Effects of co-composting of farm manure and biochar on plant growth and carbon mineralization in an alkaline soil. Environ. Sci. Pollut. Res. 24, 26060–26068.

Raison, R.J., 1979. Modification of the soil environment by vegetation fires, with particular reference to nitrogen transformations: a review. Plant Soil 51, 73–108.

Ren, J., Zhang, L., Duan, Y., Zhang, J., Evers, J.B., Zhang, Y., Su, Z., van der Werf, W., 2019. Intercropping potato (Solanum tuberosum L.) with hairy vetch (Vicia villosa) increases water use efficiency in dry conditions. Field Crop. Res. 240, 168–176.

Saifullah, Dahlawi, Naeem, S., Rengel, A., Naidu, Z., R, 2018. Biochar application for the remediation of salt-affected soils: challenges and opportunities. Sci. Total Environ. 625, 320–335.

Thorp, K., Ale, S., Bange, M., Barnes, E., Lascano, R., McCarthy, A., Nair, S., Paz, J., Rajan, N., Reddy, K., Wall, G., White, J., 2014. Development and application of process-based simulation models for cotton production: a review of past, present, and future directions. J. Cotton Sci. 18, 1–38.

Wang, J., Du, G., Tian, J., Zhang, Y., Jiang, C., Zhang, W., 2020. Effect of irrigation methods on root growth, root-shoot ratio and yield components of cotton by regulating the growth redundancy of root and shoot. Agric. Water Manag. 234, 106120.

Wang, X., Liu, G., Yang, J., Huang, G., Yao, R., 2017. Evaluating the effects of irrigation water salinity on water movement, crop yield and water use efficiency by means of a coupled hydrologic/crop growth model. Agric. Water Manag. 185, 13–26.

Wang, X., Li, Y., Chau, W.H., Tang, D., Chen, J., Bayad, M., 2021b. Reduced root water uptake of summer maize grown in water-repellent soils simulated by HYDRUS-1D. Soil Tillage Res. 209, 104925.

Wang, X., Li, Y., Wang, H., Wang, Y., Biswas, A., Chau, W.H., Liang, J., Zhang, F., Bai, Y., Wu, S., Chen, J., Liu, H., Yang, G., Pulatov, A., 2022. Targeted biochar application alters physical, chemical, hydrological and thermal properties of salt-affected soils under cotton-sugarbeet intercropping. Catena 216, 106414.

Wang, X.Y., Yang, T., Shen, L., Zhang, W.L., Wan, S.M., Zhang, W., Li, L.H., 2021a. Formation of factors influencing cotton yield in jujube–cotton intercropping systems in Xinjiang, China. Agrofor. Syst. 95, 177–189.

Willey, R.W., 1979. Intercropping - its importance and research needs. Part 2. Agronomy and Research Approaches.

Wrb, I., 2006. World Reference Base for Soil Resources, second ed.

Wu, Y., 2019. Influences of Biochar on Soil Productivity of Sloping Farm Land in Black Soil Region (Ph.D. thesis). Northeast Forest University (in Chinese with English abstract).

Xu, R., Zhao, H., Liu, G., Li, Y., Li, S., Zhang, Y., Liu, N., Ma, L., 2022. Alfalfa and silage maize intercropping provides comparable productivity and profitability with lower environmental impacts than wheat–maize system in the North China plain. Agric. Syst. 195, 103305.

Xu, Z.K., 1980. The Improvement of Saline-alkali Soil in Xinjiang. Volksverlag Xinjiang, Xinjiang.

Yan, Q., Dong, F., Li, J., Duan, Z., Yang, F., Li, X., Lu, J., Li, F., 2019. Effects of maize straw-derived biochar application on soil temperature, water conditions and growth of winter wheat. Eur. J. Soil Sci. 70, 1280–1289.

Yang, P., Hu, H., Tian, F., Zhang, Z., Dai, C., 2016. Crop coefficient for cotton under plastic mulch and drip irrigation based on eddy covariance observation in an arid area of northwestern China. Agric. Water Manag. 171, 21–30.

Yuan, C., Feng, S., Huo, Z., Ji, Q., 2019. Effects of deficit irrigation with saline water on soil water-salt distribution and water use efficiency of maize for seed production in arid Northwest China. Agric. Water Manag. 212, 424–432.

Zhang, D., Du, G., Sun, Z., Bai, W., Wang, Q., Feng, L., Zheng, J., Zhang, Z., Liu, Y., Yang, S., Yang, N., Feng, C., Cai, Q., Evers, J.B., van der Werf, W., Zhang, L., 2018. Agroforestry enables high efficiency of light capture, photosynthesis and dry matter production in a semi-arid climate. Eur. J. Agron. 94, 1–11.

Zhang, X., Qu, J., Li, H., La, S., Tian, Y., Gao, L., 2020. Biochar addition combined with daily fertigation improves overall soil quality and enhances water-fertilizer productivity of cucumber in alkaline soils of a semi-arid region. Geoderma 363, 114170.

Zhao, W., Zhou, Q., Tian, Z., Cui, Y., Liang, Y., Wang, H., 2020. Apply biochar to ameliorate soda saline-alkali land, improve soil function and increase corn nutrient availability in the Songnen Plain. Sci. Total Environ. 722, 137428.

Zhu, H., Yang, J., Yao, R., Wang, X., Xie, W., Zhu, W., Liu, X., Cao, Y., Tao, J., 2020. Interactive effects of soil amendments (biochar and gypsum) and salinity on ammonia volatilization in coastal saline soil. Catena 190, 104527.

Zong, R., Wang, Z., Zhang, J., Li, W., 2021. The response of photosynthetic capacity and yield of cotton to various mulching practices under drip irrigation in Northwest China. Agric. Water Manag. 249, 106814.