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# Rational biochar application rate for cotton nutrient content, growth, yields, productivity, and economic benefits under film-mulched trickle irrigation

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ABSTRACT

Biochar application to soils has been proven to be an efficient way for yield enhancement in agricultural systems. However, what is the most economical biochar application rate (BCAR) for cotton in saline-alkali soils in arid and semi-arid zones remains unclear. To narrow the gap, this study aims to investigate how biochar application affected the nutrient content, growth, yield, quality, and productivity of cotton, and to find the rational BCAR. The three-year field experiments of biochar application combined with plastic film mulched drip irrigation were conducted for cotton in Xinjiang, China. The biochar was continuously applied to the farmland at 0 (in 2018)+ 0 (in 2019)+ 0 (in 2020), 10 + 10 + 10, NT (no test)+ 25 + 25, 50 + 50 + 30, and 100 + 100 +NT t ha$^{-1}$ during cotton growth period of 2018–2020. The cotton growth, yield, and quality indicators were observed and used for computing water-fertilizer productivity. The cost-benefit analysis was referred to recommend a rational BCAR. All four biochar application treatments increased the leaf/stem/root nutrient (N, P, and K) content than control during different cotton growth stages. The daily relative content of chlorophyll increased with the increasing BCAR and were larger at biochar treatments of 50 and 100 t ha$^{-1}$ than 0, 10, and 25 t ha$^{-1}$. The growth and yield-related indicators (plant height, stem diameter, leaf area index and seed yield), irrigation water productivity, and partial fertilizer (N, P, and K) productivity consistently increased than control under biochar application conditions, and the BCAR of 10 t ha$^{-1}$ showed the greatest advantages in enhancing germination rates, cotton yields, water-fertilizer productivities, and financial income than biochar treatments of 0, 25, 50 and 100 t ha$^{-1}$. However, neither cotton fiber quality indices (length, Micronaire, strength or uniformity index) were significantly affected by biochar applications. Based on the economic analysis, the rational BCAR was 10 t ha$^{-1}$ each year (continued for three years) for cotton planting, which was a best dose that could be applied to arid zones and have not been reported before.

## 1. Introduction

Cotton (*Gossypium hirsutum L.*) is an essential economic commodity for millions of smallholder farmers in China (Wang et al., 2022a,b). However, soil salinization and water resource shortage are the main factors restricting cotton production and sustainable agricultural

*Abbreviations:* BCAR, biochar application rate; LAI, Leaf area index; DAS, Days after sowing; $NO_3^-$, Nitrate nitrogen; K, potassium; P, Phosphorus; IWP, irrigation water productivity; IWUE, Irrigation water use efficiency; PFP, Partial factor productivity; LSD, least significant differences.

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development in arid and semi-arid regions. The combined interactions of low precipitation, shallow groundwater level and intense evaporation induce more severe soil salinity. The low quality of the saline-alkali soils leads to reduced soil water-nutrient retention capacity and crop productivity, and threatens the sustainable development of agriculture (Meena et al., 2019). Therefore, many studies have explored the benefits of biochar applications for cotton nutrient content, growth, yields, productivity, and economic benefits.

Biochar is produced by the thermal cracking of bio-organic materials (such as straw) under hypoxia or anaerobic conditions at 300–1000 ℃ (Cheng et al., 2008; Liang, 2021). Biochar is an economical and efficient soil conditioner to improve the soil environment and enhance crop yields (Akhtar et al., 2014), especially for low-quality soils. Biochar addition to lands has comprehensive positive influences on agricultural systems. First, biochar improves soil physical properties including enhance water holding capacity (Streubel et al., 2011), decrease bulk density, increase soil porosity in the no mulching zones (Liang et al., 2021). It also increases saturated soil water content, field capacity and planar soil water storage, and improve water retention and crop growth (Devereux et al., 2012). Second, biochar also enhances soil chemical properties and increase nutrient content. Biochar increases soil organic carbon (Xiao et al., 2016), enhances nutrient components such as soil mineral N content (ammonium, nitrate and total nitrogen) and dissolved organic carbon (Nelissen et al., 2015; Sun et al., 2019). Karthik et al. (2019) found that biochar application rate (BCAR) at 4.0 t $ha^{-1}$ significantly improved soil physical-chemical properties of a cotton field. Third, biochar addition reduced the differences between day and night soil temperatures (by 0.66–1.39 °C) (Liu et al., 2018) and mitigated some of the "pulse" effects of rainfall on emissions (Maucieri et al., 2017). Forth, the addition of biochar elevated soil quality and promoted root growth and crop production significantly (Zhang et al., 2020), and the grand mean increase was 10% (Jeffery et al., 2011). Finally, biochar lowers water demand substantially and provides a novel solution for agricultural sustainability in salt-affected regions (Lee et al., 2022). Overall, biochar addition is an efficient technique for promoting agricultural productivity and profit.

Previous research has assessed biochar application influences on soil environment and crop productivity in order to find the most suitable application rate or threshold. For example, for rice and durum wheat yields, the best application was 10 t $ha^{-1}$ (Zhang et al., 2012). For a winter wheat plus summer maize rotation it was 16 t $ha^{-1}$ (Zhang et al., 2017). For wheat, higher (50%, 75%, and 100%) BCARs were good and the maximal 1000-grain-weight was obtained under no farm manure and biochar 100% applications (Qayyum et al., 2017). The growth, physiology and yield of wheat were affected positively by biochar amendment (Akhtar et al., 2015), particularly under high salinity level. For maize, the biochar treatment of 5% w/w (among 1%, 2%, and 5%, w/w) (Kim et al., 2016) or 30 t $ha^{-1}$ (Jia et al., 2020) resulted in the highest yields. Pandit et al. (2018) recommended 15 t $ha^{-1}$ for a maize-mustard field cropping system. Conversely, researches showed no significant or decreasing effect of biochar application on crop yield (Bohara et al., 2018; Lai et al., 2013). Specifically, the optimal rate of 4 t $ha^{-1}$ (among 0, 2, 4, 8 t $ha^{-1}$) biochar amendment effectively promoted cotton performance (Singh et al., 2021).

The determination of rational biochar application parameters is not only important but also necessary for field practices and cost/income planning. This is due to more biochar application costed higher investment (Kammann et al., 2011). Although the most appropriate BCAR may induce the highest yields, water and fertilizer utilization efficiency, and economic benefits, it is difficult to determine the best dose. Because it is affected not only by biochar production sources and soil properties, the irrigation and fertilization schedules, but also by crop types and varieties, not to say most of the experiments are site- and time-specific.

Compared with the world's major cotton-producing countries, cotton yields in Xinjiang, China was 25% and 96% higher than those of Brazil and the United States, respectively, during the past several years (Feng et al., 2017). However, extensive salinized land and deserts occupied 31.1% and 22.5% of the arable land of Xinjiang, respectively (Liang et al., 2020; Wang et al., 2021). The limited land area results in cotton production facing competitive challenges to maintain high quality and productivity and sustainable development. In addition, the long-term mean annual precipitation of Xinjiang is below 200 mm, and water-saving irrigation is necessarily extended, especially the plastic film mulched drip irrigation (Li et al., 2021a, 2021b, 2017). We assume that there were advantages of biochar application in improving soil environment and crop production on saline-alkali soils in Xinjiang, and the investigation of biochar effects on cotton growth, yields, productivity and benefits are necessary and important. Considering the inconsistent results from previous studies, here we further assume that the most appropriate BCAR is within ranges of 0–20 t $ha^{-1}$ for applying to cotton in arid zones of Xinjiang.

So far, few researches have investigated biochar application effects on cotton growth and yields because the relative concentrated distribution of world's cotton planting countries are mainly India, the United States of America and China. Our main goal was to determine which biochar rates resulted in both increased yield and increased economic value to the farmer. With this in mind, the specific objectives of this research were to: (1) test four biochar rates over three years for impacts on in-season growth, health, and final crop yield compared to a fertilized control with no biochar added; (2) determine whether crop quality was impacted by biochar application rate; and (3) determine the most economical biochar application rate (BCAR) for cotton by conducting an economic analysis.

## 2. Materials and methods

### 2.1. Study area and weather conditions

The cotton growth experiments were conducted in the field of the 2# company of the 31st regiment (86°56′58″E, 40°53′03″N), Yuli County, Bayingol Mongolian Autonomous Prefecture in south Xinjiang, China. The site has a temperate continental desert climate with annual mean maximum temperature of 10.1 ℃, precipitation of 43 mm, sunshine hours of 2941.8 h and potential evapotranspiration of 2471 mm (Liang et al., 2021).

The daily meteorological data during the cotton growth seasons (2018–2020) (Fig. 1) were observed with a portable weather station (HOBO U30, USA). During the three crop growth seasons, the precipitation was 22.1, 20 and 32.4 mm, the mean air temperature was 23.5, 24.1 and 24.1 ℃, the mean wind speed was 1.32, 0.81 and 0.91 m $s^{-1}$, and the solar radiation was 227.6, 240.1 and 265.2 MJ $m^{-2}$ $d^{-1}$, respectively. The field groundwater table fluctuated from 1.2 to 1.5 m.

### 2.2. Initial soil properties

Before planting in 2018, soil samples were collected at the depths of 0–100 cm to measure the initial physicochemical properties. The particle contents were measured using a Malvern laser diffractometer (Mastersizer 2000). Soil samples were air-dried, and passed through a 1-mm-in-diameter sieve, then prepared for properties measuring. Electrical conductivity ($EC_{1:5}$) and pH values of dilute soil extract at soil: water ratio of 1:5 were measured by a DDS-307 conductivity meter and a pH meter, respectively. $Na^{+}$, $Ca^{2+}$, and $Mg^{2+}$ contents were measured using an atomic absorption spectrophotometer (AA7003). The $Cl^{-}$, $HCO_3^{-}$, and $SO_4^{2-}$ contents were determined by the titration method. Following Soil Survey Staff (2006), the soil texture at 0–50 cm and 50–100 cm depths were classified as silt clay loam and sand, respectively. The soil salt content was estimated using the calibrated relationship ($SS$=3.4238 $EC_{1:5}$ +1.0513, $R^2$ =0.951). Detailed soil physicochemical properties are presented in Table S1.

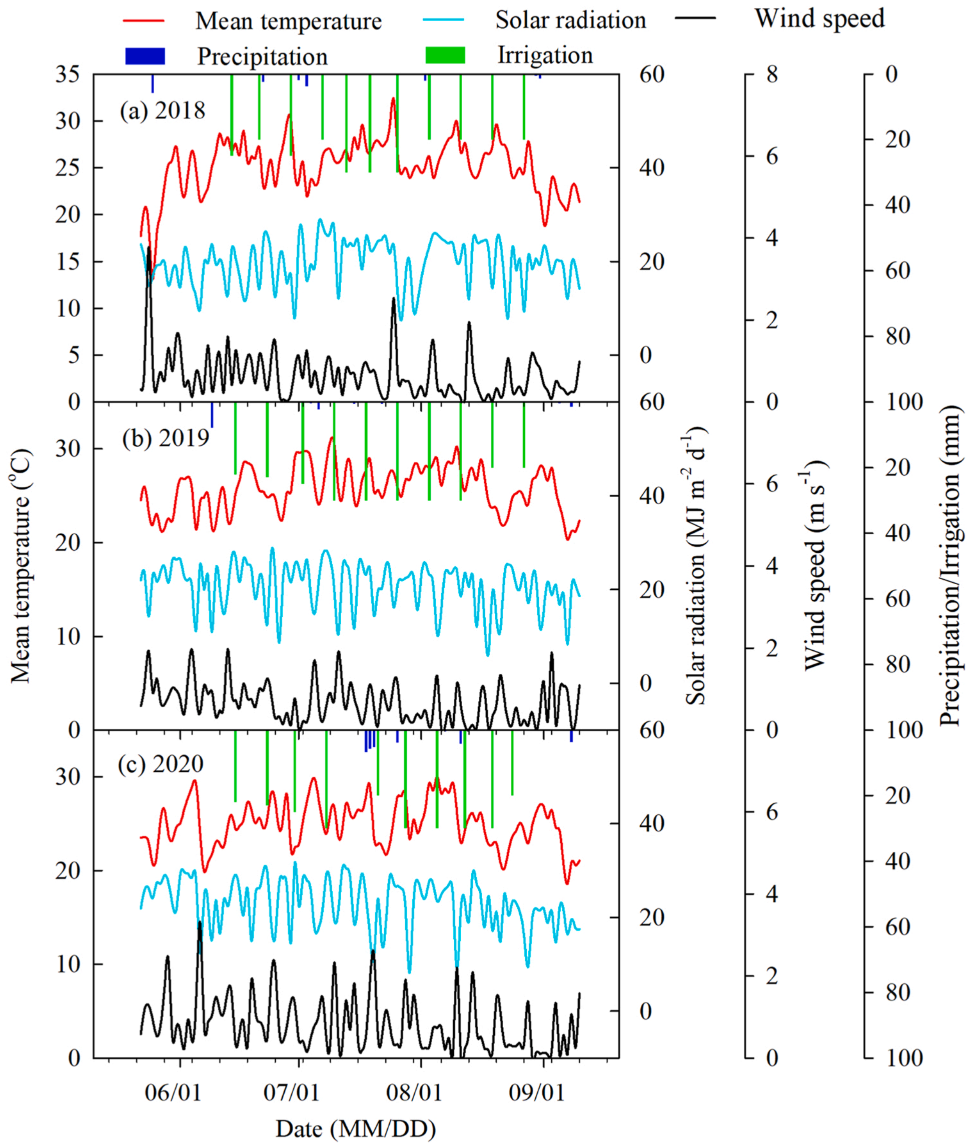


**Fig. 1.** Daily variations of climatic variables during cotton growing seasons in 2018, 2019, and 2020.

### 2.3. Field experiments

#### 2.3.1. Principal physicochemical properties of biochar used in the study

The biochar was produced by pyrolysis of Palmetto fruit branch at 500 - 600 ℃ under the anoxia condition (Zhengzhou Yongbang new energy equipment Technology Co. Ltd., China). Its particle size was $< 2$ mm, bulk density was 0.5 g cm$^{-3}$ and specific surface area was 217 m$^2$ g$^{-1}$. Its initial ($EC_{1:5}$) 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 total nitrogen, total phosphorus, available phosphorus and potassium were 2.30 g kg$^{-1}$, 0.39 g kg$^{-1}$, 91.1 mg kg$^{-1}$ and 2575 mg kg$^{-1}$, respectively. The biochar was acidified by ferrous sulfate, resulting in a biochar pH of 6.7.

#### 2.3.2. Treatments of biochar applications

The area of each field plot was 6 m × 6 m, and its field array followed a completely random block design. A 1.5-m-wide alley was set between the adjacent plots. The 2.0-m-wide protect rows were designed and planted with cotton. The biochar was uniformly spread on and thoroughly mixed with the top 30 cm soils. Biochar was continuously applied from 2018 to 2020 with 0 (in 2018)+ 0 (in 2019)+ 0 (in 2020), 10 + 10 + 10, NT (no test)+ 25 + 25, 50 + 50 + 30, and 100 + 100 +NT t ha$^{-1}$ during cotton growth period. In 2018, four BCARs of 0, 10, 50, and 100 t ha$^{-1}$ were applied. Correspondingly, the treatments were named as B0, B10, B50 and B100 in turn. From the test results of 2018, between BCARs of 10 and 50 t ha$^{-1}$, there were a change point of BCAR which altered soil physical-chemical-thermal properties and crop growth features before and after (Liang et al., 2021). Between B10 and B50, there are peak values of soil properties or crop growth and yields in 2018. Therefore, in 2019 BCAR of 25 t ha$^{-1}$ (named as B25 treatment) was added to find the turning points more accurately. The B100 was found to be neither economic nor have typical improvement effects on the soil-plant system. Thus, in 2020, treatments B0, B10, B25 and B30 were designed while B100 was not tested (Table 1). In this year, the biochar of 30 t ha$^{-1}$ was applied to the former two B50 plots. Each treatment was replicated three times.

#### 2.3.3. Crop cultivation and planting patterns

Cotton (cultivar Xinluzhong #66) was sown on April 10, 11, and 15 and harvested on September 14, 15 and 17 in 2018–2020, respectively. Cotton sowing density was 30 seeds m$^{-2}$. The field design is displayed in Fig. 2. The drip emitter interval and the width of no mulch zone were both 30 cm. The widths of wide and narrow row zones were 66 cm and 10 cm, respectively. The average drip emit rate was 2.0 L h$^{-1}$. The

**Table 1**
The detailed description of biochar application treatments for cotton planting in 2018, 2019 and 2020. The symbol "√" and "-" mean tested or no treatment in the year.

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

cotton- drip line arrangement was referred to the local pattern of "one plastic film, two drip lines, and four rows" (Fig. 2a). The width of plastic film was 106 cm. The row interval was 10 cm.

### 2.3.4. Irrigation and fertilization schedules

The irrigation water was sourced from the Tarim River (EC range was 0.57–2.51 mS cm$^{-1}$) and irrigated by Qiala Reservoir. The average degree of mineralization of irrigation water was 1.1–1.2 g L$^{-1}$. In flood season of August, September and October, when the river-flow reaches 30 m$^3$ s$^{-1}$ or above, the degree of mineralization of irrigation water is about 1.0 g L$^{-1}$; when river-flow is less than 30 m$^3$ s$^{-1}$, the degree of mineralization of irrigation water ranged between 1.0 and 2.5 g L$^{-1}$. The detailed irrigation and fertilization schedules in 2018–2020 are given in Table 2. During the cotton growing seasons of 2018, 2019 and 2020, the total amounts of irrigation, urea, diammonium phosphate, and potassium sulfate were 260 mm, 450 kg ha$^{-1}$, 265 kg ha$^{-1}$, and 99 kg ha$^{-1}$, respectively. A winter flood irrigation of 300 mm quota was applied after the harvest (around November) to leach the accumulated soil salts.

### 2.3.5. Observation of growth and yield indicators of cotton

During the cotton seedling, squaring, anthesis, boll, boll-open (har-

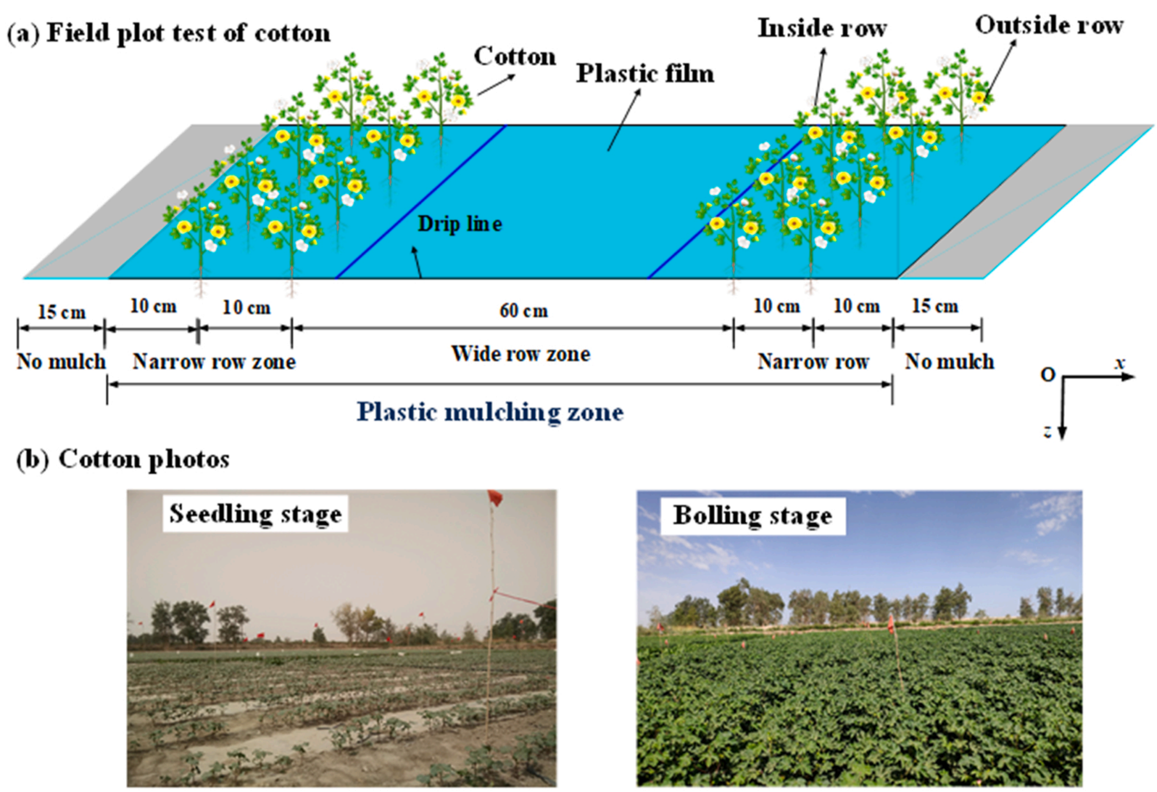


**Fig. 2.** Field plot test design and photos of cotton planting. One plastic film is mulched on two drip lines and four rows of cotton plants.

**Table 2**
Irrigation and fertilization schedules of cotton. The symbol "-" means no treatment in the year.

| 2018 | Irrigation (mm) | 2019 | Irrigation (mm) | 2020 | Irrigation (mm) | Fertilization (kg ha$^{-1}$) | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | Urea | Diammonium phosphate | Potassium sulfate |
| June-14 | 25 | April-11 | 22 | April-15 | 25 | - | - | - |
| June-21 | 20 | June-15 | 23 | June-14 | 20 | 22.8 | 9.6 | 3.6 |
| June-29 | 25 | June-23 | 25 | June-21 | 25 | 22.8 | 19.2 | 7.2 |
| July-7 | 20 | July-2 | 30 | July-7 | 20 | 28.4 | 24.0 | 9.0 |
| July-13 | 30 | July-10 | 30 | July-13 | 30 | 34.2 | 28.8 | 10.8 |
| July-19 | 30 | July-18 | 30 | July-19 | 30 | 68.4 | 28.8 | 10.8 |
| July-26 | 30 | July-26 | 30 | July-26 | 30 | 68.4 | 43.2 | 16.2 |
| Aug-3 | 20 | Aug-3 | 30 | Aug-3 | 20 | 68.4 | 43.2 | 16.2 |
| Aug-11 | 20 | Aug-11 | 20 | Aug-11 | 20 | 68.4 | 43.2 | 16.2 |
| Aug-19 | 20 | Aug-19 | 30 | Aug-19 | 20 | 68.4 | 24.0 | 9.0 |
| Aug-27 | 20 | Aug-27 | - | Aug-27 | 20 | - | - | - |
| - | 260 | – | 260 | - | 260 | 450 | 264 | 99 |

vesting) stages, every 10–15 days six plants within a predetermined area of plots was randomly selected to measure cotton growth indicators including plant height, stem diameter, leaf area, branch number, boll number per plant, aboveground dry matter, number of leaves, fruit branches, number of bolls per plant, etc. The relative content of chlorophyll in cotton was observed by a SPAD502 chlorophyll meter (Japan). The plant height and leaf area were measured using a tape, and the stem diameter was measured by a vernier caliper. The leaf area index (LAI) is estimated by (García-Vila et al., 2009):

$$LAI = 0.84 \times \varepsilon \sum_{i}^{m} \sum_{j}^{n} \frac{L_{ij} \times W_{ij}}{m \times 10^4} \tag{1}$$

where $\varepsilon$ is planting density (plant/m$^2$); $m$ is total number of plants; $n$ is total leaf number for single plant; $L_{ij}$ and $W_{ij}$ are the $j_{th}$ leaf length (cm) and width (cm) on the $i_{th}$ plant; $i$ and $j$ are the $j_{th}$ leaf on the $i_{th}$ plant. 0.84 is a conversion coefficient.

#### 2.3.6. Measurement of cotton nutrient content

During the main growth stages of cotton, three representative plants were taken to the laboratory. The soils on the plants were cleaned with deionized water. The cotton taproot, stem, and leaves were separated. The different cotton parts were put into the oven at 105 ℃ for 2 h, and oven-dried at 75 ℃ to the constant weights. An electronic balance with an accuracy of ± 0.01 g was used to measure the dry matter mass.

The dry matter was ground and passed through a 0.5-mm-in-diameter sieve, then dis-boiled with $H_2SO_4$-$H_2O_2$, and heating digested to determine the nitrogen (N), phosphorus (P) and potassium (K) contents of different cotton parts. Crop N, P, and K contents were measured using a vanadium molybdenum yellow spectrophotometry, an atomic absorption spectrophotometer (Hitachi Z-2000 series), and an AA3 continuous flow analyzer (Germany Bran+Luebbe), respectively.

#### 2.3.7. Measurement of cotton yield and quality

A square with 6.67 m$^2$ area in the plot was marked in advance. In the harvest stage of cotton, the cotton seeds were manually collected , taken to the laboratory, air dried and weighed. The cotton seed and lint were separated to measure the lint yield and percentage. The seeded cotton (20 samples) were taken, combed and collected to measure the fiber quality of cotton. The Micronaire value, fiber length and,fiber strength uniformity index were measured using an airflow meter, a length camera, and a $Y_{162}$-type bundle fiber strength machine, respectively.

### 2.4. Computation of the efficiency and benefits

#### 2.4.1. Irrigation water productivity and partial fertilizer productivity

The irrigation water productivity (*IWP* ) is the ratio of cotton yield (t ha$^{-1}$) to irrigation amount (mm), calculated for each treatment (Li et al., 2018):

$$\text{IWP}=\text{Yield/Irrigation} \tag{2}$$

The partial fertilizer productivity (PFP) is the ratio of cotton yield to fertilization amount.

$$\text{PFP} = \text{Yield/Fertilization} \tag{3}$$

PFP of phosphorus, potassium and nitrogen are calculated for each treatment.

#### 2.4.2. Economic analysis

The total cost of each treatment considered materials, water and labor. The material cost involves cost of biochar, fertilizer (urea, potassium dihydrogen phosphate and potassium sulfate), cotton seed, plastic film, drip irrigation tapes, agricultural machinery and pesticides. Biochar cost 10 RMB yuan kg$^{-1}$; Urea, potassium dihydrogen phosphate and potassium sulfate were 2.2, 2.7 and 1.8 RMB yuan kg$^{-1}$, respectively. Water cost total 3000 RMB yuan for each growth season. The sum of labor fee, machinery fee and pesticide were 11925 RMB yuan for each growth season. Revenue was mainly from the sale income. The economic benefit (net profit) was calculated by:

$$\text{Economic benefit} = \text{revenue - cost} \tag{4}$$

The SPSS 17.0 software was used to complete one-way analysis of variance (ANOVA). It tested the significance of the differences in the soil physicochemical properties between different treatments by the least significant differences (LSD) at the $P < 0.05$ level. Microsoft Office Excel 2016 and SigmaPlot 12.0 were used to draw figures.

## 3. Results

### 3.1. Nutrient content and growth indices of cotton affected by biochar

#### 3.1.1. Nutrient content of cotton leaf, stem and root affected by biochar

Based on the measurements, the nutrient (N, P and K) content of cotton leaf, stem and root during anthesis, boll development and boll-open stages were compared for 2018 and 2019 (Fig. 3). The results showed that leaf N content was larger both at the anthesis and boll-open stages than at the bolling stage in 2018 and 2019. Root N content were larger at the boll-open stage in both years. Additionally, at the boll-open stage, BCAR of 10 t ha$^{-1}$ achieved the largest root N content in 2018, while in 2019 it was 50 t ha$^{-1}$. Stem N content was smaller at the anthesis stage both for 2018 and 2019, differed for the bolling stage in the two years, and occupied around 1/3 of the total N content of cotton. Total N content of cotton achieved the highest values for bolling and boll-open stages at BCAR of 10 t ha$^{-1}$ in 2018 and 50 t ha$^{-1}$ in 2019, respectively ( Figs. 3a and 4f and Table S2).

P content of leaf, stem and root were much smaller than N content. At most of the growth stages, leaf, stem and root P content accounted each 1/3 of the total, respectively. Biochar application changed P content compared to no biochar treatment. Total P content of cotton achieved the highest values for the anthesis and boll-open stages at changing BCARs of 10, 50 or 100 t ha$^{-1}$ in 2018 and 2019, respectively (Fig. 3aa–ff and Table S3). The ranges of leaf, stem and root K content were close to those of N content under different conditions. BCAR of 50 and 10 t ha$^{-1}$ contributed to the largest K content in 2018 and 2019, respectively (Fig. 3aa–ff and Table S4).

Overall, biochar application increased N, P and K contents for cotton growth both in 2018 and 2019 compared to no biochar condition. The range of increased percentage of N, P and K were (N) − 38.2% (in B100 treatment, 2019, stem) to 219.4% (in B10 treatment, 2019, taproot) (Table S2), (P) − 37.0% (in B100 treatment, 2019, stem) to 179.2% (in B10 treatment, 2019, taproot) (Table S3), and (K) − 28.2% (in B100 treatment, 2019, stem) to 154.3% (in B10 treatment, 2019, taproot), respectively (Table S4) compared to no biochar treatment. The content of N, P, K reached the highest increase at the BCAR of 10 t ha$^{-1}$. Too high BCAR of biochar (>50 t ha$^{-1}$) was not beneficial to cotton growth.

#### 3.1.2. Germination and chlorophyll of cotton affected by biochar

The main growth stages of cotton are sowing (April 10, 11, and 15 in 2018, 2019 and 2020), seedling (June 14, 15, and 14 in 2018, 2019 and 2020), bud (June 25, 26, and 28 in 2018, 2019 and 2020), anthesis (July 7, 10, and 13 in 2018, 2019 and 2020), bolling (August 3, 11, and 11 in 2018, 2019 and 2020) and boll-open (August 27, 30, and September, 3 in 2018, 2019 and 2020), respectively.

The germination rates of cotton with the variate biochar application rate are compared in Fig. 4. In 2018, 2019 and 2020, cotton germination rate ranged between 0.53 and 0.73, 0.73–0.93, and 0.88–0.95, respectively. The largest values occurred at the BCAR of 10 t ha$^{-1}$ and there were significant differences between the four treatments. The ranges of germination rates increased in the 2nd and 3rd years, showing positive

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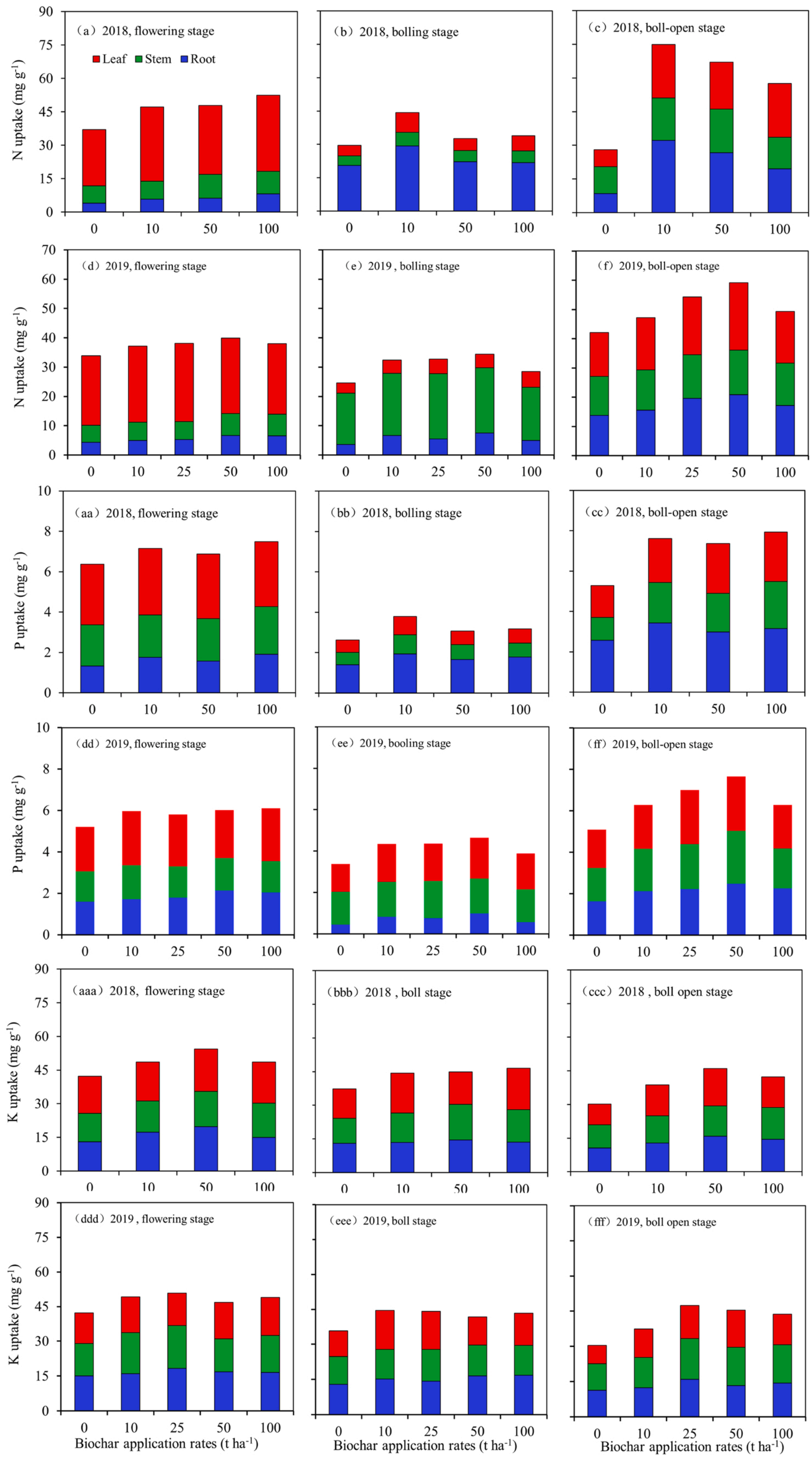


**Fig. 3.** Content of N, P and K during anthesis, boll development and boll-open stages of cotton in 2018 and 2019 at different biochar application amounts.

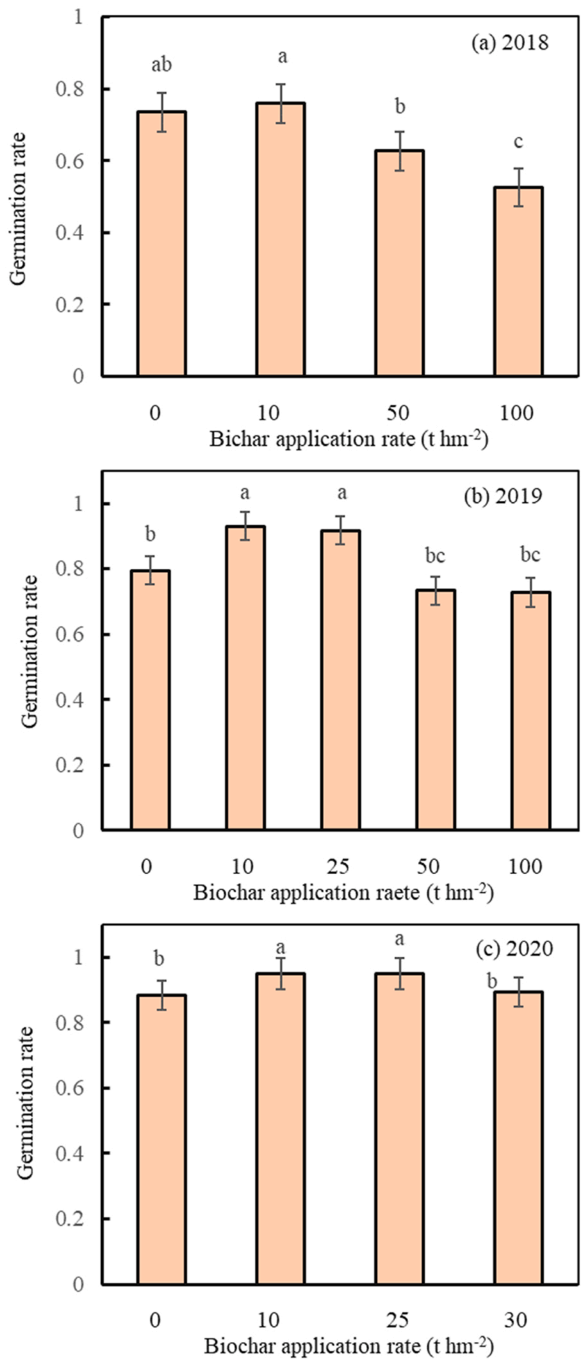


**Fig. 4.** The germination rate of cotton in 2018, 2019 and 2020.

influence of continuous biochar application. However, BCAR greater than 25 t ha$^{-1}$ were not appropriate in improving germination rates of cotton.

The temporal variations and fluctuations of relative content of chlorophyll during cotton growth stages of 2018 and 2019 (Fig. 5) showed the generally higher values of B100 and B50 than B25, B10 and B0 treatments. Overall, chlorophyll fluctuation patterns were similar for inside and outside rows. In both 2018 and 2019, the relative content of chlorophyll at inside and outside rows increased first and then decreased to the lowest values before the 90 th days after sowing (DAS), and then increased until harvest. Biochar application increased relative content of chlorophyll during cotton growth stages both in 2018 and 2019 compared to B0 treatment.

The observed values of relative content of chlorophyll in inside and outside rows of cotton are plotted in Fig. 6. The values of relative content of chlorophyll in inside rows of cotton were smaller than outside rows of cotton for B0, B10 and B50 treatments, but were a little larger than values of outside rows for B100 treatment. There were very good linear correlations between the two and the coefficient of determination values varied from 0.691 to 0.849. The linear slopes were smallest for treatment B10 and largest for B100 both in 2018 and 2019. The continuous biochar application slightly changed the relationship between inside and outside rows of cotton chlorophyll.

#### 3.1.3. Growth indices of cotton affected by biochar

The temporal variations of cotton plant height, stem diameter and LAI during cotton growth stages of 2018, 2019 and 2020 (Fig. 7) indicated that: (1) The plant height, stem diameter and LAI increased with the growth stages before the 105th DAS for all the treatments and years. The plant height and stem diameter stopped increasing and the LAI decreased after the 105th DAS since the plants were pinched with tip pruning. (2) The differences of cotton growth indicators were smaller in 2018, but larger in the second planting year 2019, and small in 2020. These differences showed an improvement effects of 3-year continuous application of biochar on cotton growth. (3) Continuous biochar application with BCARs of 10, 25, and 50 t ha$^{-1}$ improved cotton growth, especially at BCAR of 10 t ha$^{-1}$. However, continuous biochar application of 100 + 100 t ha$^{-1}$ or 50 + 50 + 30 t ha$^{-1}$ continuously decreased cotton growth. We implied that the improper application of 2-year 100 + 100 t ha$^{-1}$ or 3-year 50 + 50 + 30 t ha$^{-1}$ were not proper application patterns for cotton planting. However, 2-year 50 + 50 t ha$^{-1}$ application did not decrease cotton growth either. (4) Overall, there was generally a decreasing ranking of continuous application rate for improving cotton growth, namely 10 + 10 + 10 t ha$^{-1}$, NT+ 25 + 25 t ha$^{-1}$, 50 + 50 + 30 t ha$^{-1}$, 0 + 0 + 0 ha$^{-1}$, and 100 + 100 +NT t ha$^{-1}$ in turn.

### 3.2. Yield-related indices of cotton affected by biochar

#### 3.2.1. Yield compositions of cotton

The measured cotton boll density, single boll weight, branch number per plant, lint percentage and lint yield along with the statistical differences ($P < 0.05$) were compared for different biochar application treatments in the three years (Table 3). For boll density, branch number and lint yield, the BCAR of 10 t ha$^{-1}$ (B10) had the peak values of cotton yield compositions in 2018–2020 with significant differences when compared to the other biochar treatments, and resulted in the most significant improvement of cotton yield. While for single boll weight and lint percentage, there were not always significant differences among different biochar treatments. Additionally, the BCAR of 25 t ha$^{-1}$ (B25) showed potential in improving boll density, branch number and lint yield (with significant differences when compared to the other biochar treatments). Under most conditions, BCAR of 100 t ha$^{-1}$ significantly decreased boll density, branch number per plant, and lint yield of cotton. Based on these results, we consider BCAR of 100 t ha$^{-1}$was too high for cotton growth and yields.

#### 3.2.2. Quality of cotton

The observed quality indices of cotton in 2018, 2019 and 2020 (Table 4) showed that biochar application had little effects on changing cotton fiber quality. BCAR of 10 t ha$^{-1}$ (B10) increased fiber length and uniformity index but didn't improve micronaire and strength. There were no significant differences among the four cotton quality indices at different BCARs, which were consistent in the all 3 years.

### 3.3. Efficiency and productivity of cotton affected by biochar

The computed yields, irrigation water productivity (IWP) and partial fertilizer productivity (PFP) of cotton in 2018, 2019 and 2020 are presented in Table 5. Significant differences were observed among different

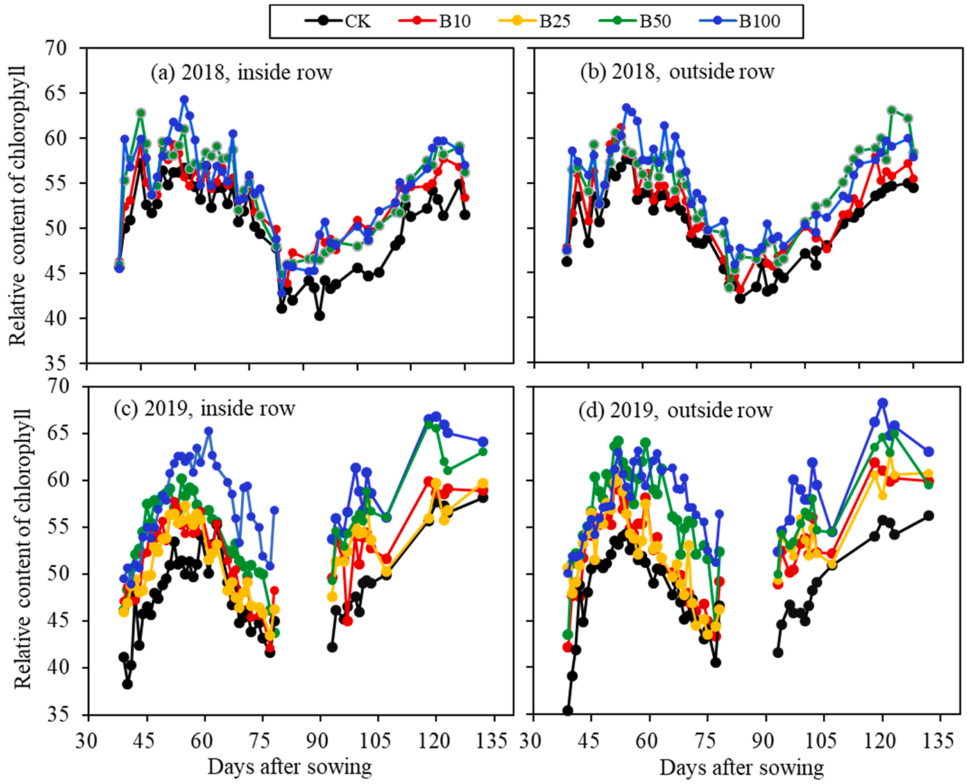


**Fig. 5.** The variations of relative content of chlorophyll for cotton planted in inside and outside rows during growth periods of 2018 and 2019.

treatments. Although there were differences between the three years, the yields, IWP and PFP for N, P and K for B10 treatment consistently had peak values in 2018, 2019 and 2020. Except B10, treatments B25 and B50 also improved the IWP and PFP of cotton when compared to B0, however, the improved effects were generally smaller than B10. The productivity decreasing effects of B100 on IWP and PFP in 2018 and 2019 were consistently shown for cotton. In 2020, B30 decreased the IWP and PFP of cotton.

### 3.4. Economic benefit of biochar application on cotton

The income, cost and economic benefit of biochar application on cotton are presented in Table 6 for different treatments and planting years. Notice that not all treatments were applied in 2018–2020, only B0 and B10 were continuously conducted. The treatments B0, B10, and B25 had significant higher economic benefits than treatments B25, B50 and B100, of which, treatment B10 had the highest economic benefit in 2019 and 2020. BCARs of 50 + 50 + 30 and 100 + 100 t ha$^{-1}$ had negative economic benefits. Generally, there were negative/low economic benefits for biochar application treatments of B25, B50 +B30 and B100. Also, there was great economic benefit of no biochar application on cotton, and this was attributed to the high economic benefit of cotton itself.

Overall, considering the comprehensive responses of nutrient content, the relative content of chlorophyll, the growth- and yield- related indicators, and the economic benefit of cotton, the recommended most appropriate BCAR for cotton was 10 t ha$^{-1}$ per year if continuously applied for 3 years.

## 4. Discussions

### 4.1. Influences of biochar application on soil properties

The crop yield enhancement by biochar application was activated by the gradually improved soil environments over time. Biochar application improved soil physical and hydraulic characteristics significantly. For example, biochar decreased soil bulk density and increase soil macroporosity (>50 μm) by creating new accommodation pores (Andrenelli et al., 2016). The oxidized biochar can retain more water in sandy soils, enhance water-holding-capacities, and increase soil water retention (Suliman et al., 2017). Biochar can significantly enhance soil pH, nutrient contents, soil microbial biomass carbon/organic carbon, nitrogen, base cations and enzymatic activities (Arif et al., 2016; Jin et al., 2019). The alkaline biochar applied at recommended rate (e.g., 10 t ha$^{-1}$ from Sandhu et al., 2017) can increase cold water extractable carbon fraction of acidic sandy loam soil. Additionally, our observation in Fig. 8 for 2019 showed the comprehensive effects of biochar on decreasing soil bulk density especially at the top layers (0–30 cm), (1) on improving soil moisture of no mulch and narrow row zones when the biochar application rate was less than 25 t ha$^{-1}$, (2) on decreasing soil salt content at biochar application rate of 10 t ha$^{-1}$, and (3) on increasing nitrate and organic carbon content when biochar application rate was increasing. The overall improvement of soil environment by biochar application provided good water and nutrient environment for crop growth. These improvements stabilize the increase of cotton production and improves feasibility in arid and semi-arid zones. Therefore, there is strong support for biochar's potential in agriculture.

We confidently think that biochar application improves soil environment if properly added to soils. However, there is a significant lack of investigation on biochar application effects on cotton production, especially how to determine a rational biochar application rate.

### 4.2. The roles of soil additive or conditioner in saline-alkali soils

Soil conditioner/additive played important roles in modifying saline-alkali soils. In general, it changes quality of saline-alkali soils by regulating soil pH value, reducing soil salt content, improving soil structure, rising water retention capacity, adjusting microbial environment, or promoting seed germination and growth. For example, biochar (Haider et al., 2022), biomass pyrolysis fluid (Wang et al., 2022a,b), humic acid

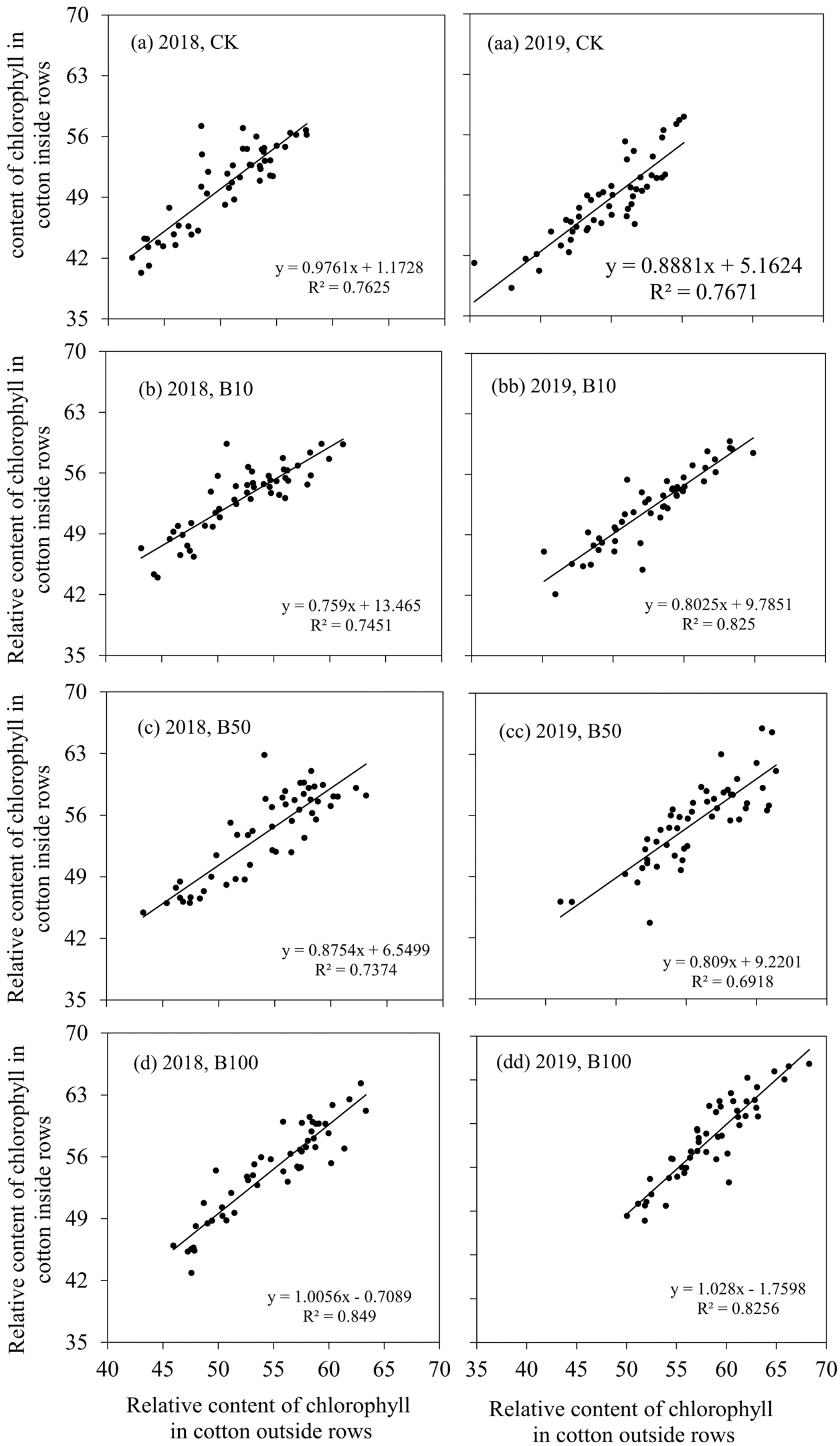


**Fig. 6.** The relationship between relative contents of chlorophyll for cotton at outside and inside rows.

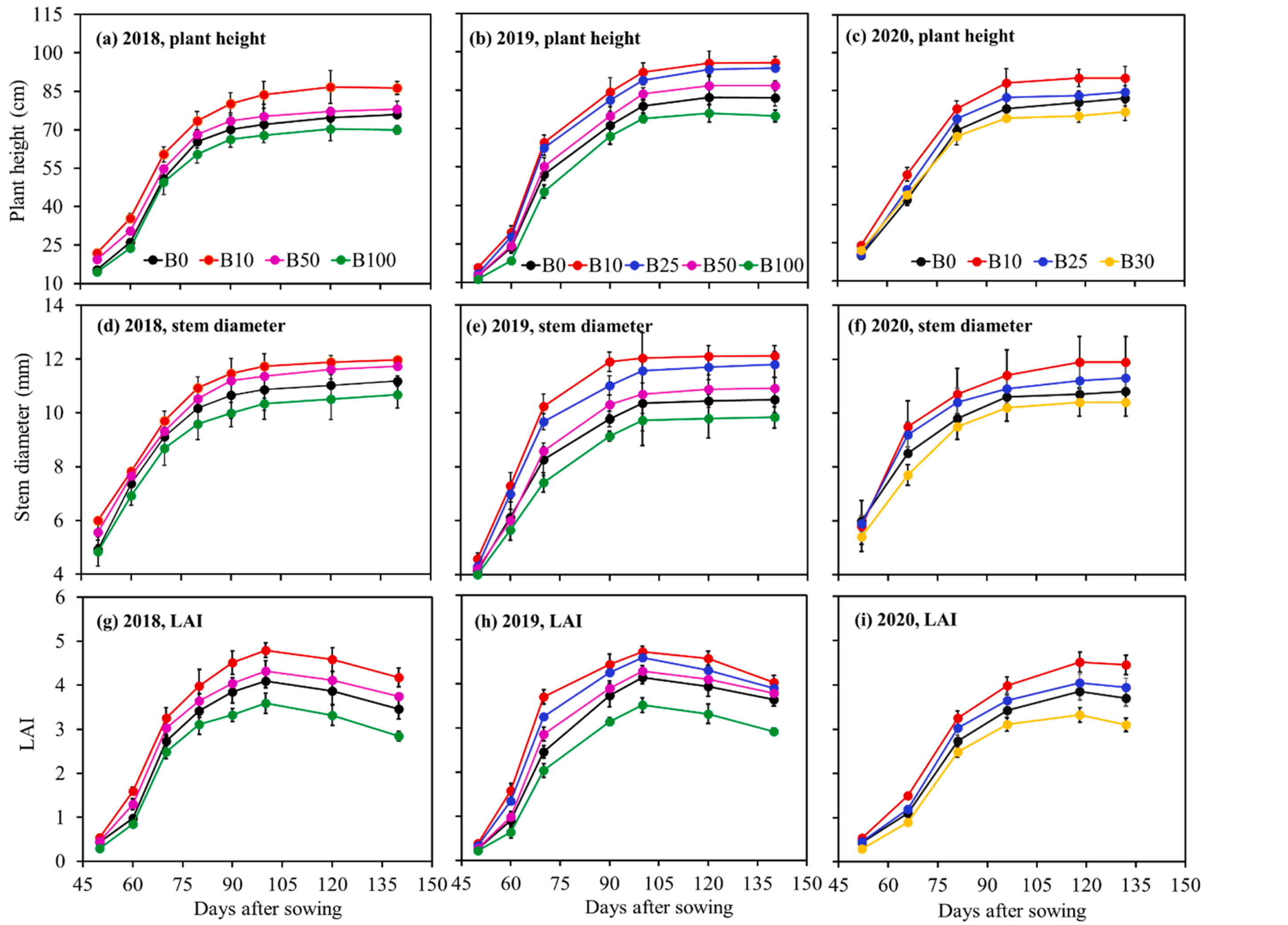


**Fig. 7.** Growth features of plant height, stem diameter and LAI during the main growth periods of cotton for different biochar application treatments in 2018, 2019 and 2020.

**Table 3**
Effects of biochar application on yield compositions of cotton in 2018, 2019, and 2020. Note that the recommended rate is in bold. Different letters indicate statistical differences among treatments at the significance level P < 0.05.

| Year | Treatment | Boll density (boll No. $m^{-2}$) | Single boll weight (g) | Branch number per plant | Lint percentage (%) | Lint yield (kg $ha^{-1}$) |
|---|---|---|---|---|---|---|
| 2018 | B0 | 110.6 ± 1.9b | 5.14 ± 0.07a | 6.67 ± 1.03ab | 44.0 ± 0.8a | 2642 ± 46b |
| | B10 | **133.0 ± 9.3a** | **5.10 ± 0.20a** | **7.33 ± 0.82a** | **44.5 ± 0.8a** | **3016 ± 220a** |
| | B50 | 116.5 ± 6.2b | 5.01 ± 0.30a | 6.83 ± 0.75ab | 43.9 ± 1.1a | 2558 ± 175b |
| | B100 | 95.9 ± 6.4c | 4.99 ± 0.28a | 6.00 ± 0.89b | 43.4 ± 1.8a | 2076 ± 100c |
| 2019 | B0 | 109.2 ± 5.3ab | 5.43 ± 0.41 BCE | 7.83 ± 1.72ab | 45.5 ± 1.7a | 2688 ± 111b |
| | B10 | **115.7 ± 8.5a** | **6.16 ± 0.27a** | **8.83 ± 0.98a** | 47.3 ± 1.6a | **3503 ± 33a** |
| | B25 | 117.5 ± 4.5a | 5.84 ± 0.23ab | 8.0 ± 1.26ab | 45.6 ± 1.2a | 3272 ± 109a |
| | B50 | 108.9 ± 2.2ab | 5.63 ± 0.37ab | 6.67 ± 1.75b | 46.8 ± 0.9a | 2866 ± 186b |
| | B100 | 103.7 ± 2.6b | 4.88 ± 0.17c | 6.33 ± 1.03b | 47.6 ± 3.0a | 2407 ± 176c |
| 2020 | B0 | 115.6 ± 13.3c | 5.34 ± 0.55a | 6.34 ± 0.55b | 44.8 ± 1.4a | 2197 ± 284.4c |
| | B10 | **152.7 ± 10.5a** | 6.07 ± 0.26a | **8.97 ± 0.26a** | 46.6 ± 1.1a | **3324 ± 297.5a** |
| | B25 | 131.6 ± 10.0b | 5.57 ± 0.19a | 8.57 ± 0.19a | 47.3 ± 0.8a | 2741 ± 279.9b |
| | B30 | 111.3 ± 5.3c | 5.47 ± 0.28a | 5.47 ± 0.28b | 45.2 ± 2.8a | 1842 ± 110.7d |

and sodium carboxymethyl cellulose (Shan et al., 2022), gypsum-like $Ca^{2+}$ solid agents, organic/inorganic acids (Wang et al., 2010) and many other types of soil conditioner have been some additives applied to lands in recent years. As a water soluble polyelectrolyte, hydrolytic polymaleic anhydride reduced the soil pH and EC in saline-alkali (Wang et al., 2010). Dephenolization pyrolysis fluid is another kind of soil conditioner which reduced total soil salt content effectively (Wang et al., 2022a,b).

As mentioned above, biochar was shown to have potentials in changing soil environment and plant yields. It could reduce soil bulk density by 9%, and increase saturated hydraulic conductivity by 88% (from 6.1 to 11.4 cm $h^{-1}$, Oguntunde et al., 2008; Agegnehu et al.,

**Table 4**
Effects of biochar application on quality of cotton fiber.

| Year | Treatment | Length (mm) | Micronaire | Strength (cN/tex) | Uniformity index (%) |
|---|---|---|---|---|---|
| 2018 | B0 | 30.0 ± 0.28a | 5.05 ± 0.04a | 27.05 ± 0.08a | 85.95 ± 0.92a |
| | B10 | 30.05 ± 0.64a | 4.84 ± 0.12a | 27.05 ± 0.35a | 85.7 ± 0.57a |
| | B50 | 29.75 ± 0.07a | 4.88 ± 0.13a | 26.58 ± 0.5a | 85.55 ± 0.21a |
| | B100 | 29.55 ± 0.21a | 4.87 ± 0.05a | 26.90 ± 0.14a | 85.50 ± 0.28a |
| 2019 | B0 | 30.33 ± 0.30a | 5.08 ± 0.09a | 28.41 ± 0.02a | 85.36 ± 0.40a |
| | B10 | 30.35 ± 0.33a | 5.07 ± 0.05a | 28.23 ± 0.65a | 85.79 ± 0.33a |
| | B25 | 29.73 ± 0.40a | 5.08 ± 0.04a | 28.31 ± 0.03a | 85.30 ± 0.06a |
| | B50 | 29.78 ± 0.20a | 5.03 ± 0.03a | 28.17 ± 0.11a | 85.41 ± 0.75a |
| | B100 | 29.57 ± 0.39a | 5.02 ± 0.06a | 28.20 ± 0.69a | 85.15 ± 0.13a |
| 2020 | B0 | 30.12 ± 0.21a | 5.02 ± 0.07a | 28.03 ± 0.43a | 85.82 ± 0.43a |
| | B10 | 30.32 ± 0.23a | 5.05 ± 0.06a | 27.98 ± 0.21a | 85.65 ± 0.32a |
| | B25 | 30.36 ± 0.30a | 4.98 ± 0.02a | 27.78 ± 0.05a | 85.31 ± 0.01a |
| | B30 | 29.25 ± 0.32a | 4.88 ± 0.03a | 27.77 ± 0.13a | 85.21 ± 0.21a |

**Table 5**
Effect of biochar application rate on seed cotton yield, irrigation water productivity (IWP) and partial fertilizer productivity (PFP) for the 3 planting years. Note that the recommended rate is in bold.

| Year | Treatment | Yield (kg ha$^{-1}$) | Irrigation water productivity (kg m$^{-3}$) | Partial fertilizer productivity (kg kg$^{-1}$) | | |
|---|---|---|---|---|---|---|
| | | | | N | P | K |
| 2018 | B0 | 5680 ± 174b | 2.18 ± 0.07b | 12.6 ± 0.4b | 21.5 ± 0.7b | 57.4 ± 1.8b |
| | B10 | **6784 ± 582a** | **2.61 ± 0.22a** | **15.1 ± 1.3a** | **25.7 ± 2.2a** | **68.5 ± 5.9a** |
| | B50 | 5828 ± 292b | 2.24 ± 0.11b | 13.0 ± 0.6b | 22.1 ± 1.1b | 58.9 ± 2.9b |
| | B100 | 4776 ± 46c | 1.84 ± 0.02c | 10.6 ± 0.1c | 18.1 ± 0.2c | 48.2 ± 0.5c |
| 2019 | B0 | 5911 ± 270b | 2.27 ± 0.11b | 13.1 ± 0.6b | 22.4 ± 1.0b | 59.7 ± 2.7b |
| | B10 | **7417 ± 183a** | **2.85 ± 0.07a** | **16.5 ± 0.4a** | **28.1 ± 0.7a** | **74.9 ± 1.8a** |
| | B25 | 7172 ± 185a | 2.76 ± 0.07a | 15.9 ± 0.4a | 27.2 ± 0.7a | 72.4 ± 1.9a |
| | B50 | 6131 ± 400b | 2.36 ± 0.15b | 13.6 ± 0.9b | 23.2 ± 1.5b | 61.9 ± 4.1b |
| | B100 | 5060 ± 94c | 1.95 ± 0.04c | 11.2 ± 0.2c | 19.2 ± 0.4c | 51.1 ± 1.0c |
| 2020 | B0 | 4903 ± 634.9 BCE | 1.89 ± 0.24b | 10.9 ± 1.4c | 18.6 ± 2.4c | 49.5 ± 6.4c |
| | B10 | **7133 ± 638.3a** | **2.74 ± 0.25a** | **15.9 ± 1.4a** | **27.0 ± 2.4a** | **72.0 ± 6.4a** |
| | B25 | 5794 ± 591.8 BCE | 2.23 ± 0.23ab | 12.9 ± 1.3b | 21.9 ± 2.3b | 58.5 ± 6.0b |
| | B30 | 4075 ± 244.9c | 1.57 ± 0.10b | 9.1 ± 0.5c | 15.4 ± 0.9d | 41.2 ± 2.5d |

2017). Biochar increased soil pH values from 7.1 to 8.1 at 39 t ha$^{-1}$ (Granatstein et al., 2009), or from 6.0 up to 9.6 (Steiner et al., 2008). From experiment of Lashari et al. (2013), application of biochar together with poultry manure compost to saline soil significantly decreased salinity by 3.6 g kg$^{-1}$ and increased soil pH/organic C/available P/bulk

**Table 6**
Effects of biochar application on economic benefit of cotton in 2018, 2019, and 2020.

| Year | Treatment | Income (RMB) | Cost (RMB) | Economic benefit (RMB ha$^{-1}$) |
|---|---|---|---|---|
| 2018 | B0 | 47,717.9b | 19,510.5d | **28,207.4a** |
| | B10 | 56,989.0a | 29,510.5c | 27,478.5b |
| | B50 | 48,961.9b | 69,510.5b | - 20,548.6c |
| | B100 | 40,115.9c | 19,510.5a | - 79,394.6d |
| 2019 | B0 | 49,653.2b | 19,510.5e | 30,142.7b |
| | B10 | 62,303.6a | 29,510.5d | **32,793.1a** |
| | B25 | 60,242.3a | 44,510.5c | 15,731.8c |
| | B50 | 51,498.7b | 69,510.5b | - 18,011.8d |
| | B100 | 42,505.7c | 19,510.5a | - 77,004.8e |
| 2020 | B0 | 41,184.4c | 19,510.5d | 21,673.9b |
| | B10 | 59,914.7a | 29,510.5c | **30,404.2a** |
| | B25 | 48,672.1b | 44,510.5b | 4161.6c |
| | B30 | 34,225.8c | 49,510.5a | - 15,284.7d |

density by 0.3, 2.6 g kg$^{-1}$, 27 mg kg$^{-1}$, and 0.1 g cm$^{-3}$, respectively. The added biochar have altered the microbial activity and abundance of denitrifying genes in soils which regulated the emission of $N_2O$ (Shaaban et al., 2018). In addition, different types of biochar have shown great potential in increasing biomass yield of rice by 14% (in China) to 294% (in Colombia), of maize by 11–150% in China, USA, Colombia, Pakistan or Japan, of cowpea by 45% in Brazil, of sweet potato by 54% in China, and of wheat in Pakistan by 65% (Haider et al., 2022). However, little research investigated the influences of biochar on cotton nutrient uptake, growth and yields, and obtained the best BACR for cotton irrigated by plastic film mulched trickle irrigation and planted in arid zone. This research has also shown the more positive influences of biochar on plant height, stem diameter, leaf area index, seed yield, irrigation water productivity, and partial fertilizer (N, P, and K) productivity and economic income of cotton, especially at the best dose of 10 t ha$^{-1}$.

### 4.3. Rational biochar application rate

Rational biochar application involves the application pattern, the application frequency (times and total period), the application way (apply once or continuously apply), and the application amount/rate/dose. The most common and efficient application pattern is to mix biochar uniformly with top layer soils. There are a range of popular application period/frequency including 1–2 years (Akhtar et al., 2014; Arif et al., 2016; Li et al., 2018; Maucieri et al., 2017; Zhang et al., 2012, 2017), 3–6 years (Jin et al., 2019; Major et al., 2010; Pandit et al., 2018), and 9 years (Yi et al., 2020). For soil managers, there are different aims which determine biochar application one or more times. However, two-year is the recommended minimum observation period because biochar addition may not affect crop yields in the first year under some circumstances (Pandit et al., 2018).

The application rate/amount/dose is a very important technique parameter in biochar addition practice because it can affect crop growth, yields and productions to a high extent. However, researches have seldom directly compared the effects of BCAR differences on crop yields because it needs more economic investment. Some researchers compared influences of biochar addition or no addition on crop yields (Akhtar et al., 2014). Several researchers found that as BCAR increased (from 15, 25–40 t ha$^{-1}$ in Pandit et al., 2018 and from 0% to 100% in Qayyum et al., 2017), crop (maize/mustard and wheat) grain yields achieved the peaks at the highest biochar addition levels (40 t ha$^{-1}$ or biochar percentage of 100%). In this research, we observed decreasing cotton growth/yields with the increasing BCARs during 2018–2020 (Fig. 5). There were several reasons for differences in research findings. First, our studied site belongs to an arid and semi-arid region. Our farmland is highly salinized, the trickle irrigation affects the soil water and salt movement along with biochar addition, and the internal interaction mechanics of soil and plants are likely to be complex.

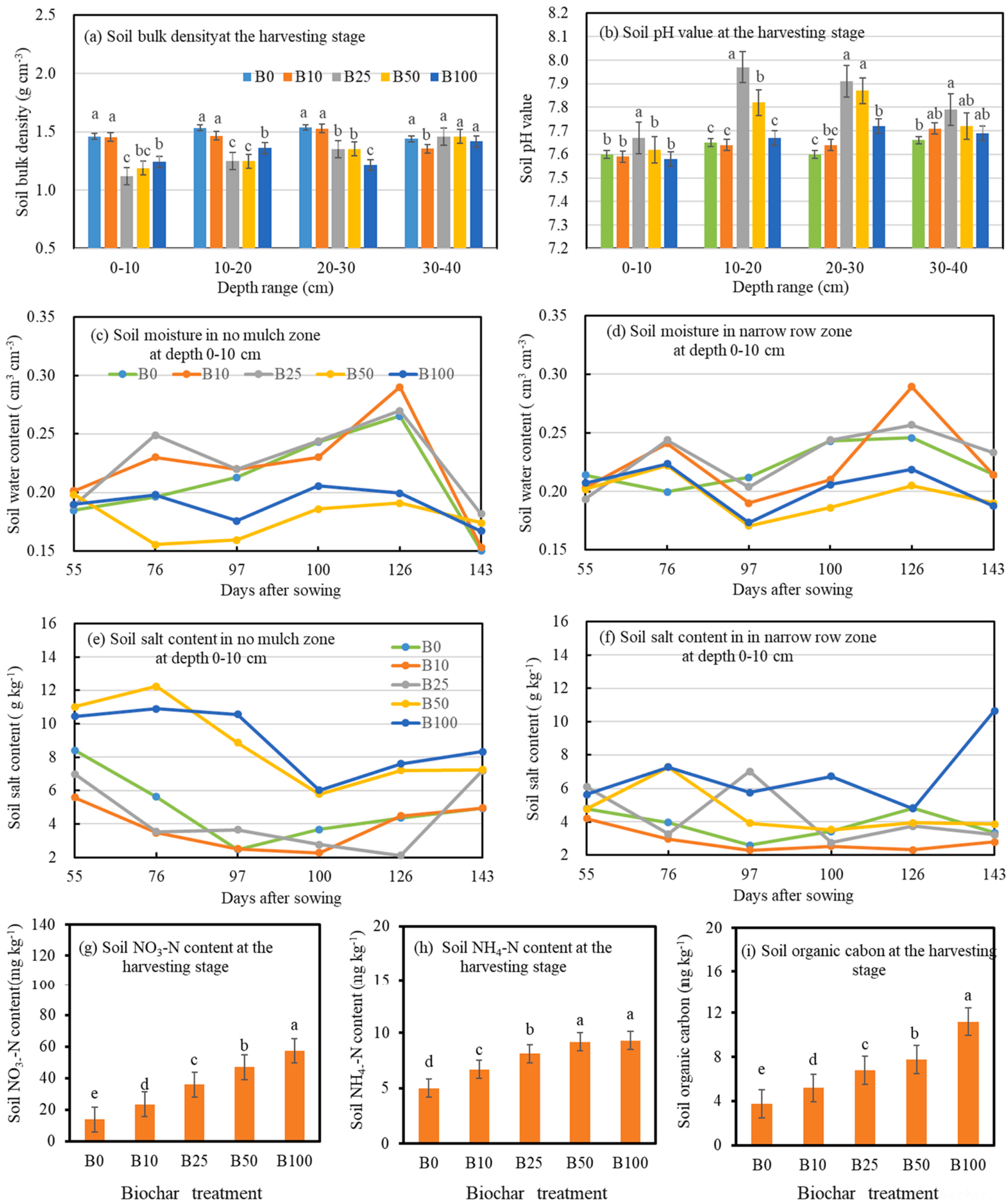


**Fig. 8.** Soil property variation for different treatments in 2019.

Second, the biochar itself contains different kinds of chemicals. After application, these chemicals increased soil salt content (Liang et al., 2021), and therefore, too high BCAR restricted crop growth. From this view, a rational BCAR is needed for crops planted in saline-alkali soils.

However, it is not adequate to determine a rational BCAR only through observing how soil quality and crop yields were improved, although most of the previous researches focused on this. Economic benefits at various BCARs varied greatly. A cost-benefit analysis is necessary when assessing biochar effects on agricultural system. Pandit et al. (2018) considered the agronomic costs and biochar production costs (including $CH_4$ emission cost) and obtained highest benefit at 15 t ha$^{-1}$ biochar application. In our research, the highest benefit was obtained at 10 t ha$^{-1}$, based on the economic analysis. This level was close to Pandit et al. (2018) and suitable for cotton. The finally determined rational BCAR of 10 t ha$^{-1}$ for cotton was a key technique parameter which could be used in the farmland for field management. Under our rational BCAR, the profit of cotton will be 10.93326 billion RMB (about 1.60783 billion US $ taking exchange rate of 6.8) for Xinjiang. China is extending cotton area, which was 3028.1 thousand hectares in 2021 according to China statistics Bureau. Our research demonstrated considerable economic profit potential if biochar is rationally applied.

In general, the same application rate makes the responses of soil and plant simpler when other factors were fixed. However, year by year (2018–2020) the application rate of biochar were adjusted according to the observed data of current year, which avoid continue the wrong trial (e.g., the B100 which costed highest but produced less). Further studies are needed to test the effects of non-continuously application of biochar or same biochar application rate of continuous application on soil and plant system.

## 5. Conclusions

Biochar applications increased the nutrient (N, P and K) contents during different growth stages of cotton, and the peak values were generally at the BCAR of 10–50 t $ha^{-1}$ (total 30–130 t $ha^{-1}$ under three-year continuous application). The relative content of chlorophyll increased with the increasing BCAR, and its values in inside rows were highly correlated with values in outside rows. The growth- and yield-related indicators increased significantly under biochar application conditions, and the BCAR of 10 t $ha^{-1}$ showed advantages in enhancing cotton growth and yields. Consequently, the irrigation water and partial fertilizer productivities also achieved peak values at BCAR of 10 t $ha^{-1}$. This is a reasonable biochar application dose, which was newly presented for cotton planting in arid zone. However, none of the cotton quality indices (length, Micronaire, strength, and uniformity index) were significantly affected by biochar applications. Through the economic analysis, BCAR of 10 t $ha^{-1}$ (total 30 t $ha^{-1}$ for 3-year continuous application) was recommended as the most economic and efficient dose for cotton planting in the arid and semi-arid farmland. Since there were complicated interactions of soil, biochar and crops, further studies considering multi-discipline overlap are needed to reveal the yield increase mechanics of crops.

## 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.

## Data availability

Data will be made available on request.

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## Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2022.108079.

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