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Straw Returning Measures Enhance Soil Moisture and Nutrients and Promote Cotton Growth

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Abstract: In order to investigate the comprehensive effects of straw returning on soil physical and chemical properties, as well as cotton growth in Jiangsu, China, and to determine suitable high-yield and efficient straw returning measures, this study implemented three different straw returning methods: straw mulching (SM), straw incorporation (SI), and straw biochar (BC), with no straw returning served as a control (CT). The study aimed to assess the impact of these straw-returning measures on soil nutrients, soil moisture content, soil water storage, and deficit status, as well as primary indicators of cotton growth. The findings revealed that the total available nutrient storage under SM, SI, and BC showed an increase of 11.93%, 11.15%, and 32.39%, respectively, compared to CT. Among these methods, BC demonstrated a significant enhancement in soil organic carbon content, available phosphorus, and available potassium. Furthermore, SM exhibited a considerable increase in soil moisture content across all layers (0–40 cm), resulting in an average water storage increase of 7.42 mm compared to CT. Consequently, this effectively reduced the soil water deficit during the cotton development period. Moreover, the height of cotton plants was increased by SM, SI, and BC, with SM promoting the greatest growth rate of up to 66.87%. SM resulted in an 11.17 cm increase in cotton plant height compared to CT. Additionally, SM contributed to higher chlorophyll content in leaves at the end of the growth period. Overall, the indicators suggest that straw mulching is particularly effective in enhancing soil moisture and nutrient distribution, especially during dry years, and has a positive impact on promoting cotton development. Based on the results, straw mulching emerges as a recommended straw-returning measure for improving soil quality and maximizing cotton production in the study area.

Keywords: soil moisture; nutrient; cotton; straw; mulching; biochar

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1. Introduction

Cotton (*Gossypium* spp.) is a significant commercial crop worldwide and serves as the primary source of natural textile fiber. In China, cotton holds a crucial strategic position and has played a pivotal role in increasing agricultural output and revenue [1]. However, due to limited arable land availability, expanding the area dedicated to cotton cultivation is challenging. Consequently, increasing cotton yield per unit area has become the primary strategy for augmenting China's cotton supply. Effective soil management is essential for achieving higher cotton yields and maintaining soil health, thereby ensuring the sustainability of cotton production [2–4]. Crop straw, a valuable renewable resource, is rich in organic matter, such as carbon, nitrogen, phosphorous, potassium, medium and trace elements, lignin, and cellulose. It plays a vital role as a transporter of matter, energy, and nutrients. One common practice in agricultural production worldwide is the return of straw to the soil, which significantly enhances the soil environment, soil fertility, and, consequently, crop yields [5]. Numerous studies have demonstrated the positive impact of returning straw on soil fertility, soil structure, water retention, and the soil microbial environment, ultimately leading to increase crop yields [6–10]. Studies by Wang et al. have shown that the combined application of nitrogen fertilizer and straw returning improved soil nutrient status, cotton canopy photosynthetic capacity, seed cotton yield, and nitrogen utilization efficiency [11]. Additionally, research by Tian et al. indicated that biochar application had a favorable impact on cotton growth, soil fertility, and nitrogen retention [12]. Biochar, in particular, significantly increased soil organic carbon content and available potassium levels, leading to enhanced cotton output and fiber quality [12].

Different methods can be employed to return straw to the field, such as smashing and direct plowing, surface covering, compost generation, or biochar production. These various techniques have distinct impacts on soil physical and chemical properties, soil fertility, and crop production [13]. Ma et al., in a four-year field experiment, demonstrated that straw-biochar incorporation significantly increased the availability of nitrogen, phosphorus, and potassium in soil under the condition of equal carbon input [14]. This method also promoted cotton root biomass, enhanced the canopy's apparent photosynthesis rate, and increased nitrogen, phosphorus, and potassium absorption by the canopy, ultimately resulting in the highest cotton yield. Conversely, the smallest yield improvement was observed when straw mulching reduced the soil's surface temperature during the early stages of cotton growth [14]. Based on extensive field studies, Ma et al. investigated the effects of cotton straw and cotton straw biochar on the transformation of nitrogen fertilizer into soil organic nitrogen components and cotton production [15]. The findings indicated that biochar application had a more positive impact than straw on the total nitrogen content in the soil, apparent nitrogen recovery rate, and cotton yield. Continuous biochar application significantly enhanced cotton's nitrogen utilization efficiency, overall production, and the conversion of nitrogen fertilizer into organic nitrogen in the soil. In a study by Zhang et al., the promotion effect of different straw-returning methods on winter wheat production was examined under saline irrigation with equivalent carbon input. It was discovered that combining straw mulching and biochar application resulted in improved water and salt conditions in the soil, as well as a more favorable nutrient environment for winter wheat growth. Compared to solely applying straw mulching or biochar amendment, the combined approach yielded the highest wheat production [16]. In conclusion, it is evident that different straw returning practices have diverse impacts on soil properties, nutrient composition, and, ultimately, crop development and yield. Moreover, the selection of straw-returning methods should consider local conditions, such as regional weather, soil types, and crop characteristics, as these factors vary significantly [17]. It is crucial to take into account the specific conditions and regional factors when determining the appropriate straw-returning measure for a particular area. Currently, research on the effects of straw returning on soil properties and cotton growth is mainly concentrated in major cotton-growing regions in China, such as Xinjiang, Hebei Province, and Shandong Province [18,19]. However, in Jiangsu Province, which is part of the cotton-producing region in the Yangtze River Basin, studies on the application of straw returning measures in cotton production are limited. Existing research in Jiangsu primarily focuses on the impact of straw returning on cotton growth and yield formation [11,20], with minimal investigation into the mechanism underlying the effects on soil properties, such as nutrients and moisture. Additionally, the unique climatic conditions in Jiangsu, including heavy rainfall from June to July, reduced sunshine duration, and high air temperature and humidity in summer, may present challenges to the implementation of certain straw returning methods that have proven effective in other regions. Therefore, it is important to conduct research specifically tailored to the cotton production circumstances in Jiangsu to determine the most appropriate straw-returning method for the region.

This study aimed to investigate the impact of different straw-returning methods, including straw mulching (SM), straw incorporation (SI), and biochar (BC), on soil nutrients, soil moisture, and cotton growth in cotton fields. The research was conducted through box planting experiments. The objective was to establish a theoretical basis for selecting appropriate straw-returning practices suitable for local cotton production. The ultimate goal is to effectively utilize straw resources and achieve sustainable high yields in cotton production.

2. Materials and Methods

2.1. Experimental Area

The experiment was conducted from May to October 2022 at the Agricultural Water and Hydrological Ecological Experimental Site in Yangzhou City, Jiangsu Province, China (32°21′ N, 119°24′ E). The site is situated in the Jianghuai Plain, characterized by a subtropical monsoon climate. The climate in the region is moderate, with an average annual air temperature of 14.8 °C and distinct four seasons (spring, summer, autumn, and winter). Precipitation is unevenly distributed throughout the year, with an average annual rainfall of 1063 mm, of which 70% occurs between April and September. The region experiences 223 frost-free days per year. Figure 1 illustrates the precipitation distribution, air temperature changes, and irrigation patterns observed during the experiment.

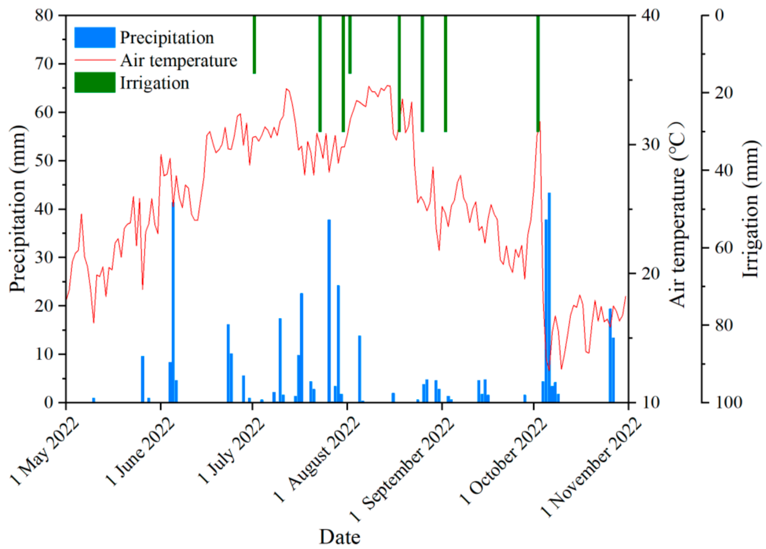

Figure 1. Distribution of precipitation, variations in air temperature, and irrigation of cotton in the study area during the experiment.

2.2. Experimental Desgin

The experiment was conducted using planting boxes. Four different treatments were implemented, including: (1) straw mulching (SM)—500 g of crushed wheat straw was spread evenly over the soil surface, forming a 5 cm-thick mulching layer; (2) straw incorporation (SI)—500 g of straw was evenly blended with the soil in the cultivation layer (0–15 cm); (3) biochar (BC)—350 g of maize straw-derived biochar was mixed with the soil in the cultivation layer; (4) conventional tillage (CT)—the field received no straw application. Each treatment had three replications. Cotton (Sumian 12 variety) was selected as the test crop. In early July, cotton seedlings were transplanted from a seedling tray to the planting box. Each planting box accommodated four plants, with a spacing of 20 cm between plants and rows. The dimensions of the planting box were 80 cm in length, 40 cm in width, and 52 cm in height. The box was made of polypropylene, a durable material resistant to sun and cold. To prevent plant root rot, a water storage chassis was installed, and a waterproof plug was fitted at the bottom of the box to prevent leakage during irrigation. To mitigate the impact of direct sunlight on soil temperature and hinder cotton development, the exterior of the planting box was covered with a heat-insulating film throughout the experiment. The soil used in the experiment was silty loam, which had been naturally dried and processed through a 10 mm sieve. The soil's dry density was maintained at a constant value of 1.25 g·cm^{-3} during filling. The soil was filled in four layers, with each layer compacted evenly as it was added. The field capacity of the soil was approximately 25% (volumetric moisture content). Prior to cotton transplantation, each planting box received 20 g of a special compound fertilizer with nitrogen, phosphorus, and potassium contents of 18%, 17%, and 5%, respectively. In late July, an additional 30 g of the fertilizer was applied to each planting box. Throughout the cotton growing season, consistent management practices such as spraying and weeding were implemented.

2.3. Measurement Indicators and Methods

2.3.1. Soil Nutrient

Soil samples were collected using a soil drill from various points within the experimental area. Samples were taken from three layers: 0–5 cm, 5–10 cm, and 10–20 cm. These samples were then mixed to create a representative composite sample for each treatment. The following soil nutrients were analyzed: (1) soil organic carbon—soil organic carbon content was determined using the potassium dichromate oxidation titration method; (2) available nitrogen—available nitrogen content was measured using the alkali N-proliferation method; (3) available phosphorus—available phosphorus content was assessed using the Olsen method; and (4) available potassium—available potassium content was determined using the acetamide extraction flame photometry.

The following formula was used to calculate the soil nutrient storage (G_s, kg·ha^{-1}) for each nutrient [21]:

$$G_s = H_a \cdot \rho_b \cdot C_n / 10 \quad (1)$$

where H_a represents the thickness of the arable layer (cm), ρ_b represents the bulk density of the soil (g·cm^{-3}), and C_n represents the content of specific soil nutrients (g·kg^{-1}).

The total available nutrient storage (G_{sT}, kg·hm^{-2}) refers to the sum of the organic carbon, available nitrogen, available phosphorus, and available potassium content in the soil. It was calculated as follows:

$$G_{sT} = G_{sC} + G_{sN} + G_{sP} + G_{sK} \quad (2)$$

where G_{sC}, G_{sN}, G_{sP}, and G_{sK} represent the storage of organic carbon, available nitrogen, available phosphorus, and available potassium, respectively.

2.3.2. Soil Moisture Content

Soil moisture content was determined using the drying method. Soil samples were collected at different stages of cotton growth: the bud stage, flower and boll stage, and boll opening stage. Samples were taken at depths of 10 cm, 20 cm, 30 cm, and 40 cm. The soil samples were first weighed to determine their wet weight. Next, the samples were dried in an oven at 105 °C until they reached a constant weight, and their dry weight was obtained. The soil mass water content (ω, g·g^{-1}) was calculated using the following formula [22]:

$$\omega = \frac{M_1 - M_2}{M_2 - M_a} \times 100\% \quad (3)$$

where M_1 is the mass of the natural soil sample, g; M_2 is the mass of the dried soil sample, g; and M_a is the mass of the aluminum box, g.

2.3.3. Soil Water Storage and Soil Water Deficit

Soil water storage (*SWS*, mm) is the amount of water stored in a specific thickness of the soil layer. The calculation formula is as follows [23]:

$$SWS = \sum_{i=1}^{n} (\theta_i \times h_i) \quad (4)$$

where θ_i represents the volumetric moisture content of the *i*-th soil layer (*n* layers in total), cm^3·cm^{-3}, and h_i represents the thickness of the soil layer, mm.

Soil water deficit (*D*, %) refers to the amount of soil moisture lacking for plant growth. This can be calculated as follows [24]:

$$D = \frac{D_a}{F} \times 100\% \quad (5)$$

$$D_a = F - SWS \quad (6)$$

where D_a represents the amount of soil water deficit, mm, and F represents the field capacity, mm.

2.3.4. Cotton Growth Indicators

From August to October 2022, measurements of cotton plant height and chlorophyll content were taken at seven-day intervals. The height of the plant was measured by determining the distance from the stem's base to the top using a tape measure. The relative chlorophyll content of the leaves was measured using the SPAD 502 (Konica Minolta Sensing, Osaka, Japan). The chlorophyll content was measured on the upper, middle, and lower layers of the cotton leaves, and the values were averaged.

2.4. Date Analysis

The data obtained from the experiment were processed and analyzed using various software tools. Microsoft Excel (version 2019) by Microsoft Inc., Redwood City, WA, USA, was used for data processing. OriginPro 2022 by OriginLab Co., Northampton, MA, USA, was utilized for creating plots and visualizations of the data. SPSS 25.0 by IBM Corp., Armonk, NY, USA, was employed for data variance analysis and correlation analysis. To determine significant differences between different experimental treatments, Duncan's multiple range test was performed. This test allows for multiple comparisons while maintaining a significance level of 0.05.

3. Results

3.1. Storage of Soil Organic Carbon, Nitrogen, Phosphorus, and Potassium

From Table 1, it can be seen that, under different straw returning measures, when compared to CT, SM's soil organic carbon and available potassium increased by 12.06% and 6.59%, SI's soil organic carbon, available nitrogen, available phosphorus, and available potassium increased by 10.44%, 13.02%, 9.34%, and 6.59%, and BC's soil organic carbon, available nitrogen, available phosphorus, and available potassium increased by 30.39%, 2.75%, 24.94%, and 56.2%, respectively. These findings indicate that all three straw returning measures (straw mulching, straw incorporation, and biochar application) improved soil nutrient content and enhanced soil fertility retention. It is worth noting that biochar application had a significant impact on soil organic carbon, available phosphorus, and available potassium ($p < 0.05$).

Table 1. Soil nutrient content under different straw returning measures.

Experimental Treatment	Organic Carbon ($g \cdot kg^{-1}$)	Available Nitrogen ($mg \cdot kg^{-1}$)	Available Phosphorus ($mg \cdot kg^{-1}$)	Available Potassium ($mg \cdot kg^{-1}$)
SM	4.83 ± 0.51 ab	35.68 ± 4.64 a	22.70 ± 2.41 a	91.67 ± 8.74 a
SI	4.76 ± 0.46 ab	42.35 ± 4.07 b	25.04 ± 6.53 ab	97.33 ± 2.31 a
BC	5.62 ± 1.32 a	38.50 ± 2.04 ab	28.62 ± 5.82 b	134.33 ± 49.94 b
CT	4.31 ± 0.57 b	37.47 ± 3.64 ab	22.90 ± 0.69 a	86.00 ± 10.54 a

Note: SM—straw mulching; SI—straw incorporation; BC—application of biochar; CT—conventional tillage without straw returning to the field. The data are the means ± standard deviation of three replicates. Duncan's multiple range test results show that different lowercase letters in the same column indicate significant differences in soil nutrients for straw-returning treatments ($p < 0.05$). Sample date: 23 October 2022.

After implementing various straw-returning methods, the soil nutrient content and storage underwent considerable changes (Table 2). The total available nutrient storage of SM, SI, and BC increased by 11.93%, 11.15%, and 32.39%, respectively, compared to CT. Analysis of nitrogen, phosphorous, and potassium storage in the arable layer revealed that different straw-returning measures had minimal impact on available nitrogen and phosphorus. However, they had a significant impact on organic carbon and available potassium. Compared to CT, SM, SI, and BC increased the storage of soil organic carbon and available potassium in the arable layer. BC treatment had the most significant effect, increasing the storage of organic carbon and available potassium by 32.16% and 58.02%, respectively, compared to CT ($p < 0.05$). These findings indicate that the application of biochar (BC) had a particularly positive influence on soil organic carbon and available potassium storage, leading to improved overall soil nutrient storage.

Table 2. Soil nutrient storage under different straw returning measures.

Experimental Treatment	Depth of Arable Layer (cm)	Bulk Density ($g \cdot cm^{-3}$)	Organic Carbon ($kg \cdot hm^{-2}$)	Available Nitrogen ($kg \cdot hm^{-2}$)	Available Phosphorus ($kg \cdot hm^{-2}$)	Available Potassium ($kg \cdot hm^{-2}$)	Total Available Nutrients ($kg \cdot hm^{-2}$)
SM	15	1.151 a	8083 ab	59.67 a	37.97 a	153.31 a	8333.95 ab
SI	15	1.074 b	7999 ab	71.21 b	42.10 ab	163.67 a	8275.98 ab
BC	15	1.108 ab	9517 a	65.14 ab	48.43 b	227.29 b	9857.86 a
CT	15	1.164 a	7201 b	62.67 ab	38.30 a	143.84 a	7445.81 b

Note: SM—straw mulching; SI—straw incorporation; BC—application of biochar; CT—conventional tillage without straw returning to the field. Duncan's multiple range test results show that different lowercase letters in the same column indicate significant differences in soil bulk density and nutrient storage for straw-returning treatments ($p < 0.05$).

3.2. Effects of Different Straw Returning Measures on Soil Moisture Content

Figure 2 illustrates the soil moisture content in the 0–40 cm soil layer under different straw returning measures. Among the treatments, SM resulted in the highest soil moisture content, followed by SI, CT, and BC at depths of 10, 20, 30, and 40 cm. At a depth of 10 cm, SM increased soil moisture content by 1.29%, 2.01%, and 1.60% compared to SI, BC, and CT, respectively. At a depth of 20 cm, BC exhibited lower soil moisture content compared to SM, SI, and CT, with reductions of 2.33%, 0.83%, and 0.45%, respectively. In the 30–40 cm soil layer, the average soil moisture content of SM was significantly higher than that of BC and CT by 1.90% and 1.75%, respectively ($p < 0.05$). When comparing SI to BC and CT, the average soil moisture content in the 30–40 cm soil layer increased by 0.52% and 0.37%, respectively. The soil moisture content of SM was consistently higher at each depth within the 0–40 cm soil layer compared to the other three treatments. Additionally, it can be observed that the soil moisture content of each treatment increased as the depth of the soil increased. At a depth of 40 cm, the soil moisture content of SM, SI, BC, and CT increased by 1.19%, 1.26%, 1.30%, and 0.98%, respectively, compared to that at a depth of 10 cm.

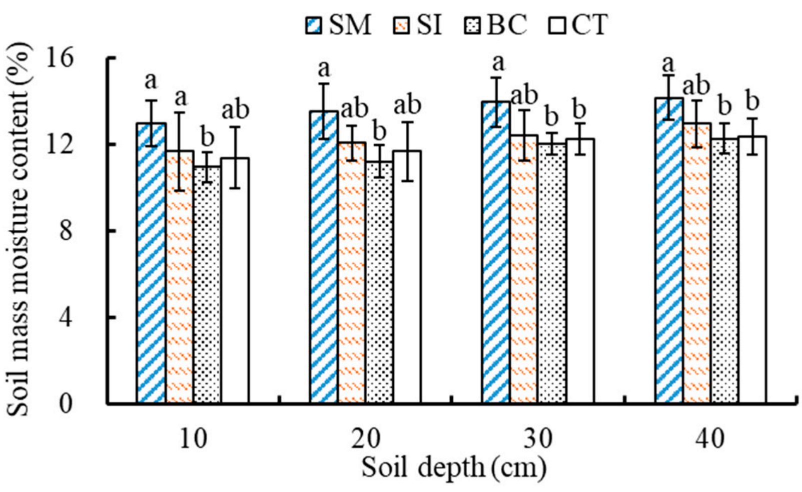

Figure 2. Soil mass moisture content at different depths under different straw returning measures. Different lowercase letters at the same soil depth indicate significant differences in soil mass moisture content for straw returning treatments according to Duncan's multiple range test ($p < 0.05$).

3.3. Effects of Different Straw Returning Measures on Soil Water Storage and Water Deficit

Figure 3 illustrates that the water storage in the 0–40 cm soil layer in SM was greater than that in SI, BC, and CT by an average of 5.89, 8.39, and 7.42 mm and was significantly different from those in SI BC, and CT at the end of the cotton growth period ($p < 0.05$). BC resulted in lower water storage in the 0–40 cm soil layer compared to SM, SI, and CT, with average reductions of 16.51%, 4.92%, and 1.91%, respectively. During the dry period with sparse rain in the middle of the growing season (August to September), the soil water storage of all treatments was drastically decreased. However, SM exhibited improved soil moisture retention in the 0–40 cm layer. On 27 August and 12 September, SM had an average increase of 2.27 mm in the 0–40 cm layer compared to CT. SI did not show significant differences in soil moisture retention compared to CT from July to September ($p > 0.05$). However, it substantially enhanced soil moisture at the end of the cotton growth period, with a water storage increase of 11.39 mm in the 0–40 cm soil layer compared to CT ($p < 0.05$).

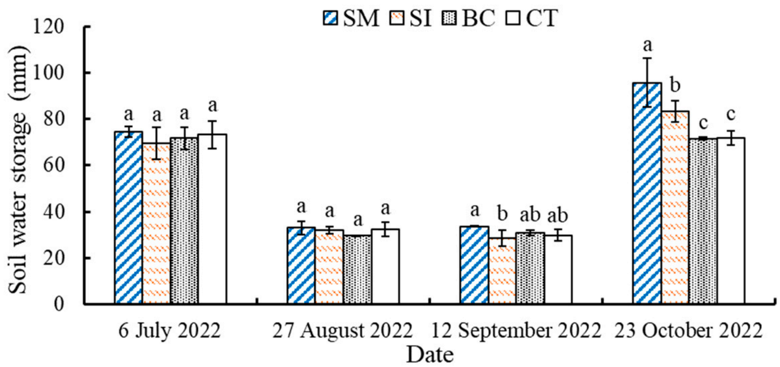

Figure 3. Variations in soil water storage under different straw returning measures. Different lowercase letters on the same date indicate significant differences in soil water storage for straw-returning treatments according to Duncan's multiple range test ($p < 0.05$).

The analysis in Table 3 reveals varying degrees of soil water deficits under different straw returning measures from July to October. Each treatment's soil water deficit in July was greater than 41%, with SI reaching a maximum of 45.59%. August and September were characterized by scorching weather and limited rainfall, resulting in severe soil water deficits for all treatments. The deficits were above 73%, with SI reaching 78% in September. The rise in October rainfall contributed to a reduction in the soil water deficits of all treatments. SM had the lowest soil water deficit (25.25%), which was significantly lower than the deficits of SI, BC, and CT by 9.63%, 18.87%, and 18.53%, respectively ($p < 0.05$). Compared to CT, SM had a smaller soil water deficit in the months of July, August, September, and October, with reductions of 1.13%, 0.47%, 3.08%, and 18.53%, respectively. These findings demonstrate that straw mulching effectively reduces soil water deficit and improves soil water storage.

Table 3. Soil water deficit (%) under different straw returning measures.

Experimental Treatment	Date (Year/Month/Day)			
	6 July 2022	**27 August 2022**	**12 September 2022**	**23 October 2022**
SM	41.70 ± 1.82 a	74.22 ± 2.19 a	73.67 ± 0.27 a	25.25 ± 8.24 a
SI	45.59 ± 5.38 a	75.06 ± 1.18 a	77.72 ± 2.71 b	34.88 ± 3.56 b
BC	44.04 ± 3.67 a	76.93 ± 0.23 a	75.99 ± 0.87 ab	44.12 ± 0.43 c
CT	42.83 ± 4.58 a	74.69 ± 2.29 a	76.75 ± 1.94 ab	43.78 ± 2.39 c

Note: The data are the means ± standard deviation of three replicates. Different lowercase letters on the same date indicate significant differences in soil water deficit for straw returning treatments according to Duncan's multiple range test ($p < 0.05$).

3.4. Effects of Different Straw Returning Measures on the Height and Chlorophyll Content of Cotton Plants

All treatments throughout the experiment showed an increasing trend in cotton plant height over time, as seen in Figure 4. SM had the most significant increase in plant height among the four treatments. By the end of the growth period, the plant height in the SM treatment had increased by 27.67 cm compared to the beginning of the growth period. The growth rate of plant height in SM reached 66.87%, which was higher by 6.17 cm, 5.00 cm, and 11.17 cm than that of SI, BC, and CT, respectively. The growth rates of plant height for SI and BC treatments were 34.61% and 24.24%, respectively. The cumulative plant height growth for SI and BC treatments was 5 cm and 6.16 cm more than that of the CT treatment. These results indicate that straw mulching, straw incorporation, and biochar application all successfully promote cotton plant height growth. Among them, straw mulching had the most significant impact, resulting in robust nutritional development in cotton plants.

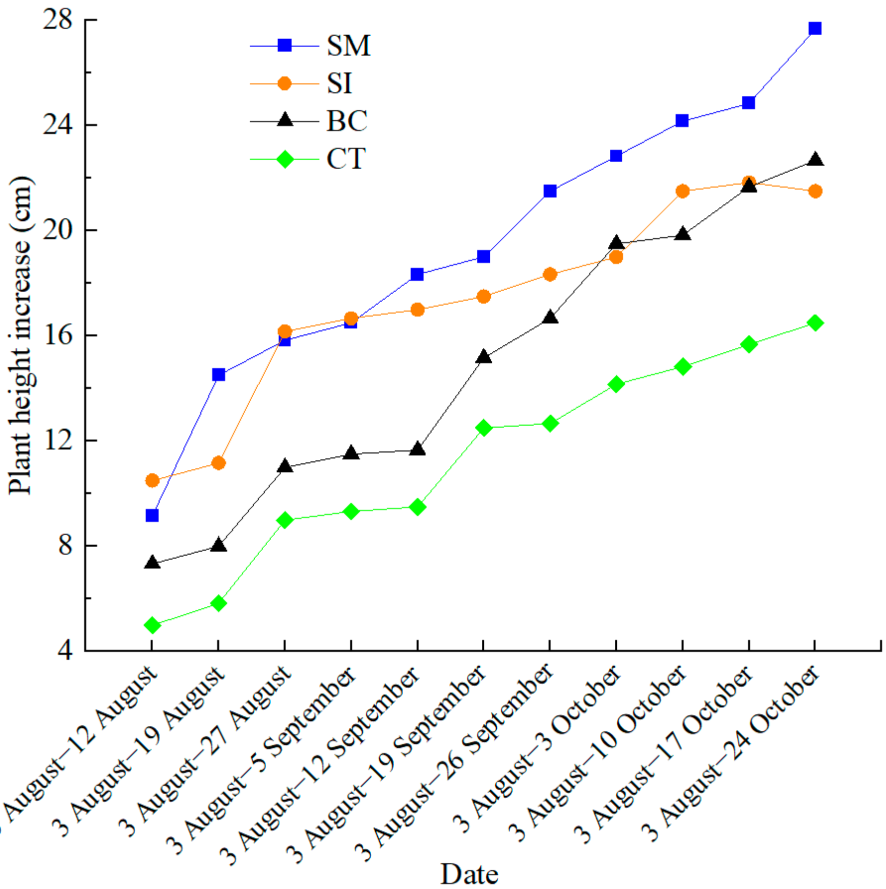

Figure 4. Height growth of cotton plants under different straw returning measures. Each point on the graph shows the growth in cotton plant height over the corresponding period, which is calculated by deducting the plant height at the start of the period from the plant height at the conclusion of the period.

As shown in Figure 5, at the cotton bud stage, BC exhibited a slightly higher chlorophyll content compared to SM, SI, and CT. The differences in chlorophyll content were 4.66%, 1.66%, and 0.53%, respectively. At the boll opening stage, SM had a higher chlorophyll content compared to SI, BC, and CT. The differences in chlorophyll content were 10.77%, 3.01%, and 0.82%, respectively. These findings suggest that the use of biochar can result in higher chlorophyll content in cotton plants during the early growth stage. However, at the end of the cotton growth period, straw mulching emerged as an efficient method to increase the chlorophyll content in plant leaves.

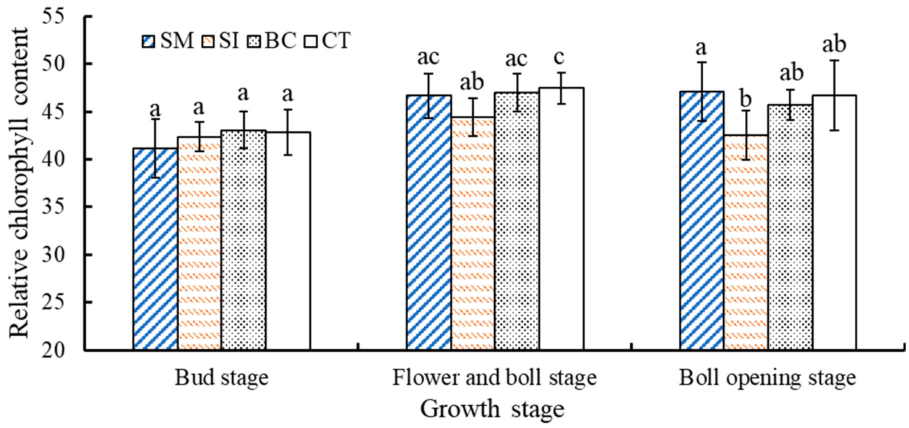

Figure 5. Effects of different straw returning measures on cotton's chlorophyll content. Different lowercase letters at the same growth stage indicate significant differences in relative chlorophyll content for straw-returning treatments according to Duncan's multiple range test ($p < 0.05$).

4. Discussion

4.1. Effects of Different Straw Returning Measures on Soil Nutrients

Soil nutrient content plays a vital role in plant growth and is an essential indicator of soil fertility and ecosystem health in agriculture [25,26]. Crop straw is rich in nutrients, such as carbon, nitrogen, phosphorus, and potassium, making it a valuable source for replenishing soil nutrients lost through erosion and crop uptake, thus enhancing soil fertility and preventing fertility decline [27,28]. The results of this study demonstrate that different straw-returning measures, including straw mulching, straw incorporation, and biochar application, have a significant impact on increasing soil carbon, nitrogen, phosphorus, and potassium levels (Tables 1 and 2). The direct effect of returning straw is to raise soil nutrient levels by introducing mineral nutrients and organic matter into the soil [29,30]. Straw and biochar, both rich in organic carbon, increase the organic matter content in the soil. The addition of biochar and straw enhances the availability of bioavailable carbon, providing energy for soil microorganisms and promoting nitrogen mineralization [31,32]. The presence of phosphorus in biochar and straw increases the availability of phosphorus in the soil, while the ash in biochar contains potassium salts that raise the availability of potassium while enhancing the efficiency of organic matter conversion [33,34]. Consequently, the application of straw and biochar enhances the availability of nitrogen, phosphorus, potassium, and organic carbon in the soil. The increase in soil nutrients can be attributed to the abundant nutrient elements present in straw and biochar. Overall, all straw-returning methods contribute to varying degrees of soil fertility improvement and nutrient enrichment (Tables 1 and 2). Among them, straw carbonization (biochar) exhibited the most significant accumulation of soil nutrients (Table 2). The findings of this study align with previous research [35–37], which has shown that biochar can be utilized as a soil amendment to improve soil fertility, increase carbon stocks, and enhance soil organic matter. Furthermore, the addition of biochar to soil can augment the soil's surface area and cation exchange capacity, leading to increased nutrient adsorption, particularly for nitrogen, phosphorus, and potassium, and subsequently enhancing their availability in the soil. In this study, straw mulching and straw incorporation also contributed to the enrichment of soil nutrients, but their impact was comparatively less significant compared to the application of biochar (Tables 1 and 2). This finding is consistent with other relevant research [38]. One possible explanation is that straw undergoes a process of decomposition and mineralization after being returned to the field, resulting in a delayed release of nutrients. Additionally, there may be a competition for nutrients between mineralized microorganisms and crop roots, further influencing nutrient availability.

4.2. Effects of Different Straw Returning Measures on Soil Moisture Status

Soil moisture plays a crucial role in crop development, especially in regions with low precipitation and high evaporation rates. Insufficient soil moisture is a primary limiting factor for crop growth [39], and soil evaporation is a significant mechanism through which water is lost in agricultural land [40]. To optimize water use efficiently and enhance agricultural productivity, it is essential to minimize ineffective water loss, reduce soil evaporation, and maximize water retention in the soil for crop growth and development [41]. The findings of this study indicate that straw mulching practices have a positive impact on soil water storage and reduce soil water deficit (Figure 3 and Table 3). These outcomes are consistent with previous research [42]. The presence of straw mulch creates a loose and porous covering that minimizes soil evaporation and slows down the rate of soil moisture loss. Additionally, when the straw is spread on the soil surface, it has the capability to absorb natural rainfall and irrigation water, prolonging the duration of water interaction with the soil and increasing water infiltration into the soil. Consequently, by controlling crop evaporation and facilitating the penetration of precipitation, straw mulching enhances soil moisture status. This study reveals a contradictory result, as it suggests that biochar application decreases the soil's water retention capacity (Figure 2). This finding conflicts with previous research indicating that biochar can enhance water retention in soils. One possible explanation is that the incorporation of biochar into the soil introduces organic matter containing hydrophobic groups, which can reduce water retention [43]. Biochar exhibits water-repellent properties, causing water to remain as liquid droplets on the soil surface, impeding long-term infiltration and leading to increased water evaporation [44]. Additionally, the experiment was conducted in a dry and hot climate with limited rainfall. The black color of biochar, when added to the soil, intensifies soil heat absorption and reduces surface reflectivity, resulting in elevated soil temperatures and accelerated soil moisture evaporation, leading to decreased soil moisture levels. The above explanations have been confirmed in relevant studies [45,46]. Furthermore, straw incorporation in this study did not improve the soil's water storage capacity during the dry months of July through September (Figure 3). This lack of improvement could be attributed to the increased porosity and permeability of the topsoil due to straw incorporation, resulting in excessive soil looseness, high evaporation rates, and poor water retention. As indicated in Table 2, the straw incorporation treatment exhibited the lowest soil bulk density (1.074 g/cm^3), significantly lower than that of bare land (1.164 g/cm^3) and straw mulching treatment (1.151 g/cm^3) ($p < 0.05$). This suggests that incorporating straw into the soil alters the structure, making it porous and loose, which consequently accelerates soil moisture evaporation under drought conditions, in line with relevant conclusions from other studies [47].

4.3. Effects of Different Straw Returning Measures on Cotton's Chlorophyll Content

Chlorophyll, as the primary pigment in plant photosynthesis, plays a crucial role in photosynthetic activity, nutrient content, crop health, and ultimately crop yield. It serves as a vital indicator for measuring crop growth [48,49]. The SPAD value, which represents the chlorophyll content in plant leaves, has become a valuable tool for assessing vegetation development [50]. Chlorophyll is a fundamental photosynthetic pigment involved in the process of photosynthesis and serves as a key determinant of photosynthetic capacity. The chlorophyll content, to a certain extent, determines the photosynthetic rate and the production of photosynthetic products. Insufficient chlorophyll content leads to reduced photosynthetic rates, hampering the generation of organic matter and energy output, ultimately negatively impacting crop yields. Moreover, dynamic changes in chlorophyll content also serve as an indicator of plant age, as crops with strong yields tend to possess long-lasting green leaves [51,52]. Previous studies have indicated that the application of appropriate straw mulch to wheat can significantly enhance its chlorophyll content and photosynthetic rate [53]. The results of this study indicate that straw mulching had a positive effect on the chlorophyll content of cotton leaves, particularly after the flower and boll stages (Figure 5). This improvement can be attributed to several factors. Firstly, straw mulching enhances soil nutrient availability and water retention, providing favorable conditions for crop growth and development. By improving the overall growth environment for crops, straw mulching increases the chlorophyll content in leaves, delays leaf senescence, and enhances the photosynthetic properties of cotton plants. However, it is important to note that straw incorporation and biochar application, although contributing to some improvement in soil nutrient levels (Tables 1 and 2), resulted in decreased soil water storage and exacerbated soil water deficit compared to bare land during the primary growth period of cotton (July to September). Straw incorporation led to reduced soil water storage and increased soil water deficit in July, August, and September compared to bare land (reducing soil water storage by 3.54 mm, 0.48 mm, and 1.25 mm, respectively, and increasing soil water deficit by 2.76%, 0.37%, and 0.97%, respectively) (Figure 3 and Table 3). Similarly, biochar application in July and August resulted in decreased soil water storage (reducing storage by 1.55 mm and 2.87 mm, respectively, compared to bare land) and increased soil water deficit (increasing deficit by 1.21% and 2.24%, respectively) (Figure 3 and Table 3). It is worth noting that the experimental period from July to September coincided with extremely high temperatures and prolonged drought conditions without significant rainfall. The recorded temperatures in July, August, and September were exceptionally high, reaching 39.8 °C, 41.8 °C, and 35.6 °C, respectively, while the corresponding rainfall amounts were significantly low, with only 130.4 mm, 32.8 mm, and 16.4 mm recorded (Figure 1). Soil moisture plays a dominant role in crop growth and development, and the negative effects of straw incorporation and biochar application on soil moisture outweighed the potential benefits of improved soil nutrient availability. Consequently, this had a limiting impact on the growth of cotton plants.

5. Conclusions

The results of the study demonstrate that straw mulching (SM), straw incorporation (SI), and biochar application (BC) have positive effects on soil nutrient levels. In particular, BC and SM contribute to increased storage of organic carbon and available potassium in the soil's cultivation layer. SM enhances soil water storage in the 0–40 cm soil layer throughout the entire growth period, effectively reducing soil water deficit. However, during the drought period from July to September, SI leads to a decrease in water storage in the 0–40 cm soil layer. At the end of cotton growth, SI increases water storage in the 0–40 cm soil layer by 11.39 mm compared to CT ($p < 0.05$). Throughout the entire growing period, BC has had a negative impact on soil moisture content. Additionally, SM, SI, and BC all promote the height growth of cotton plants. SM specifically increases the chlorophyll content of leaves at the end of cotton growth.

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