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Effects of biochar and irrigation regime on soil carbon and nitrogen distribution in wheat fields: A two-year field study

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Abstract: To clarify the responses of soil carbon and nitrogen to biochar amendment under deficit irrigation, a two-year field experiment was conducted in wheat fields of northern Xinjiang with a completely randomized block design. Four biochar rates (0, 10, 20, 30 t/ha, namely B0-B3) and three irrigation regimes were set. Irrigation volumes were 4500, 4050 and 3600 m³/ha in 2021 (namely W0, W1, W2), and adjusted to 4500, 4050 and 3825 m³/ha in 2022 (namely W0, W1, W2'). Two-way ANOVA was used to analyze the main and interactive effects of biochar dosage, irrigation level and experimental year on all indicators. The results revealed that biochar application significantly increased soil organic carbon (SOC) and total nitrogen (TN) contents. Biochar and irrigation exerted significant interactive effects on SOC in the second year ($P < 0.05$). SOC and TN were higher in the 0-20cm soil layer than in the 20-40cm layer. The B2W1 treatment had the highest SOC and TN levels, which were 23.33% and 22.46% higher than those of B0W1, respectively. Biochar significantly regulated SOC and TN contents in 0.25-2mm soil aggregates across both soil layers. The TN contribution proportion of soil aggregates was markedly affected by biochar addition and irrigation reduction. In the second year, more than 40% of soil TN was distributed in 0.25-2 mm aggregates, and its contribution trend was consistent with that of SOC. Both treatments significantly affected wheat yield ($P < 0.05$). Proper biochar application combined with moderate irrigation reduction improved grain yield, which increased first and then decreased with reduced irrigation and increased biochar input. Collectively, the optimal biochar application rate was 10-20 t/ha, and the recommended irrigation volume was 4050 m³/ha with a 10% reduction. This matching pattern can achieve efficient water saving and stable soil carbon sequestration in irrigated farmlands.

Keywords: biochar; irrigation regime; aggregates; organic carbon; total nitrogen

Introduction

It is postulated that biochar, a porous organic soil amendment, possesses strong water retention capacity, which can improve irrigation water use efficiency and boost crop water productivity¹⁻³. A study by Cakmakc⁴ revealed that applying 1% biochar under 50% deficit irrigation effectively increased irrigation water productivity and achieved water conservation. Singh⁵ reported that the application rate of 13 t·hm⁻² biochar enabled 70% crop evapotranspiration irrigation to replace full irrigation in sweet corn cultivation. Moreover, numerous studies have confirmed that biochar can improve agricultural productivity, facilitate soil carbon sequestration and reduce carbon emissions⁶⁻⁷. An 8-year field trial conducted by Sun⁸ demonstrated that long-term biochar addition elevated soil organic carbon content. Qian⁹ further indicated that 3% biochar addition not only improved soil fertility but also promoted crop growth.

Irrigation farmlands in northern Xinjiang are core grain-producing areas and typical oasis agricultural zones. Soil fertility degradation and water resource shortage are two major constraints limiting local crop production. Therefore, exploring feasible approaches to improve soil quality and realize agricultural water conservation is of great practical significance for irrigated farming regions. Biochar application has been widely adopted to stabilize and promote crop yields in northern Xinjiang's irrigated farmlands. Existing relevant studies mainly focus on the combined application of biochar and chemical fertilizers, soil salinization improvement and heavy metal remediation¹⁰⁻¹².

Despite abundant prior investigations, few studies have systematically clarified the coupled effects of biochar addition and regulated irrigation regimes on field water-saving potential and soil carbon sequestration performance. The specific mechanisms underlying how biochar regulates soil carbon and nitrogen distribution under different irrigation quotas remain poorly understood. Clarifying both short-term and long-term effects of biochar application on field water use efficiency as well as soil carbon and nitrogen allocation is essential to alleviate regional water supply-demand conflicts and promote the sustainable development of oasis irrigation agriculture.

Against this background, a two consecutive years of field experiment (2021-2022) was

conducted in typical oasis agricultural areas of northern Xinjiang to explore the effects of biochar application on soil carbon and nitrogen distribution characteristics. By setting varied irrigation quotas, this study further analyzed the response patterns of soil carbon and nitrogen dynamics to irrigation regulation. The main research objective was to quantify the variations in soil carbon and nitrogen contents across different soil aggregate fractions, soil layers and experimental years under combined biochar addition and regulated irrigation treatments.

We formally proposed two quantitative testable hypotheses: (i) Specified dosages of biochar combined with appropriate irrigation quotas can markedly increase soil carbon and nitrogen concentrations, with more prominent improvement effects observed in macroaggregates; (ii) Rational biochar application rates can simultaneously raise wheat yield, reduce irrigation water input and accumulate more soil organic carbon. The findings of this study can provide theoretical basis and technical support for formulating biochar-based water-saving irrigation management practices in arid oasis irrigated regions.

1. Materials and Methods

1.1 Overview of Experimental Plots

A stationary experiment was conducted at the Qitai Wheat Experiment Station between 2021 and 2022. The station is located at an altitude of 1174 meters (42°45'-45°29'N, 89°13'-91°22'E). The meteorological data for the experiment station are as follows: the climate is temperate continental semi-desert semi-arid, with an average annual temperature of 5.5°C, an average temperature of 23.7°C in July and a maximum temperature of 39°C. The mean temperature in January is -18.9°C. The annual mean relative humidity is 60%. The period of the time during which frost is not a concern lasts for 153 days, spanning from late April to early October. The mean annual precipitation is 269.4 mm. The irrigated desert soil properties are as follows: pH 8.3, salt content 1.4 g·kg⁻¹, organic matter content 13.8 g·kg⁻¹, total nitrogen content 2.2 g·kg⁻¹, rapidly available phosphorus content 11.4 mg·kg⁻¹, rapidly available potassium content 147.0 mg·kg⁻¹, and alkaline hydrolysis nitrogen content 128.7 mg·kg⁻¹.

1.2 Materials

The biochar utilized in the experimental procedure was produced from maize straw and obtained from Liaoning Jinhefu Agricultural Science and Technology Co. Ltd in China. This biochar was prepared via carbonization for 4 h at 450 °C and had a particle size of 1.5-2.0 mm, a H/C of 0.52, a pH of 9.3, total nitrogen content of 21.8 g·kg⁻¹, total phosphorus of 10.6g·kg⁻¹, total potassium of 21.5g·kg⁻¹, available nitrogen of 5.4mg·kg⁻¹, and available phosphorus of 200.9 mg·kg⁻¹.

1.3 Experimental Design

A two-factor randomized complete block design was employed for the field test. The study involved the application of varying amounts of biochar: 0 t/ha (B0), 10 t/ha (B1), 20 t/ha (B2), and 30 t/ha (B3). In 2021, the irrigation volume was 4500 m³/ha (W0), 4050 m³/ha (W1, representing a 10% reduction in water usage), and 3600 m³/ha (W2, representing a 20% reduction in water usage). Because the 20% irrigation reduction (W2) caused a severe yield loss in 2021, we adjusted the irrigation amount to 85% of the normal level in the second year. In 2022, the irrigation volume was 4500 m³/ha (W0), 4050 m³/ha (W1), and 3825 m³/ha (W2', representing a 15% water reduction in water usage). Consequently, a total of 12 experimental plots were established, each comprising three replicates. The wheat was planted in rows with a distance of 0.2 meters between them and a density of 450×10⁴ hm⁻². In 2021, biochar was utilized as a basal fertilizer at a depth of 30 cm beneath the tillage layer. No further application of biochar were made. The remaining management practices were in accordance with the established norms within their respective domains.

1.4 Measurement Items and Methods

1.4.1 Soil Sample Collection and Sieving

A five-point sampling procedure was used to collect soil samples following the winter wheat harvest. In 2021, samples were collected at a depth of 0-30 cm. In 2022, samples were collected at depths of 0-20 cm (S1) and 20-40 cm (S2). The samples were then air-dried in a well-ventilated, shaded area. Soil aggregate fractions were determined using a dry-sieving method. Specifically, a 500g air-dried soil sample was manually sieved for 2-3 minutes through a set of sieves with mesh sizes of 2mm, 0.25mm, and 0.053mm. After allowing the particles to settle for one minute, the aggregates retained on each sieve were weighed and

stored in separate bags.

1.4.2 Determination of Soil Organic Carbon Levels

Soil organic carbon content was determined using the potassium dichromate external heating method. For each group, a 0.5 g sample of ground, sieved soil was placed into a conical flask, followed by the addition of 10 mL of 1 mol·L⁻¹ K₂Cr₂O₇ solution. The flask was rotated to ensure thorough mixing, after which 10 mL of concentrated H₂SO₄ was added while gently swirling for one minute. The mixture was then allowed to stand for 30 minutes. Subsequently, the solution was diluted with deionized water to a final volume of 250 mL. Five to six drops of phenanthroline indicator were added, and the solution was titrated with 0.5 mol·L⁻¹ FeSO₄ solution.

1.4.3 Measurement of the Soil Nitrogen

Total soil nitrogen was determined using the Kjeldahl method. For each group, three replicate 0.5 g samples of ground, sieved soil were placed into dry digestion tubes. Then, 2g of catalyst (K₂SO₄:GuSO₄:Se=100:10:1) and 5 mL of concentrated H₂SO₄ were added. Digestion was carried out on a digestion furnace. After digestion was complete, the solution was allowed to cool, followed by the addition of 20mL of 10mol·L⁻¹ NaOH solution. The resulting mixture was then transferred to a semi-automatic Kjeldahl nitrogen analyzer for total nitrogen measurement.

1.4.4 Calculation of Organic Carbon and Nitrogen Contribution Rates of Soil Aggregates

The contribution rate of soil organic carbon (SOC) or total nitrogen (TN) for a given aggregate size fraction was calculated using the following formula:

$$CR_i = \frac{C_i \times M_i}{T} \times 100\%$$

$$M_i = \frac{\text{mass of aggregates in fraction } i}{\text{Total mass of all aggregates}} \times 100\%$$

Where: CR_i is the contribution rate (%) of SOC or TN from the 'i'-th aggregate size fraction (e.g., >2 mm, 2-0.25 mm) to the total SOC or TN in the bulk soil; C_i is the content of SOC or TN (g·kg⁻¹) measured within the 'i'-th aggregate size fraction; M_i is the mass proportion (%) of the 'i'-th aggregate size fraction relative to the total mass of all soil aggregates; T is the total content of SOC or TN (g·kg⁻¹) in the bulk soil (unfractionated soil).

The SOC and TN contents in each aggregate fraction (C_i) were determined as described in

sections 1.4.2 and 1.4.3, respectively. The mass proportion (M_i) of each aggregate fraction was obtained from the dry-sieving procedure described in section 1.4.1.

1.4.5 Measurement of Wheat Yield

In each plot, a representative 1m² area with uniform crop growth was selected to measure the number of effective panicles prior to harvest. After threshing and natural air-drying, the grain weight from the 1 m² area was recorded. The thousand-grain weight and grain yield were then calculated based on a moisture content of 13%. Taking factor A (biochar application rate) and factor B (irrigation water amount) as independent variables, and yield Y as the dependent variable, a quadratic polynomial multiple regression fitting was conducted to obtain the regression equation.

1.4.6 Statistical analysis

All the statistical analyses were performed using Design Expert 11 (Vela Software, Inc., Toronto, Canada) and DPS 7.05 (Ruifeng Information Technology Co., Ltd, Hangzhou, China), and drawn with origin 2021 (MicroCal, Inc., Hampton, USA). The comparisons of treatment means were performed using Duncan's new multiple range test at $P < 0.05$.

2. Results and Analysis

2.1 Soil Organic Carbon Content

Soil organic carbon (SOC) content was significantly regulated by biochar application rate and irrigation regime. As illustrated in Figure 1, biochar incorporation effectively increased soil SOC concentration, whereas severe irrigation deficit (W2, W2') reduced SOC accumulation. Meanwhile, SOC content in the second year was lower than that in the year when biochar was first applied. Under the same irrigation condition, soil SOC content increased initially and then decreased with the rise in biochar dosage, and the 20 t/ha biochar treatment (B2) obtained the highest SOC level. In the biochar application year, the B2W0 group had the maximum SOC content; relative to B0W0, the SOC content of B2W1 increased by 29.19% and 22.01%, respectively. In the subsequent year, B2W1 showed the highest SOC value, which was 60.78% higher than that of B0W0. Moderate irrigation reduction was conducive to SOC accumulation. Specifically, 10% irrigation reduction greatly promoted SOC content under B2 treatment in the second year, while excessive

water shortage led to a distinct decline in SOC. Under 10% reduced irrigation, biochar dosage exerted a significant influence on soil SOC content ($P < 0.05$). In all treatments, SOC content in the 0-20 cm topsoil layer (S1) was consistently higher than that in the 20-40 cm subsoil layer (S2). In particular, SOC content in B2W1 was 23.33% higher than that in B0W1, suggesting that the combination of 20 t/ha biochar and 4050 m³/ha irrigation was the optimal pattern to facilitate soil SOC sequestration.

2.2 Soil Aggregate Organic Carbon Contents

Biochar amendment significantly increased organic carbon content in soil aggregates. Irrigation volume exerted a notable influence on organic carbon levels in 0.25-2 mm aggregates across different biochar application rates (B1, B2, B3). Overall, aggregate-associated organic carbon content first increased and then decreased with decreasing irrigation amount. Throughout the experiment, organic carbon content of soil aggregates in the 0-20 cm topsoil layer (S1) was consistently higher than that in the 20-40 cm subsoil layer (S2).

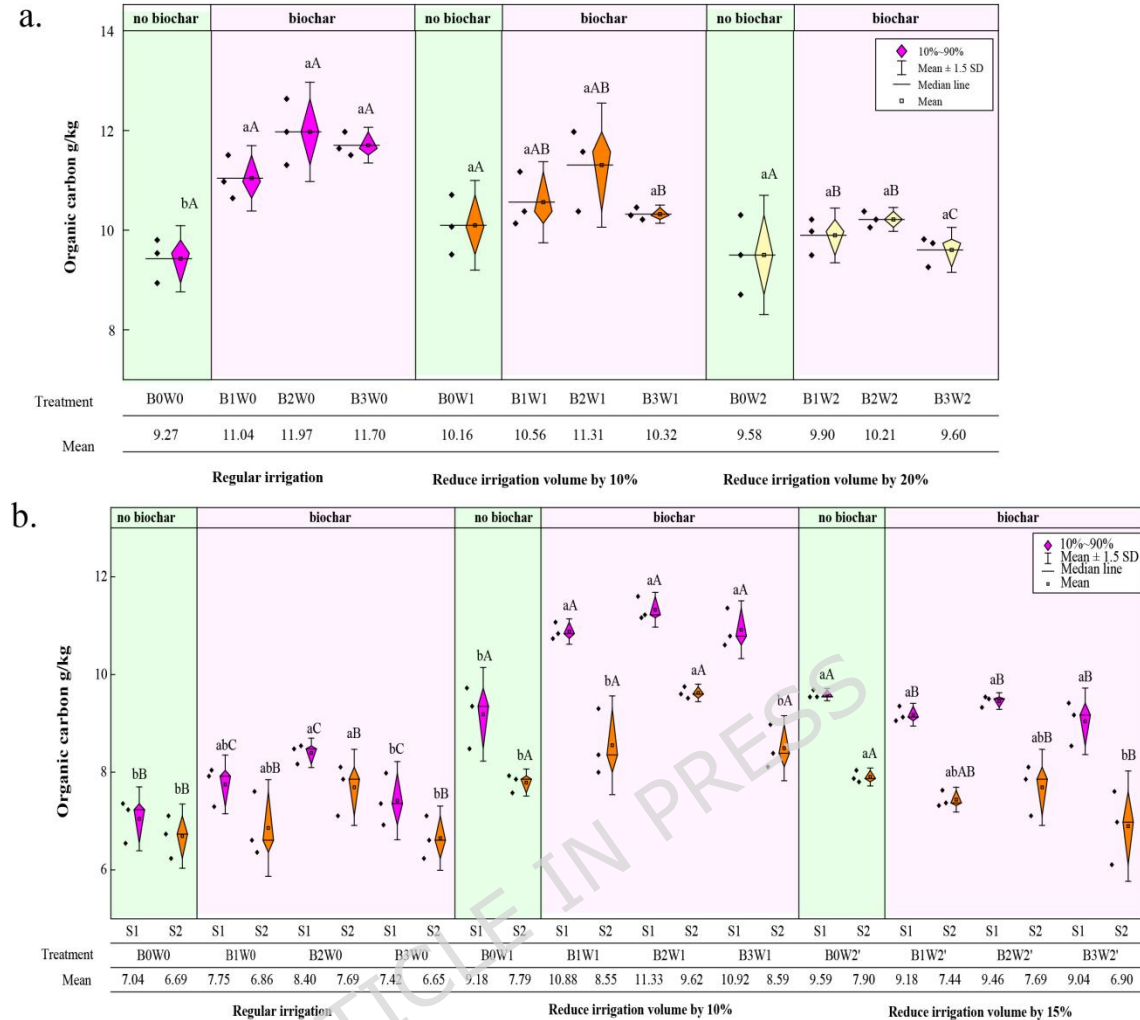


Figure 1 Contents of organic carbon in soil in different groups in 2021 and 2022

Note: In this figure, a and b represent the contents of total nitrogen in the soil in different groups in 2021 and 2022, respectively; S1 and S2 represent the 0-20 cm layer and the 20-40 cm layer.

Different lowercase letters indicate that there are significant differences among treatments under the condition of consistent irrigation water level, and different capital letters indicate that there are significant differences among treatments under the condition of consistent biochar application amount, the same below.

Aggregate organic carbon content rose first and then declined with increasing biochar application rates. Biochar exerted the most prominent promoting effect on organic carbon within 0.25-2 mm aggregates. In the topsoil layer (S1) under 10% irrigation reduction (W1), the organic carbon content of these aggregates in the B2W1 treatment was 24.27% higher than that in the B0W1 treatment. Under 15% irrigation deficit (W2), the 10 t/ha biochar

treatment (B1) reduced organic carbon content across all aggregate fractions relative to B0W2. By contrast, the 20 t/ha biochar application (B2) effectively increased organic carbon content in all soil aggregate sizes under the same water deficit condition.

Table 1 Contents of organic carbon in soil aggregates of different groups in 2022 (g·kg⁻¹)

Treatment t	Particle size of aggregates /mm							
	S1 (0-20 cm)				S2 (20-40 cm)			
	>2	2~0.25	0.25~0.05 3	<0.053	>2	2~0.25	0.25~0.05 3	<0.053
CK	6.57±0.5 2e	6.82±1.2 3d	7.56±0.2 9f	7.23±0.86c	5.15±0.5 8d	6.15±1.04 d	7.65±0.29 bcd	7.81±0.76c d
B1W0	7.07±0.7 6e	8.15±1.3 7cd	8.48±0.4 3de	7.32±1.04c	5.49±0.8 6cd	8.48±0.86 bc	6.32±0.76 de	7.15±0.29 d
B2W0	7.32±0.2 9e	9.23±0.8 6c	8.56±0.1 4cde	8.48±1.32 bc	6.65±0.2 9abc	8.81±1.60a b	6.98±0.86c de	8.31±0.29c d
B3W0	7.23±0.6 6e	7.23±0.8 6d	7.81±0.7 2ef	7.40±0.72c	5.49±0.5 0cd	7.65±0.29 bc	6.48±0.50 de	6.98±1.32 d
B0W1	8.89±0.5 2d	9.23±1.3 9c	9.39±0.1 5bc	9.23±1.95 b	7.32±0.7 6ab	7.95±0.06 bc	7.98±0.50 bc	7.91±0.40c d
B1W1	10.47±0. 25ab	10.89±0. 38ab	10.77±0. 10a	11.39±0.6 3a	7.65±0.5 7ab	8.70±0.25 bc	8.15±1.75 bc	9.71±0.25a b
B2W1	10.97±0. 25a	11.47±0. 66a	11.31±0. 63a	11.55±0.2 9a	7.98±1.0 0a	10.14±0.7 6a	9.96±0.45a	10.41±0.4 1a
B3W1	10.23±1. 08abc	11.17±0. 38a	10.89±0. 38a	11.38±0.1 3a	7.48±1.0 0ab	8.95±0.55a b	8.81±0.29a b	9.11±0.22 bc
B0W2'	9.67±0.1 8bcd	9.58±0.1 3bc	9.79±0.1 6b	9.31±0.38 b	7.49±0.1 3ab	7.96±0.08 bc	8.09±0.25 bc	8.07±0.10c d
B1W2'	8.98±1.5 2cd	9.44±0.1 0bc	9.06±0.7 6bcd	9.23±0.50 b	6.98±1.0 0ab	7.61±0.33 bc	7.53±0.05 bcd	7.63±0.30 d

B2W2'	9.11±0.2	9.51±0.1	9.39±0.1	9.81±0.38	6.82±0.2	8.81±0.76a	7.48±0.50	7.65±1.26
	3cd	0bc	5bc	b	9abc	b	bcd	d
B3W2'	8.95±0.8	8.32±0.1	9.23±0.9	9.68±0.27	6.31±1.0	7.32±0.76c	6.15±0.57e	7.81±1.26c
	4cd	5cd	0bcd	b	5bcd	d		d

2.3 Soil Aggregate Organic Carbon Contribution Rate

Biochar application exerted variable effects on the organic carbon (OC) contribution rate of soil aggregates across different treatment groups. Specifically, biochar amendment increased the OC contribution rate of 0.25-2 mm aggregates, though no significant differences were detected among biochar treatments. In both the 0-20 cm topsoil (S1) and 20-40 cm subsoil (S2) layers, OC input was predominantly derived from 0.25-2 mm aggregates, accounting for over 40% of the total OC contribution. The smallest aggregate fraction (<0.053 mm) exhibited the lowest OC contribution rate, at approximately 6%.

Under conventional irrigation and 10% irrigation reduction regimes, biochar addition significantly elevated the OC contribution rate of <0.053 mm aggregates. In contrast, when irrigation was reduced by 15%, biochar application led to varying degrees of decline in the OC contribution rate of this fine aggregate fraction.



Figure 2 Organic carbon contribution rate of soil aggregates of different groups in 2022

2.4 The Content of Total Nitrogen in Soil

Soil total nitrogen (TN) content was jointly regulated by irrigation volume and biochar application rate. As illustrated in Figure 3, biochar amendment significantly increased soil TN concentration. Under constant irrigation conditions, soil TN content first increased and then decreased with increasing biochar dosage. Additionally, TN levels were higher in the biochar application year than in the subsequent year.

The B2W0 treatment achieved the highest TN content, which was 67.24% higher than that of the B0W0 treatment. Across all treatments, TN content in the 0-20 cm topsoil layer (S1) was consistently higher than that in the 20-40 cm subsoil layer (S2). Specifically, the S1 layer of the B2W1 treatment had the maximum TN content, showing a 22.46% increase compared to the S1 layer of B0W0. In contrast, the S2 layer of the B0W2' treatment exhibited the lowest TN content, a 12.5% reduction relative to the S2 layer of B0W0. Notably, the combination of 20 t/ha biochar and 4050 m³/ha irrigation maintained the highest TN concentration in both the biochar application year and the subsequent year, outperforming all other treatment combinations.

2.5 Total Nitrogen Content in Soil Aggregates

Biochar amendment generally increased total nitrogen (TN) content in soil aggregates. Under constant irrigation conditions, aggregate TN content first increased and then decreased with increasing biochar dosage. Conversely, for each biochar application rate (B1, B2, B3), aggregate TN content followed the same increasing-then-decreasing trend as irrigation volume decreased. Throughout the experiment, aggregate-associated TN content in the 0-20 cm topsoil layer (S1) was consistently higher than that in the 20-40 cm subsoil layer (S2). Among different aggregate size fractions, the 0.25-2 mm fraction had the highest TN content. Biochar application exerted a positive effect on aggregate TN content at moderate rates, with the effect diminishing at higher dosages. Specifically, biochar notably elevated TN content in 0.25-2 mm and <0.053 mm aggregates. Under 10% irrigation reduction (W1), the B2W1 treatment showed the most significant TN increase (24.04%) compared to B0W1. Similarly, under 15% irrigation deficit (W2), the variation trend was consistent with that under 10% reduction, though no significant differences were detected among treatments. The B2W2 treatment exhibited the largest TN increment

(36.96%) relative to B0W2.

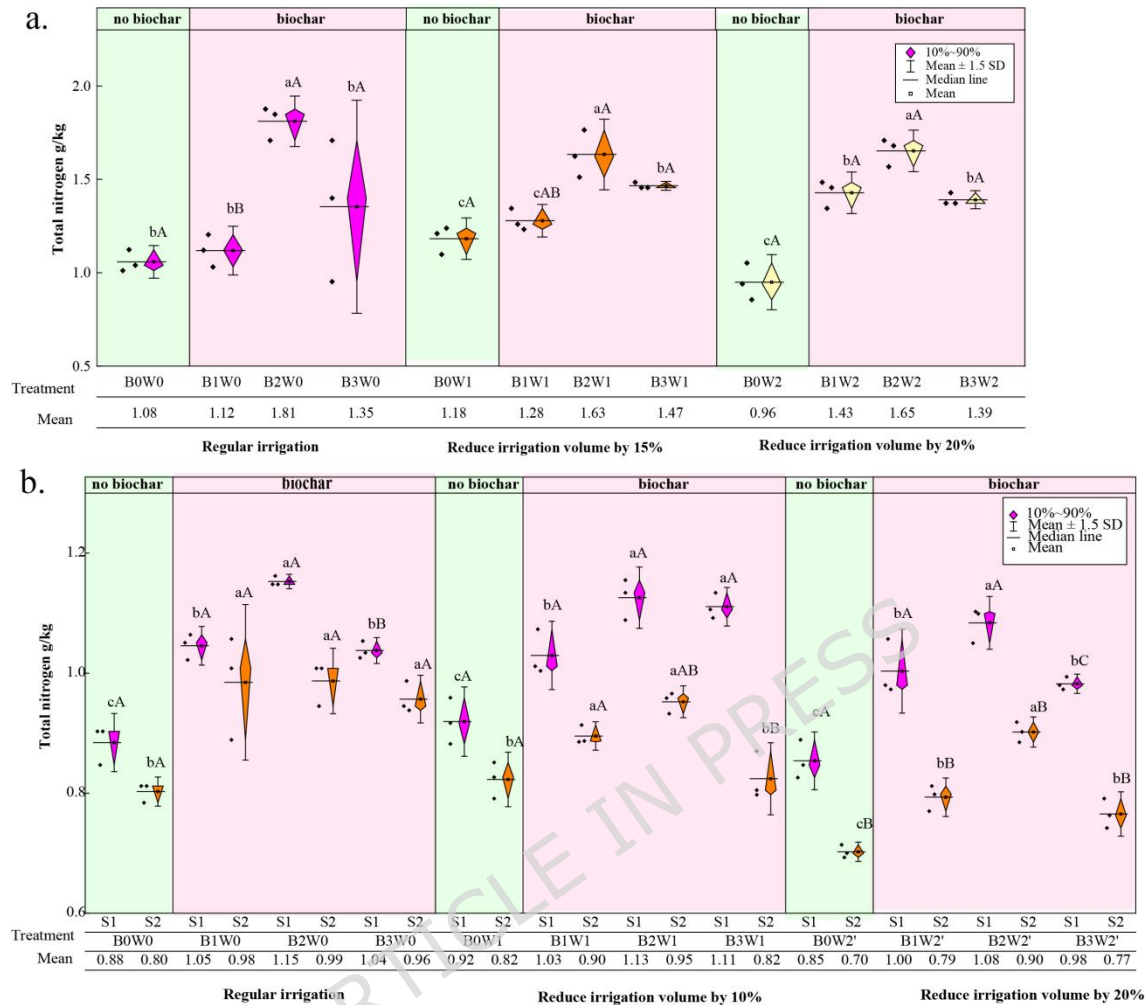


Figure 3 Contents of total nitrogen in soil in different groups in 2021 and 2022

Note: In this figure, a and b represent the contents of total nitrogen in the soil in different groups in 2021 and 2022, respectively. S1 and S2 represent the 0-20 cm layer and the 20-40 cm layer, respectively.

In the 20-40 cm subsoil layer (S2), total nitrogen (TN) content in 0.25-2 mm soil aggregates decreased with reducing irrigation volume. For treatments with the same biochar application rate, aggregate TN content consistently declined as irrigation amount decreased. Specifically, the B2W2 treatment (20 t/ha biochar + 15% irrigation reduction) had significantly lower aggregate TN content compared to the B2W0 treatment (20 t/ha biochar + conventional irrigation).

2.6 Total Nitrogen Contribution in Soil Aggregates

Different treatments generated distinct effects on the total nitrogen (TN) contribution rate of soil aggregates. Biochar addition increased the TN contribution rate of 0.25-2 mm aggregates, and no significant differences were detected among treatments. In both S1 (0-20 cm) and S2 (20-40 cm) soil layers, TN was mainly distributed in 0.25-2 mm aggregates, accounting for around 40% of the total. By contrast, the TN contribution rate of aggregates smaller than 0.053 mm was the lowest, only about 5%.

Under conventional irrigation and 10% irrigation reduction, biochar application markedly raised the TN contribution rate of <0.053 mm aggregates. Nevertheless, under 15% irrigation reduction, biochar addition decreased this proportion across all applied rates.

With biochar amendment and 10% irrigation reduction, the contribution rate of 0.25-2 mm aggregates first increased and then decreased. Among all groups, the B2W1 treatment showed the greatest promotion effect, with its TN contribution rate rising by 4.37 and 1.83 percentage points in S1 and S2 layers respectively relative to B0W1. When biochar application rate was fixed, the TN contribution rate of 0.053-0.25 mm aggregates varied obviously with changing irrigation amounts.

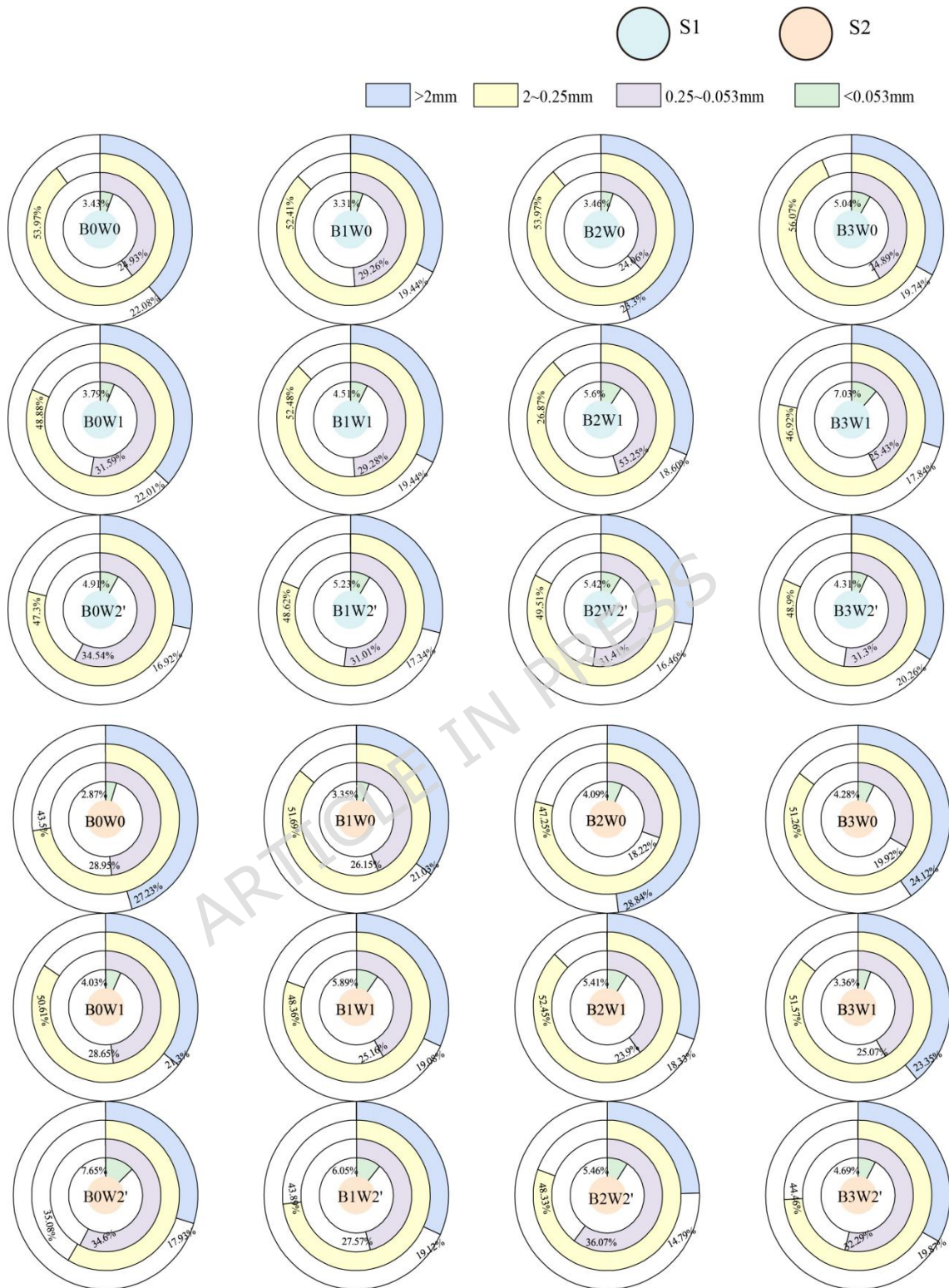


Figure 4 Total nitrogen contribution rate of soil aggregates of different groups in 2022

Table 2 Contents of total nitrogen in soil aggregates of different groups in 2022 ($\text{g}\cdot\text{kg}^{-1}$)

Treatmen t	Particle size of aggregates /mm							
	S1 (0-20 cm)				S2 (20-40 cm)			
	>2	2~0.25	0.25~0.05 3	<0.053	>2	2~0.25	0.25~0.05 3	<0.053
CK	0.78±0.0 8bc	1.00±0.0 7e	0.95±0.1 1e	0.80±0.10 de	0.67±0.0 5abcd	0.89±0.02 de	0.93±0.02 bc	0.72±0.04 d
B1W0	0.81±0.0 7bc	1.20±0.0 2abc	1.19±0.0 4ab	0.98±0.03c	0.78±0.2 6ab	1.05±0.04a bc	1.19±0.31a	0.91±0.03 b
B2W0	1.05±0.0 4a	1.33±0.1 6a	1.27±0.0 6a	0.97±0.17c	0.81±0.0 3a	1.11±0.04a	0.93±0.08 bc	1.09±0.06a
B3W0	0.85±0.0 6bc	1.23±0.0 1abc	1.12±0.0 5bcd	0.95±0.03c d	0.77±0.0 4ab	1.09±0.03a	0.89±0.08c	1.07±0.03a
B0W1	0.78±0.0 3bc	1.04±0.0 7de	1.11±0.0 9bcd	0.75±0.09e	0.70±0.0 2abc	0.93±0.04c de	0.91±0.06 bc	0.75±0.04c d
B1W1	0.79±0.0 9bc	1.22±0.0 3abc	1.18±0.0 3ab	0.92±0.07c d	0.70±0.0 3abc	1.00±0.00a bcd	0.83±0.06c	1.05±0.09a
B2W1	0.90±0.0 6b	1.29±0.0 2ab	1.24±0.0 2a	1.07±0.06 bc	0.72±0.0 1abc	1.08±0.01a b	0.91±0.02 bc	1.09±0.07a
B3W1	0.85±0.0 6bc	1.14±0.0 4cd	1.13±0.0 3bc	1.33±0.02a	0.66±0.0 2bcd	0.95±0.17 bcd	0.92±0.03 bc	0.77±0.06c d
B0W2'	0.72±0.0 4c	0.92±0.0 6e	0.97±0.0 9e	0.80±0.09 de	0.52±0.0 4d	0.61±0.06f	0.84±0.03c	0.84±0.03 bc
B1W2'	0.77±0.1 5bc	1.18±0.1 2bc	1.01±0.0 3de	1.06±0.10 bc	0.59±0.0 3cd	0.81±0.07e	0.85±0.04c	0.92±0.07 b
B2W2'	0.82±0.1 3bc	1.26±0.0 1abc	1.09±0.0 5bcd	1.17±0.03 b	0.61±0.0 2cd	1.02±0.02a bc	1.09±0.05a b	0.89±0.02 b
B3W2'	0.79±0.0 3bc	1.18±0.0 3bc	1.04±0.0 3cde	0.92±0.06c d	0.60±0.0 6cd	0.82±0.07e	0.87±0.03c	0.77±0.04c d

2.7 Wheat Yield

Irrigation amount exerted an extremely significant effect on spring wheat yield ($P < 0.01$). At a fixed biochar application rate, grain yield decreased gradually with the reduction in irrigation water. Under identical irrigation conditions, wheat yield increased first and then declined as biochar dosage rose. Severe water deficit at 3600 m³/ha (W2) and 3825 m³/ha (W2') led to yield reduction even with high biochar input. Overall, wheat yield was higher in the second experimental year than in the biochar application year.

In the first year, the maximum yield of 7437.6 kg/ha was recorded in the B1W0 treatment, followed by B2W0 (7353.88 kg/ha) and B1W1 (6884.8 kg/ha). In the second year, the B2W1 treatment achieved the highest yield of 8442.62 kg/ha. Under the irrigation level of 4050 m³/ha, biochar application at B1, B2 and B3 levels effectively improved wheat yield. Compared with B0W0, the yield increases of B1W1, B2W1 and B3W1 in the first year were 6.51%, 2.93% and 0.85%, respectively. In the second year, the yield increments reached 9.12%, 17.01% and 6.45%.

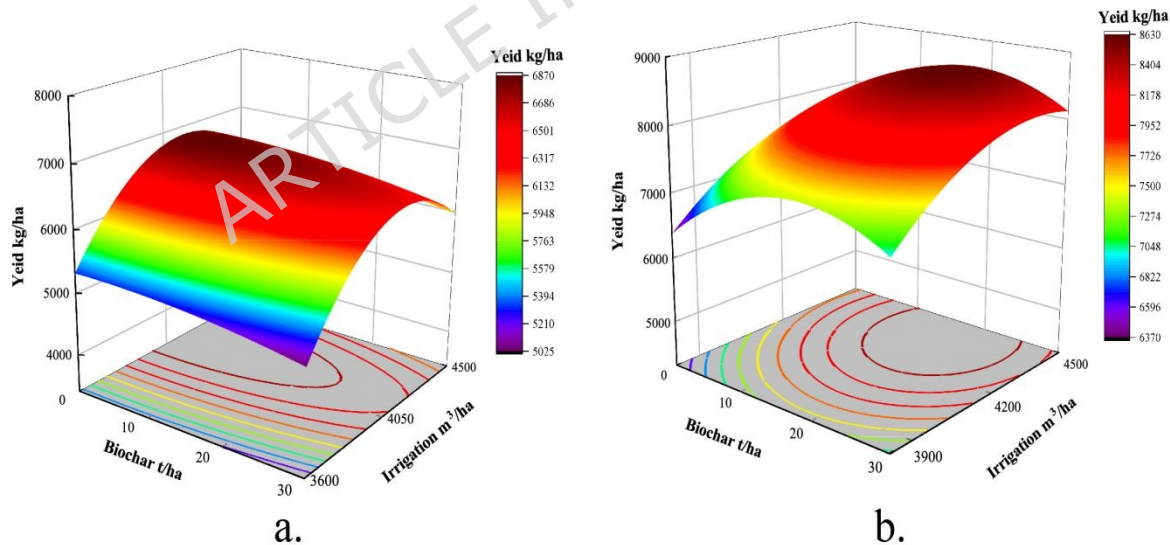


Figure 5 Wheat yield of different groups in 2021 and 2022

Note: Generated using OriginPro 2021 (based on fitting equation from Design Expert 11)

3. Discussion

3.1 Effects of biochar and irrigation on soil organic carbon and total nitrogen contents

Soil organic carbon (SOC) and total nitrogen (TN) are core indicators for evaluating soil fertility¹³. Consistent with previous studies, the present study confirmed that biochar amendment effectively elevated soil SOC and TN concentrations. Such increments are mainly attributed to the intrinsic high carbon property of biochar, which directly supplements soil carbon pools and raises overall SOC levels. In addition, abundant surface functional groups and charged sites on biochar can adsorb soil nitrogen nutrients and reduce nitrogen leaching loss, thereby retaining more nitrogen in topsoil and increasing soil TN storage¹⁴⁻¹⁷. As an important stable component of soil organic carbon, biochar helps maintain a reasonable soil C/N ratio, improves crop nutrient uptake capacity, and slows down the depletion of native soil carbon and nitrogen nutrients.

This study also found that soil SOC and TN contents in 2022 were lower than those measured in 2021. Regardless of experimental year, both SOC and TN in the 0-20 cm topsoil layer were significantly higher than those in the 20-40 cm subsoil layer, which was closely related to the surface accumulation distribution characteristics of incorporated biochar in field soil¹⁸⁻¹⁹.

3.2 Effects of biochar and irrigation on carbon and nitrogen distribution in soil aggregates

Soil aggregate formation and stability are largely governed by SOC substances, and higher SOC content is conducive to the formation of large-sized soil aggregates²⁰. Colloidal substances released from biochar can promote the aggregation of microaggregates into macroaggregates, and further increase the proportion of SOC bound in aggregates larger than 0.25 mm²¹. In this experiment, the 0.25-2 mm aggregates in topsoil exhibited the highest SOC concentration across all aggregate fractions²². Existing studies have verified that the mass proportion of >0.25 mm aggregates is significantly correlated with soil organic components, glomalin-related soil protein content and soil microbial community structure²³. With its developed porous structure and hydrophilic functional groups, biochar improves soil water holding capacity, facilitates macroaggregate formation, activates soil microbial activity, and accelerates carbon nutrient transformation within 0.25-2 mm aggregates, ultimately increasing aggregate-associated SOC and TN accumulation²⁴.

The contribution rates of aggregate-associated SOC and TN depend on aggregate composition proportion as well as internal carbon and nitrogen concentrations. Previous studies have proven that biochar increases soil carbon sequestration mainly by elevating carbon storage capacity of macroaggregates²⁵. In this study, the SOC and TN contribution rates of 0.25-2 mm aggregates increased obviously in the second year, which was consistent with previous research conclusions²².

Nevertheless, this study obtained a different result from earlier findings: biochar addition increased the SOC and TN contribution rates of aggregates smaller than 0.053 mm in 2022²⁶. This discrepancy was probably caused by long-term field mechanical tillage in the study area.

Continuous tillage induced partial soil nutrient loss, while highly humified colloidal substances tended to be enriched in microaggregates below 0.053 mm and were tightly wrapped by fine clay particles to achieve stable nutrient preservation²⁷. Besides, differences in biochar raw material types, application duration, local climatic conditions and initial soil fertility can also lead to inconsistent research conclusions across different trials.

3.3 Effects of biochar and irrigation regulation on wheat grain yield

Rational water and nutrient regulation is the key to improving crop yield, and proper water supplement under moderate water deficit can enhance crop drought resistance and promote yield formation²⁸. In this study, the combination of appropriate biochar application and moderate irrigation reduction (4050 m³/ha) achieved optimal wheat yield performance. There exists an obvious threshold effect in water-nutrient coupling during wheat growth; excessive water input will break the balanced supply relationship and inhibit yield improvement. Accordingly, excessive irrigation reduction treatments (W2, W2') with biochar addition led to varying degrees of wheat yield decline, which was in line with previous field research results²⁹.

After being incorporated into farmland soil, biochar is continuously affected by soil dry-wet alternation, freeze-thaw cycles, root exudates and microbial metabolism, and gradually undergoes natural aging and structural evolution^{30–31}. Aged biochar particles possess stronger water retention performance than newly applied biochar³², which can stably maintain soil moisture and available nutrients, facilitate nutrient absorption and utilization by wheat roots, and thus promote yield increase³³.

In the present two-year experiment, the yield promotion effect of biochar was more prominent in 2022 than in 2021, indicating that long-term soil-biochar interaction accelerated biochar aging process, and this effect was further strengthened under the unique geographical and climatic conditions of northern Xinjiang³⁴. In view of this, long-term in-situ positioning field experiments should be carried out in follow-up studies to clarify the long-term succession effects of biochar on oasis farmland soil environment and crop productivity.

4. Conclusion

After two consecutive years of field observation in northern Xinjiang irrigated farmlands, the combined application of biochar at 10-20 t/ha and a 10% reduced irrigation volume of 4050 m³/ha markedly elevated soil organic carbon and total nitrogen contents across different soil layers and aggregate fractions. This optimal combination effectively enhanced soil carbon sequestration capacity and comprehensively improved soil nutrient status, while simultaneously maintaining and boosting wheat grain yield.

In practical application, this matching regime can effectively cut agricultural irrigation water consumption, alleviate regional water resource shortage pressure, and realize the

dual goals of water conservation and soil carbon accumulation in oasis farmland ecosystems. The findings not only clarify the synergistic regulatory mechanism of biochar and deficit irrigation on farmland soil carbon-nitrogen cycling, but also offer reliable field parameters and scientific references for formulating water-saving, low-carbon and high-efficiency wheat cultivation management strategies in arid irrigated areas.

Author Contributions: The present report was conducted by LQ and ZLN, under the guidance and supervision of YWJ. The studies were carefully selected, and the data was subjected to analysis by GS,TJF. ZJS and ZLN drafted the report and subsequently evaluated and reviewed it by YWJ. All the authors approved the final version of this study.

Availability of data and materials: The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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