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Optimization of water and nitrogen management in wheat cultivation affected by biochar application – Insights into resource utilization and economic benefits

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ABSTRACT

In the context of global climate change and natural resource scarcity, agricultural production is facing multiple challenges in improving crop yields and optimizing natural resource use. It is of great practical significance to optimize agricultural practices to achieve sustainable agricultural development. In this study, a two-year winter wheat field experiment was conducted in the Guanzhong Plain, Shaanxi, China, from 2020 to 2022 to assess the effects of biochar, irrigation, and N fertilizer rates on the yield, water-nitrogen use efficiency, and economic benefits of winter wheat. Specifically, biochar was applied to winter wheat at 30 t ha^{-1} in combination with two irrigation application rates, including regular irrigation (I_{100}; actual evapotranspiration) and deficit irrigation (I_{80}; 0.8 actual evapotranspiration), and three different N fertilizer rates at 210 (N_H; conventional applied N rate by local farmers), 160 (N_M; moderate N rate), and 110 kg ha^{-1} (N_L; low N rate). The control groups in this study consisted of experimental plots under the N_M and N_0 (no N) without biochar application. The aboveground dry matter mass (ADM), yield, and net ecosystem economic budget (NEEB) of winter wheat showed increasing trends with increasing N application rates without significant differences between the N_H and N_M treatments. On the other hand, the water use efficiency (WUE), agronomic N fertilizer use efficiency (aNUE), and N fertilizer recovery efficiency (NRE) showed increasing-decreasing trends with increasing N fertilizer rates, reaching the highest values under the N_M treatment scenario. The biochar addition significantly increased the winter wheat yield and WUE ($P<0.05$). On the other hand, the I_{80} treatment resulted in higher WUE and irrigation water use efficiency (IWUE) than those under I_{100} by 5.63 and 13.52 %, respectively. TOPSIS results indicated that the combined $I_{80}B_1N_M$ treatment was the optimal winter wheat management practice, maintaining high productivity while improving resource use efficiency and economic benefits. The results of the present study provide an important scientific basis and guidance for ensuring efficient and high-quality agricultural products in the Guanzhong Plain and other regions in China with similar climatic characteristics.

1. Introduction

Wheat is one of the major grain crops in China, playing an important role in national food security and stability. Indeed, annual wheat production in China in 2023 was estimated at 134 million tons (National Bureau of Statistics of China, 2023). The Guanzhong Plain is one of the major wheat-growing areas in China. It is located in a semi-arid climate zone with relatively low annual precipitation amounts and high evapotranspiration rates. Local farmers often apply high irrigation rates to avoid yield reductions due to water scarcity in the Guanzhong Plain. However, these irrigation practices can exacerbate the pressure on limited groundwater resources, while leading to serious agricultural

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water losses, reducing water use efficiency and, consequently, seriously hindering the sustainable development of irrigated agriculture (Ullah et al., 2019; Xu et al., 2018; Yan et al., 2020). In addition, excessive nitrogen (N) fertilizer rates are applied to farmland to achieve high crop yields, which may lead to reduced N fertilizer use efficiency and cause a series of environmental pollution issues, including groundwater nitrate (NO_3^-) pollution, soil sloughing, and increased N_2O emissions from agricultural fields (Kong et al., 2016; Mehmood et al., 2019). These issues can, consequently, pose potential threats to soils, crops, and the environment. Therefore, the implementation of rational farmland water and N management measures is essential to optimize the utilization of agroecological resources and ensure food security, thereby promoting sustainable agricultural development.

Water and N are key factors regulating crop growth, thereby significantly affecting crop yields, as well as water and N use efficiency (Liu et al., 2024; Wan et al., 2024). Deficit irrigation has become an effective measure to reduce irrigation water amounts while achieving optimal water use efficiency and high crop yields under limited water resources in arid and semi-arid regions (Chai et al., 2016; Zhang et al., 2021). In fact, limited water availability through deficit irrigation can stimulate compensatory effects and limit physiological pathways in plants, resulting in high-quality and efficient crop production (Hou et al., 2019; Visconti et al., 2019). Yu et al. (2020) highlighted an increase in the WUE of wheat by 6.6 % following deficit irrigation. Mineral N fertilizer applications are the main source of soil N inputs (Du et al., 2021). Liu et al. (2023) revealed reduced wheat N use efficiency under increased N fertilizer rates. In particular, high N application rates can lead to excessive N contents in stem sheaths and leaves, restricting N and phosphorus (P) uptakes and, consequently, affecting photosynthetic efficiency and causing N wastage (Li et al., 2013; Zhang et al., 2010).

Biochar is a solid product produced through the pyrolysis process, involving the carbonization of organic materials under anoxic or anaerobic conditions (Yi et al., 2017). It is characterized by high porosity, large specific surface area, high adsorption capacity, and carbon stability (Bass et al., 2016; Ullah et al., 2017). Numerous researchers have demonstrated the effectiveness of biochar applications in improving the physicochemical properties of soils, increasing nutrient availability, and reducing greenhouse gas (GHG) emissions (El-Naggar et al., 2019; Omondi, 2016). Moreover, Major et al. (2010) showed increases in maize yields following the application of biochar through a four-year field experiment. However, Backer et al. (2016) revealed the reduced effectiveness of biochar applications in soils with high organic matter contents. On the other hand, Gul et al. (2015) pointed out the promoting effect of combined biochar and fertilizer applications on crop growth due to the enhancement of the fertilizer-derived nutrient availability and biochar-based slow releases of nutrients of applied fertilizers. However, the interaction effects of biochar and N fertilizer applications on crop growth under different water conditions require further comprehensive investigations. Ding et al. (2010) demonstrated the ability of biochar to adsorb soil nutrients and reduce N losses through soil column experiments. Li et al. (2019a) indicated the increasing effects of high biochar application rates on ammonia volatilization, thereby leading to N losses from soils. Nevertheless, the effects of biochar additions on crop growth, development, and nutrient use efficiency are still unclear due to the combined effects of numerous factors, such as climatic conditions, biochar types, biochar rates, and crop species (Jiang et al., 2024; Zhang et al., 2023). Therefore, further comprehensive assessment studies on the effects of biochar additions on agricultural production are still required.

Previous related studies have mainly focused on the effects of biochar application or water-N interactions on crop growth and nutrient use efficiency (Bai et al., 2024; Xiao et al., 2017). However, only a few research has investigated the combined effects of biochar, irrigation, and N fertilizer applications. Moreover, most of the previous irrigation control experiments were conducted under pot culture experiments and controlled laboratory conditions or incompletely controlled field conditions with rainfall interference. In this study, a two-year winter wheat field experiment from 2020 to 2022 was conducted in the Guanzhong Plain to (1) explore the interaction mechanisms and combined effects of irrigation, N fertilizer, and biochar applications on the growth, root water/N uptakes, water/N use efficiency, and economic benefits of winter wheat; (2) determine the optimal farm management practices based on experimental results to further enhance the economic benefits of winter wheat while ensuring environmentally-friendly and efficient use of natural resources.

2. Materials and methods

2.1. Field management and experimental site description

In this study, the experiment was carried out under a rain shelter at the Institute of Agricultural Water Conservation in Arid Areas, Yangling District, Shaanxi Province, China (108°04’E; 34°18’N; 506 m). The shelter was closed under precipitation events to ensure consistent climatic conditions at the experimental site with those of the surrounding fields. The mean annual temperature, evapotranspiration rate, and precipitation in the study area are 12.5 ℃, 1500 mm, and 609 mm, respectively. The soil type at the experimental site is a medium loam, with a field water holding capacity range, permanent wilting point range, and average bulk density within a 1 m soil profile of 23–25 %, 11–12 %, and 1.35 g•cm^{-3}, respectively.

2.2. Experimental design

In this study, the Xiaoyan 22 winter wheat variety was sown at a density of 165 kg ha^{-1} with a row spacing of 25 cm. The winter wheat variety was sown and harvested in October and June each year, respectively. Details on specific sowing, fertilization, and irrigation practices are provided in Table S1 and Table S2. In total, three different factors were considered in the field experiment, namely irrigation level (I), biochar application (B), and nitrogen application (N). The applied irrigation rates were determined based on the measured actual evapotranspiration (ET_c act) using a weighing lysimeter. Xu et al. (2023) revealed the lowest wheat and maize yields at irrigation levels of 0.6 ET. In this study, two irrigation levels were applied, which are I_{100} (fully irrigated at ETa) and I_{80} (deficit irrigated at 0.8 ETa). On the other hand, different N fertilizer rates were determined based on the regular N fertilizer rate (210 kg ha^{-1}) applied by local farmers in the study area, including 210 (high N rate; N_H), 160 kg ha^{-1} (moderate N rate; N_M), 110 kg•ha^{-1}(low N rate; N_L), and 0 kg•ha^{-1}(no N application; N_0). Whereas the biochar was applied at a rate of 0 t•ha^{-1} (B_0) and 30 t•ha^{-1} (B_1), according to the literature and local standards. The experiment was implemented based on two irrigation levels in combination with the B_1 and three N fertilizer application rates (N_H, N_M, and N_L). In addition, the combined B_0 treatment with the N_M and N_0 treatment scenarios were considered as the control groups in this study. Details on the experimental design of this study area are reported in Table 1, showing a total

Table 1
Design of the field experiment.

Irrigation levels	Biochar and N treatment scenarios	Biochar amount (t ha^{-1})	N application	N amount (kg ha^{-1})
I_{100}, I_{80}	B_1N_H	30	High N application (regular N fertilizer rate applied by local farmers)	210
	B_1N_M	30	Moderate N application	160
	B_1N_L	30	Low N application	110
	B_0N_M	0	Moderate N application	160
	B_0N_0	0	Without N application	0

of 10 treatment scenarios, with three replicates for each treatment and 30 randomly arranged plots. The experimental plot covered an area of 6.67 m^2 (2.13 m × 3.13 m), consisting of a pit with a reinforced concrete bottom to avoid potential water infiltration from adjacent plots. In addition, two experimental plots equipped with weighing lysimeters were set up under the $B_0I_{100}N_M$ treatment scenario.

Specifically, 60 % of the N fertilizer rates were applied as basal fertilizers at the sowing, while the remaining 40 % rates were applied at the boot stage (Table 1). In addition, phosphorus and potassium fertilizers were applied as basal fertilizers at 105 kg ha^{-1} P_2O_5 and 120 kg ha^{-1} K_2O, respectively. The applied biochar was obtained in this study through the pyrolysis of corn stover biomass charcoal at 450 °C, with a carbon (C) content, N content, and pH value of 68 %, 1.18 %, and 8.76, respectively. The biochar was first evenly sprinkled on the soil surface of the experimental plots in a single application before the winter wheat sowing in 2020 and then plowed and buried at a soil depth of about 20 cm.

2.3. Sampling and measurements

2.3.1. Aboveground dry matter mass and grain yields

In this study, 20 cm long winter wheat plants were collected at the harvest time from each plot for subsequent measurements. The plant stems, leaves and spikes were bagged and oven-dried at 105 °C for 30 min, then at a constant temperature of 75°C until reaching constant weights. The weights of the dried samples (stems, leaves, and spikes) were subsequently determined and then expressed in terms of dry matter per unit area (ha^{-1}) to obtain the aboveground dry matter mass (ADM). On the other hand, the total number of plants at the experimental site was determined by collecting winter wheat plant samples from a 1 m^2 area of each plot. The samples were threshed and dried to determine the 1000 kernel weight and total weight per unit area for the winter wheat yield measurements ($kg \bullet ha^{-1}$). The harvest index (HI) was determined according to the following formula (Li et al., 2020:):

$$\mathrm{HI} = \mathrm{Y}/\mathrm{ADM} \tag{1}$$

where Y denotes the winter wheat yield (kg ha^{-1}); ADM is the aboveground dry matter mass (kg ha^{-1}).

2.3.2. Evapotranspiration rates and water use efficiency

In this study, the winter wheat water consumption rates, represented by the evapotranspiration rates (ET), were calculated using the water balance method according to the following formula (Zhang et al., 2018):

$$\mathrm{ET} = \mathrm{I} + \Delta\mathrm{W} + \mathrm{P} + \mathrm{K} - \mathrm{D} \tag{2}$$

where I denotes the total water irrigation volume applied to winter wheat during the growing season (mm); ΔW denotes the difference in the soil water storage between the pre-sowing and post-harvest (mm); P denotes the precipitation amount (mm); K denotes the water amount entering the root zone from groundwater (mm); D denotes the amount of surface runoff (mm); P, K, and D were all neglected in the calculations.

Water use efficiency (WUE) (kg m^{-3}) and irrigation water use efficiency (IWUE) (kg m^{-3}) were calculated using the following formulas:

$$\mathrm{WUE} = \mathrm{Y}/\mathrm{ET} \tag{3}$$

$$\mathrm{IWUE} = \mathrm{Y}/\mathrm{IW} \tag{4}$$

where Y denotes the winter wheat yield (kg ha^{-1}); IW denotes the irrigation water rate (mm).

2.3.3. Soil nitrogen

Soil samples were collected in this study at the harvest time of the cultivated winter wheat from the 1 m soil profile of each plot at 10 cm intervals. The collected soil samples were air-dried, ground, and sieved. Subsequently, 1 mol L^{-1} KCl solutions were added to the samples, shaken for 30 min, and filtered to determine the ammonium N (NH_4^+-N) and nitrate N (NO_3-N) contents using a flow analyzer.

2.3.4. Nitrogen uptake and use efficiency

The dried winter wheat samples were weighed, pulverized, passed through a 0.5 mm sieve, and decocted with concentrated H_2SO_4-H_2O_2 to determine the total N contents using the AA3-type flow analyzer (Seal, Germany).

The N harvest index (NHI) (kg kg^{-1}), N partial factor productivity (NPFP) (kg kg^{-1}), agronomic N use efficiency (aNUE) (kg kg^{-1}), and N recovery efficiency (NRE) (kg kg^{-1}) were determined using the following formulas (Ciampitti and Vyn, 2011; Fageria and Baligar, 2005; Koutroubas et al., 2012):

$$\mathrm{NHI} = U_{grain}/\mathrm{U}_N \tag{5}$$

$$\mathrm{NPFP} = \mathrm{Y_N}/\mathrm{N} \tag{6}$$

$$\mathrm{aNUE} = (\mathrm{Y_N} - \mathrm{Y_0})/\mathrm{N} \tag{7}$$

$$\mathrm{NRE} = (\mathrm{U_N} - \mathrm{U_0})/\mathrm{N} \times 100\% \tag{8}$$

where U_{grain} denotes the grain N content (kg ha^{-1}); Y_N and Y_0 denote the observed winter wheat yields (kg ha^{-1}) with and without N fertilizer applications, respectively; U_N and U_0 denote the biomass N contents (kg ha^{-1}) with and without N fertilizer applications, respectively; N denotes the N application rate (kg ha^{-1}).

2.3.5. Economic benefits

The net ecosystem economic budget (NEEB) was calculated in this study based on the winter wheat yield benefits and the costs of agricultural activities, according to the following formula (Kumar et al., 2021):

$$NEEB = Yield\ income - Agricultural\ input\ costs \tag{9}$$

The winter wheat yield benefits were determined based on the market price of local crops. Related data were, in fact, obtained from the China Agricultural Information Network (http://www.agri.cn/). On the other hand, the costs of agricultural activities were related to the applied fertilizers, crop seeds, biochar, and labor (e.g., sowing and harvesting).

2.3.6. TOPSIS method

The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is a multi-objective decision-making method that can reflect the gap between programs by calculating the distance between each program and the ideal/worst programs. In this study, the TOPSIS method was used to evaluate the advantages and disadvantages of the winter wheat yields, as well as their environmental and economic benefits, under the different combined water, N, and biochar treatments. The TOPSIS method was performed by normalizing first the raw data matrix X, as follows:

$$\mathrm{X} = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{21} & x_{22} & \cdots & x_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nm} \end{bmatrix} \tag{10}$$

where n is the number of treatment scenarios; m is the number of evaluation indicators.

The normalized X is denoted as matrix Z, as follows:

$$\mathrm{Z} = \begin{bmatrix} z_{11} & z_{12} & \cdots & z_{1m} \\ z_{21} & z_{22} & \cdots & z_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ z_{n1} & z_{n2} & \cdots & z_{nm} \end{bmatrix} \tag{11}$$

The ideal (Z^+) and the worst (Z^-) solutions were determined by combining all the indicators, according to the following formula:

$$Z^+ = \left(z_1^+, z_2^+, \ldots, z_m^+\right), \quad Z^- = \left(z_1^-, z_2^-, \ldots, z_m^-\right) \tag{12}$$

where $z_j^+ = max\left(z_{ij}\right)andz_j^- = \min(z_{ij})$ represent the maximum and minimum values of the *j*th index, respectively.

The distance of the alternative solution from the ideal (D_i^+) and worst (D_i^-) solutions were determined using the following formulas:

$$D_i^+ = \sqrt{\sum_{j=1}^{m}\left(z_j^+ - z_{ij}\right)^2} \tag{13}$$

$$D_i^- = \sqrt{\sum_{j=1}^{m}\left(z_j^- - z_{ij}\right)^2} \tag{14}$$

The proximity of the evaluated solutions to the ideal and worst solutions can be expressed as follows:

$$S_i = \frac{D_i^-}{D_i^+ + D_i^-} \tag{15}$$

where S_i is the composite score index. The S_i values range from 0 to 1, indicating a worst and perfect evaluation program, respectively.

2.4. Data analysis

The experimental data were collected and analyzed in this study using Excel 2019 (Microsoft, USA) and SPSS 25.0. All the data were plotted using Origin 2023. The collected data were examined for variance homogeneity and normality. In this study, one-way analysis of variance (ANOVA) test and the least significant difference (LSD) method were performed using SPSS 25.0 to determine whether the differences in the indicators between the different treatment scenarios were statistically significant at the $P < 0.05$ level. The biochar application (B), irrigation amount (I), and N fertilizer (N) amount were used as the main influencing factors for each indicator and the two-way interaction of B × I and N × I. On the other hand, the multi-objective TOPSIS analysis was performed to synthesize the scores and evaluate the treatments.

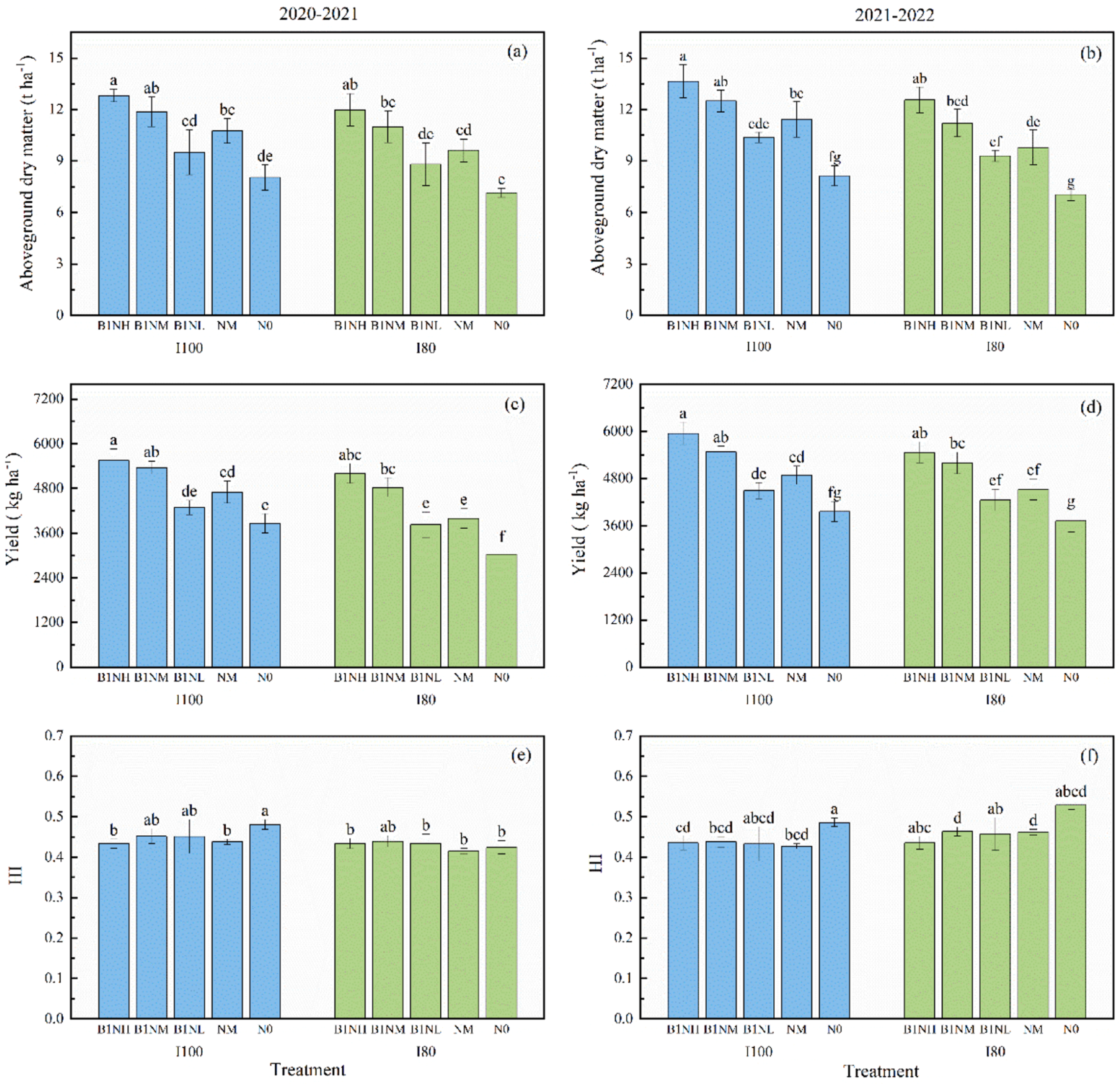

Fig. 1. Effects of the different irrigation, N fertilizer, and biochar application rates on the aboveground dry matter mass (ADM), yields, and harvest index (HI) of winter wheat in the 2020–2021 and 2021–2022 growing seasons. Different letters indicate statistically significant differences between the treatment scenarios at the $P < 0.05$ level.

3. Results

3.1. Aboveground dry matter mass, yields, and harvest index

As shown in Fig. 1, the irrigation level, N application, and biochar had different effects on the ADM, yields, and harvest index in the two-year winter wheat growing seasons. The winter wheat yield and ADM values under the different N application rates showed the decreasing order of $N_H > N_M > N_L$ at the same irrigation levels. In contrast, the winter wheat yields under the B_1N_H treatment were higher than those under the B_1N_M, B_1N_L, and B_0N_M treatments by average values of 6.25, 31.63, and 22.71 %. Whereas the observed ADM values under the B_1N_H treatment were higher than those under the B_1N_M, B_1N_L, and B_0N_M treatments by 9.56, 34.43, and 22.92 %, respectively. Although the B_1N_H treatment had a 31.25 % higher N fertilizer rate than that of the B_1N_M, no significant differences were observed in the ADM and yields of winter wheat between these treatments. The B_1 treatment resulted in significantly higher ADM and yields of winter wheat than those under the B_0 treatment by 12.71 and 15.49 %, respectively, at the same irrigation and N application rates ($P<0.05$). On the other hand, the HI showed an increasing-decreasing trend with increasing N fertilizer rates at the same irrigation and biochar rates, reaching a maximum value under the B_1N_M treatment scenario.

3.2. Evapotranspiration, water use efficiency, and irrigation water use efficiency

The obtained results revealed the effects of the different N fertilizer, irrigation, and biochar rates on the ET, WUE, and IWUE in both winter wheat growing seasons (Fig. 2). The ET values under the irrigation treatment scenarios showed the order of $I_{100} > I_{80}$ under the same N application and biochar rates. In fact, the I_{100} treatment resulted in higher ET values than those under the I_{80} treatment by 16.29 and 16.48 % in the 2020–2021 and 2021–2022 winter wheat growing seasons, respectively. On the other hand, the observed ET values under the N fertilizer and biochar rates followed the order of $B_1N_H > B_1N_M > B_1N_L$ in both winter wheat growing seasons. The I_{80} treatment scenario significantly increased the WUE values in both winter wheat growing seasons by an average of 5.63 % when compared with the I_{100} treatment under all N fertilizer and biochar treatments, except the B_0N_M treatment. In addition, the deficit irrigation treatment resulted in higher IWUE values than those under the I_{100} treatment by an average of 13.52 % over the two-year winter wheat growing seasons. In contrast, the WUE values exhibited an increasing-decreasing trend with increasing N application rates, reaching the highest value at the N_M level. The biochar addition significantly increased the WUE values by 17.51 and 29.43 % ($P<0.05$) under the I_{100} and I_{80} treatment scenarios, respectively. Whereas the IWUE values showed an increasing trend with increasing N

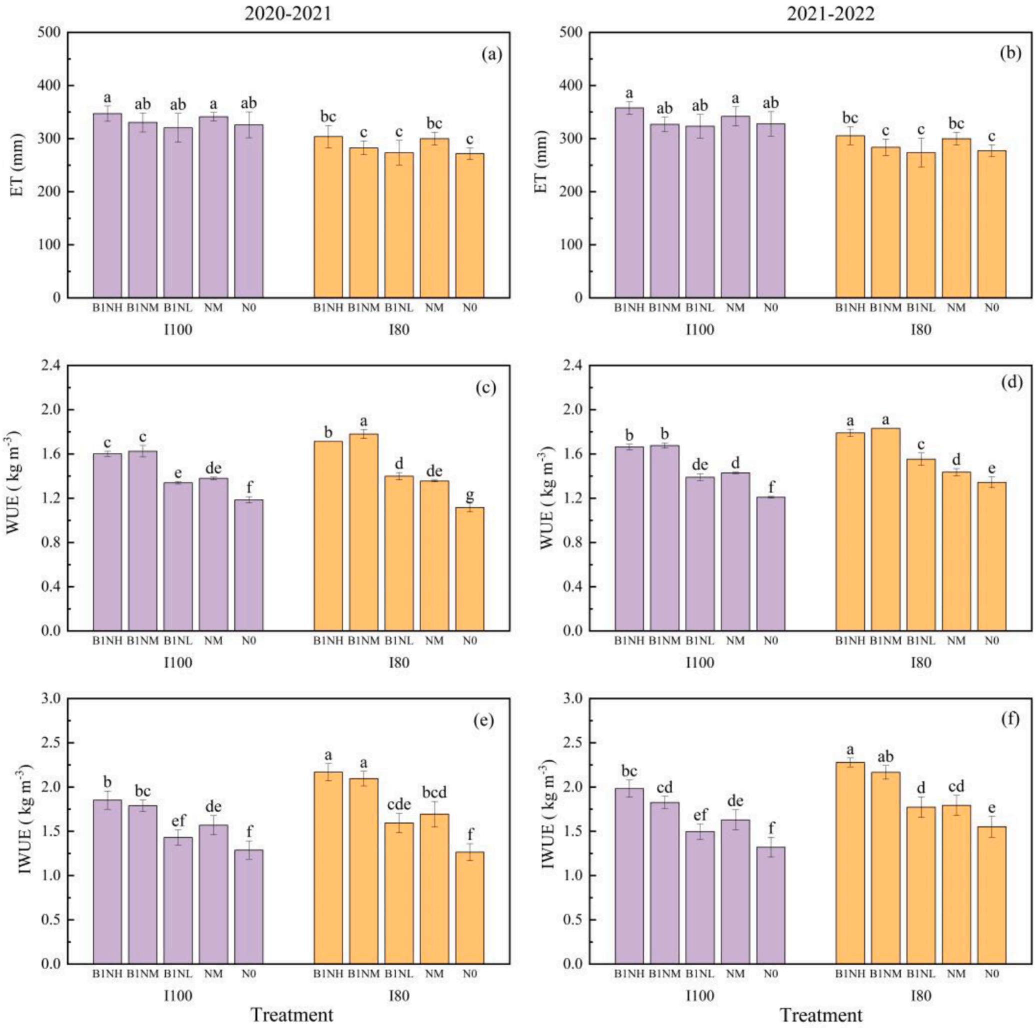

Fig. 2. Effects of the different irrigation, N fertilizer, and biochar application rates on the evapotranspiration (ET), water use efficiency (WUE), and irrigation water use efficiency (IWUE) in the 2020–2021 and 2021–2022 winter wheat growing seasons. Different letters indicate statistically significant differences between the treatments at the $P < 0.05$ level.

application rates at the different irrigation levels.

3.3. Residual soil N contents, winter wheat N uptakes, and N use efficiency

The observed NO_3^--N and NH_4^+-N contents in the 0–100 cm soil profile at the harvest time of winter wheat are shown in Fig. 3. The results showed relatively similar variation patterns of the soil NO_3^--N contents under all treatment scenarios, showing increasing-decreasing trends with soil depth. The highest NO_3^--N contents were observed in the 50–70 cm soil layer. In addition, the lowest and highest soil NO_3^--N contents were observed under the N_0 and N_H treatment scenarios, respectively. The results revealed the increasing effects of the B_1 treatment on the NO_3^--N contents in the 0–10 cm and 10–20 cm soil layers when compared with the B_0 treatment. At the I_{100} level, the B_1 treatment showed higher and lower NO_3^--N contents than those under B_0 in the 0–60 cm and 60–100 cm soil layers, respectively. This finding might be due to the adsorption effect of the biochar, enhancing the accumulation of NO_3^--N in the shallow soil layers and, consequently, restricting NO_3^--N leaching to the deeper soil layers. On the other hand, the contents of soil NH_4^+-N were lower than those of NO_3^--N, showing slight increases with increasing soil depth. In addition, the B_1 treatment resulted in lower NH_4^+-N contents in the 0–20 cm soil layer than those observed under the B_0 treatment ($P<0.05$).

In the two-year winter wheat growing seasons, the total N uptakes in the winter wheat plant organs under the different N fertilizer and biochar treatment scenarios showed the decreasing order of $N_H>N_M>N_L>N_0$ at both irrigation levels (I_{100} and I_{80}) (Table 2). However, the N_L and N_0 scenarios resulted in significantly lower total N uptakes than those observed under the N_H and N_M treatments ($P<0.05$). In addition, the B_1N_H treatment resulted in higher plant N uptakes than those under the B_1N_M, B_1N_L, B_0N_M, and B_0N_0 treatments by average values of 5.41, 25.46, 21.90, and 58.45 %, respectively. Whereas the I_{100} treatment increased the total N uptakes when compared with the I_{80} treatment by 8.96 and 9.33 % in the 2020–2021 and 2021–2022 winter wheat growing seasons ($P<0.05$), respectively. On the other hand, the biochar addition enhanced the plant N uptake. Indeed, the B_1 treatment scenario resulted in higher total N uptakes than those under B_0 by 19.07 and 13.79 % in the 2020–2021 and 2021–2022 winter wheat growing seasons ($P<0.05$), respectively. The Biochar application effectively restricted the impact of water stress on winter wheat. The observed total N uptakes under the B_0N_M and I_{100} treatments were significantly higher than those observed under the B_0N_M and I_{80} treatments ($P<0.05$). In contrast, the observed N uptakes under the N_MB_1 treatment did not show

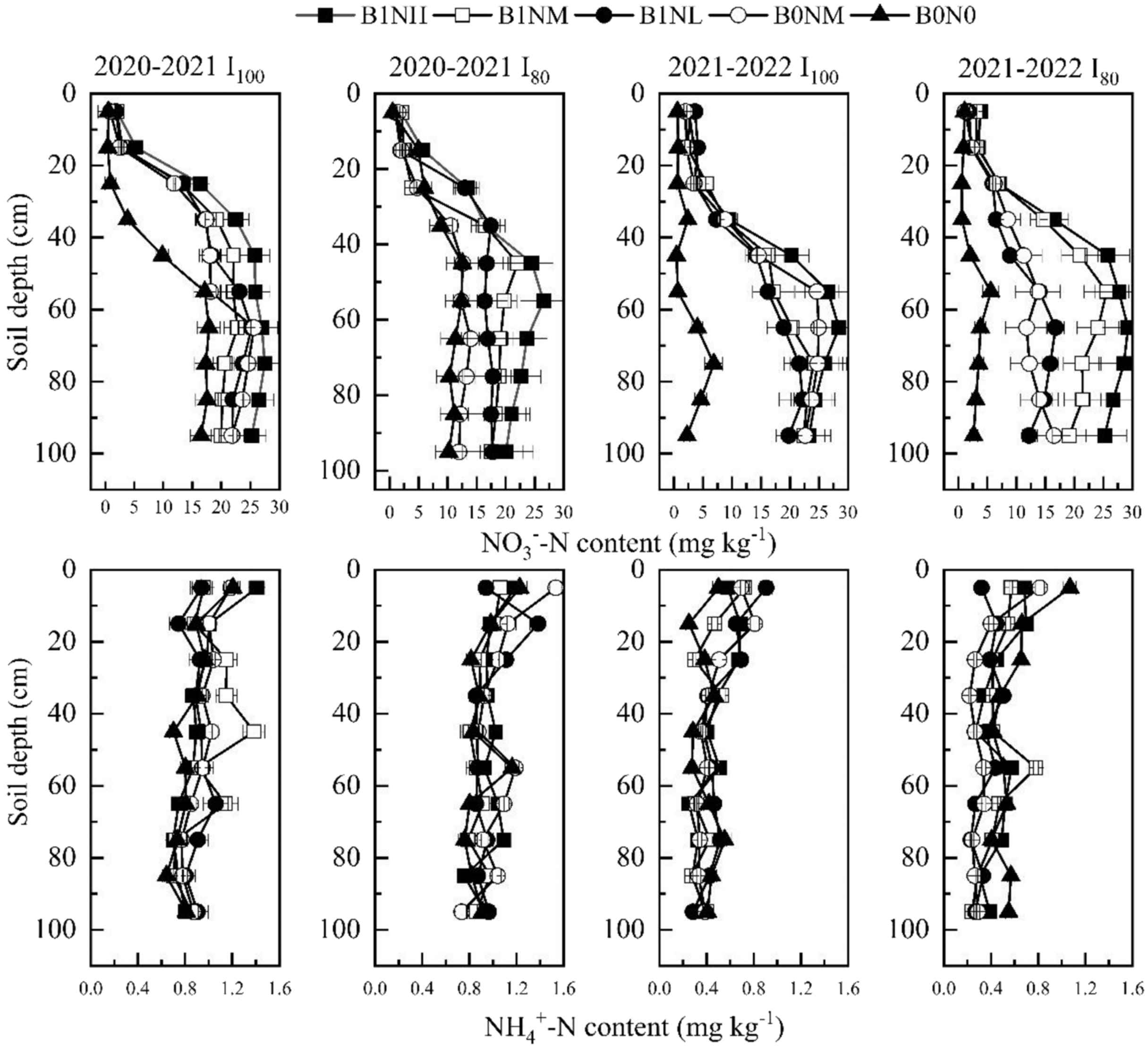

Fig. 3. Vertical variations in the NO_3^--N and NH_4^+-N contents in the 0–100 cm soil profile at the harvest time under the different irrigation, N fertilizer, and biochar application rates in the 2020–2021 and 2021–2022 winter wheat growing seasons. The different bars represent the standard deviation values of the three replicates.

Table 2

Effects of the different irrigation, N fertilizer, and biochar application rates on N uptakes in various winter wheat plant organs in the 2020–2021 and 2021–2022 winter wheat seasons.

Treatments		N uptake (kg ha^{-1}) in 2020–2021				N uptake (kg ha^{-1}) in 2021–2022			
		Stem	Leaf	Grain	Total	Stem	Leaf	Grain	Total
I_{100}	B_1N_H	40.31a	14.46a	161.77 a	216.54a	34.27a	9.36 ab	162.69 a	206.32a
	B_1N_M	37.22ab	12.56ab	156.38 a	206.16 ab	29.15ab	6.78 bc	159.05 a	194.98 ab
	B_1N_L	30.52 bcd	14.62 a	132.84 bc	177.97d	33.54a	10.25 a	122.43 cd	166.21 cd
	B_0N_M	33.54bc	15.22 a	140.27 b	189.04 cd	29.56ab	10.26 a	135.14 bc	174.96c
	B_0N_0	24.44 de	9.70 bc	104.16 d	138.31 f	24.88abc	7.07 bc	106.11 de	138.06 e
I_{80}	B_1N_H	36.38 abc	12.48 ab	159.14 a	207.99 ab	34.16a	7.24 bc	154.42 a	195.82 ab
	B_1N_M	35.20 abc	10.45 bc	155.25 a	200.89 bc	26.02abc	6.24c	150.04 ab	182.30 bc
	B_1N_L	26.53 de	11.67 abc	122.93c	161.13 e	22.30bc	5.97c	125.47c	153.73 de
	B_0N_M	29.75 cd	10.24bc	121.38c	161.37 e	27.29abc	6.41c	123.26 cd	156.96 d
	B_0N_0	20.70 e	7.86c	91.80 d	120.35 g	18.55c	6.15c	91.84 e	116.54 f
	I	ns	**	ns	ns	*	**	ns	ns
	B	**	ns	**	**	ns	ns	**	**
	N	**	**	**	**	**	ns	**	**
	B × I	ns	ns	**	**	ns	*	**	**
	N × I	**	*	**	**	*	*	**	**

Different lowercase letters in the same column indicate statistically significant differences between the treatments ($P < 0.05$). I, B, and N denote the irrigation, biochar, and N application rates, respectively. B × I represents the interaction between the biochar and irrigation rates. N × I represents the interaction between the N application and irrigation rates.

a significant difference between the I_{100} and I_{80} treatment levels ($P>0.05$). Therefore, the biochar addition significantly reduced the negative effect of the deficit irrigation on the winter wheat N uptakes in both growing seasons.

The obtained results showed significant effects of the irrigation, N fertilizer, and biochar rates on the NHI and aNUE (Fig. 4). The NHI, aNUE, and NRE values showed increasing-decreasing trends with increasing N fertilizer rates under both irrigation levels (I_{100} and I_{80}), reaching the highest values under the B_1N_M treatment. On the other hand, the NPFP exhibited a decreasing trend with increasing N application rates. Indeed, the B_1N_L treatment resulted in significantly higher NPFP values than those under the other treatments, except at the I_{80} irrigation level in the 2020–2021 winter wheat growing season. Specifically, the B_1N_L treatment increased the NPFP by 43.89, 13.49, and 34.78 % compared with the B_1N_H, $B_1N_{M,}$ and B_0N_M treatments in the 2020–2021 growing season ($P<0.05$). In the 2021–2022 growing season, on the other hand, the B_1N_L treatment resulted in higher NPFP than those under the B_1N_H, $B_1N_{M,}$ and B_0N_M treatments by 47.02, 19.13, and 38.76 %, respectively ($P<0.05$). Compared with the B_0 treatment, the B_1 treatment increased the NPFP, aNUE, and NRE by average values of 17.68, 159.45, and 112.32 %, respectively.

3.4. Economic benefits and comprehensive evaluation

The economic benefit results of winter wheat under the different irrigation, N, and biochar treatments are reported in Table 3. The results showed increases in the winter wheat yields with increasing irrigation and N fertilizer rates, thereby increasing the winter wheat-related income. Indeed, the B_1N_H treatment resulted in higher NEEB than those under the B_1N_M and B_1N_L treatments by average values of 6.72 ($P>0.05$) and 83.24 % ($P<0.05$), respectively. The biochar application improved the crop yield and NEEB. Specifically, the biochar addition increased the NEEB by 11.29 % when compared with the B_0 treatment. However, the biochar production cost is relatively high, thereby negatively affecting associated economic benefits. Hence, it is crucial to reduce the production costs of biochar through innovative production technologies and the utilization of self-produced crop residues as raw materials from farmlands. Indeed, biochar still has a great potential for application and economic benefits in the future.

According to Fig. 5, the observed winter wheat yields exhibited strong significant positive correlations with the ADM, ET, WUE, and N uptakes. These findings demonstrate the improvement effects of increased WUE on the winter wheat yield. On the other hand, the NHI values were positively correlated with the WUE and IWUE, indicating efficient and consistent water use with N uptakes and use, improving the overall winter wheat productivity and growth. Fig. 6 shows the normalization results of the nine parameters. The TOPSIS method was employed to comprehensively assess the growth, water/N use efficiency, and economic efficiency of winter wheat (Table 4). It is worth noting that B_0N_0 treatments under the I_{100} and I_{80} irrigation levels were not considered in the analysis since it was not possible to calculate the aNUE, NRE and NPFP under the N_0 treatment. Moreover, the WUE and yields of the cultivated winter wheat under this combined treatment were very low compared with those observed under the remaining treatment scenarios. According to the obtained results, the $I_{80}B_1N_M$ treatment resulted in the highest comprehensive score of 0.727, followed, respectively, by the $I_{100}B_1N_M$, $I_{80}B_1N_{H,}$ and $I_{100}B_1N_H$ treatments (Table 4).

4. Discussion

4.1. Effects of the irrigation, biochar, and N fertilizer rates on the crop growth and water use efficiency of winter wheat

Irrigation and N fertilizer applications are the key factors affecting crop growth, development, and yield. Jyolsna et al. (2024) highlighted increases in rice and wheat yields with increasing N fertilizer rates. This is mainly attributed to the increasing effects of N fertilizers on crop growth, chlorophyll contents, photosynthetic rates, and allocation of photosynthates, thereby enhancing the accumulation of crop ADM and yields (Ghoneim et al., 2018; Li et al., 2019b). In this study, the observed winter wheat yields and ADM showed similar variation trends under the N fertilizer application rates, following the decreasing order of $N_H>N_M>N_L>N_0$. However, there were no significant differences in the ADM and yield values between the N_H and N_M treatments under both irrigation treatments. Whereas the N_M treatment resulted in significantly higher ADM and yield values than those under the N_L treatment. Increasing N fertilizer rates from N_M to N_H by 31.25 % did not significantly increase the ADM and yield of winter wheat. Liu et al. (2024) highlighted the effects of irrigation on dry matter accumulation and yields of crops by regulating water supply and root nutrient uptakes. Lu et al. (2021) revealed the highest winter wheat yield under 75 % ET deficit irrigation, which is inconsistent with the results of this study. This discrepancy in the results might be attributed to the occurrence of rainfall events, providing supplemental water. Whereas the experiments of this study were conducted under a sheltered canopy without rainfall

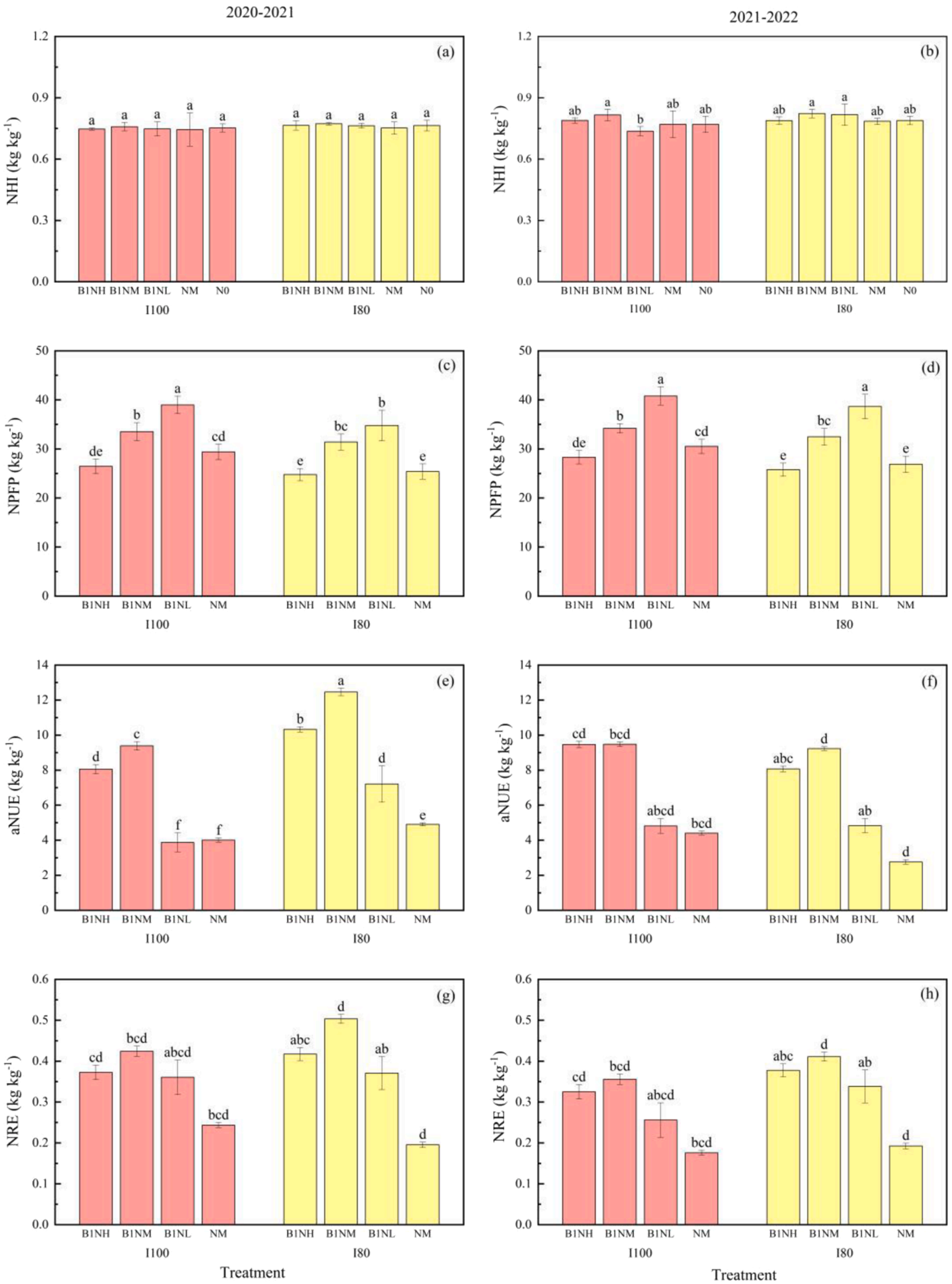

Fig. 4. Effects of the different irrigation, nitrogen fertilizer, and biochar application rates on the N harvest index (NHI), N partial factor productivity (NPFP), agronomic N fertilizer use efficiency (aNUE), and N fertilizer recovery efficiency (NRE) in the 2020–2021 and 2021–2022 winter wheat growing seasons. Different lowercase letters indicate statistically significant differences between the treatments at the $P < 0.05$ level.

Table 3
Planting costs and economic benefits of winter wheat under the different treatments in the two-year growing seasons (CNY ha^{-1} yr^{-1}).

Treatments		Relative costs(CNY ha^{-1})						Outputs (CNY ha^{-1})	NEEB (CNY ha^{-1})
		Irrigation	Biochar	Seed	Chemical fertilizer	Pesticide	Labor	Yield income	
I_{100}	B_1N_H	750	1650	750	3845.2	150	2160	16,524.1	7218.9a
	B_1N_M	750	1650	750	3456.4	150	2160	15,537.4	6621.0a
	B_1N_L	750	1650	750	3064	150	2160	12,597.1	4073.1 cd
	B_0N_M	750	0	750	3456.4	150	2160	13,755.5	6489.1a
	B_0N_0	750	0	750	2502.4	150	2160	11,212.8	4900.4bc
I_{80}	B_1N_H	600	1650	750	3845.2	150	2160	15,314.4	6159.2ab
	B_1N_M	600	1650	750	3456.4	150	2160	14,666.0	5899.6ab
	B_1N_L	600	1650	750	3064	150	2160	11,628.7	3254.7d
	B_0N_M	600	0	750	3456.4	150	2160	12,010.1	4893.7bc
	B_0N_0	600	0	750	2502.4	150	2160	9768.5	3606.1 cd

Different lowercase letters in the same column indicate statistically significant differences between the treatments ($P < 0.05$).

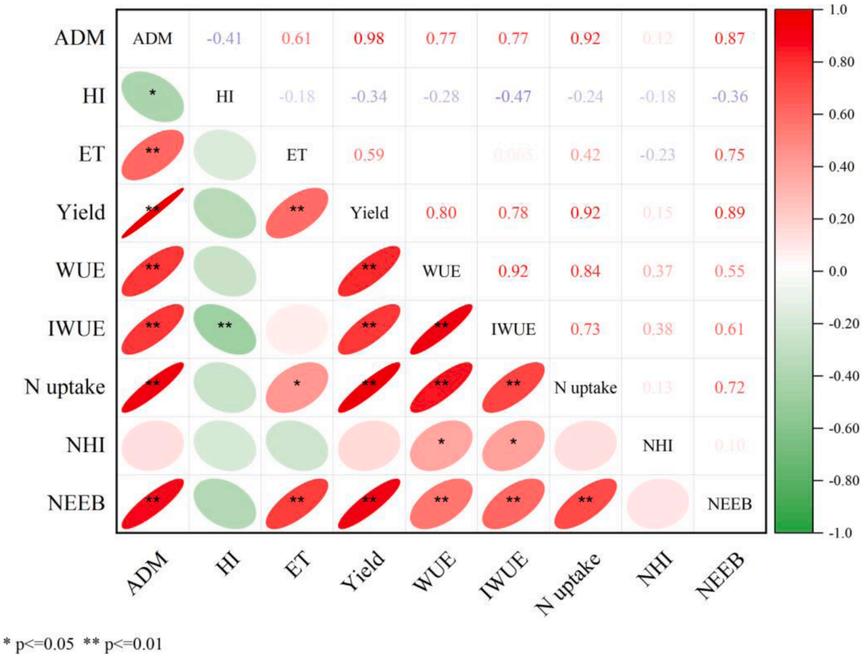

Fig. 5. Correlation analysis between the indicators under the different irrigation, N fertilizer, and biochar application rates in the 2020–2021 and 2021–2022 winter wheat growing seasons. ADM, HI, ET, WUE, IWUE, NHI, and NEEB denote the aboveground dry matter, harvest index, crop water consumption, water use efficiency, irrigation water use efficiency, N harvest index, and net ecosystem economic budget, respectively. * and ** indicate significant correlation coefficients at the $P<0.05$ and $P<0.01$ levels, respectively.

disturbance.

In this study, the biochar addition positively affected both the ADM and yield of winter wheat, which is in line with the results revealed by Zhang et al. (2020), showing slight and significant enhancement effect of biochar additions on crop yields in the first and last three years, respectively, of a six-year rice-wheat rotation planting. Similarly, Jin et al. (2019) demonstrated the enhanced effects of biochar additions on crop yields through a five-year oilseed rape plantation. Biochar can improve soil structure, adsorb soil nutrients, and enhance soil water-holding capacity through its high porosity, making nutrients more readily available for plant uptakes (Agegnehu et al., 2016; Zhang et al., 2024a). Unlike the winter wheat ADM, a significant increase in the winter wheat yield was observed following the addition of the biochar. This finding suggests that the biochar addition optimized nutrient partitioning, enhancing the effective allocation of soil nutrients in the nutrient organs of winter wheat rather than enhancing the stem and leaf growth, thereby effectively increasing the winter wheat yield and its associated economic value(Ghorbani and Amirahmadi, 2024). However, further related studies are still required to investigate the mechanisms underlying the biochar effects on nutrient uptakes and utilization in plants through isotopic labeling and biochemical indicator measurements, providing a reference for effectively utilizing biochar to enhance agricultural productivity and promote sustainable development. Such studies can provide further insights into the effective utilization of biochar to enhance agricultural productivity and promote sustainable development. This study revealed the lack of significant biochar effects on the winter wheat yields between the I_{100} and I_{80} treatments at a constant N fertilizer rate (N_M). In contrast, the observed winter wheat yield under the $I_{100}B_0$ treatment was significantly higher than that revealed under the I_{80} treatment, further demonstrating the restricting effect of the biochar application on the winter wheat yield reduction caused by deficit irrigation. Hence, the biochar application can effectively increase and stabilize winter wheat yields.

Northwest China is characterized by water scarcity due to the occurrence of low rainfall amounts and high evapotranspiration rates, greatly limiting crop production (Wang et al., 2023). Therefore, it is crucial to improve WUE to effectively promote the sustainable development of local agriculture. Numerous studies have shown that rational N fertilizer and irrigation applications are effective approaches to enhance agricultural water use efficiency (Ma et al., 2021; Wu et al.,

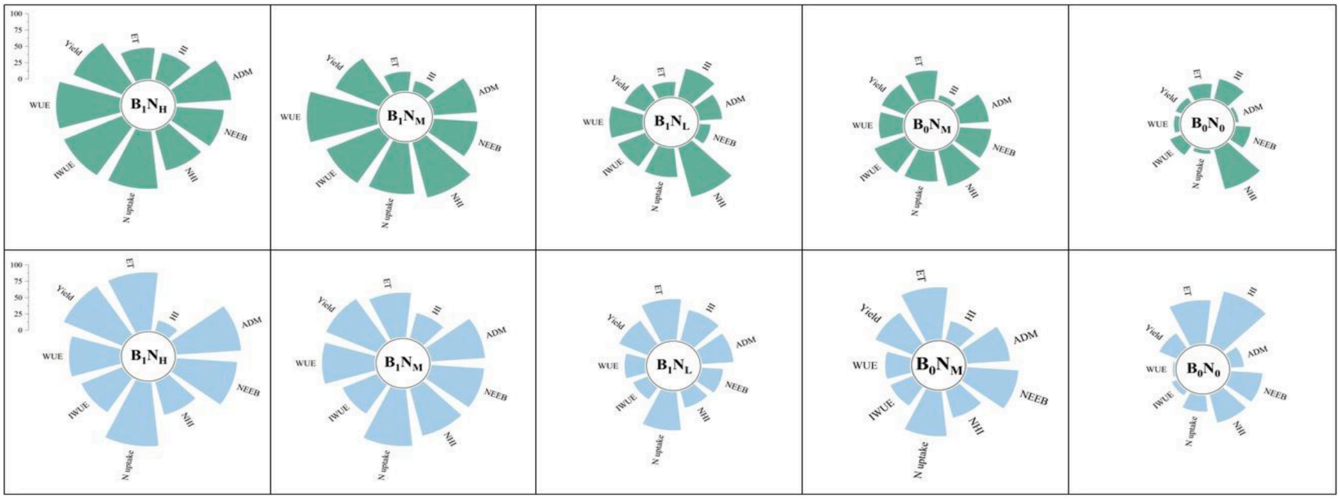

Fig. 6. Multiple objectives analysis of the different irrigation, N fertilizer, and biochar application rates in the 2020–2021 and 2021–2022 winter wheat growing seasons. ADM, HI, ET, WUE, IWUE, NHI, and NEEB denote the aboveground dry matter, harvest index, crop water consumption, water use efficiency, irrigation water use efficiency, N harvest index, and net ecosystem economic budget, respectively.

Table 4
Euclidean distances (D^+ and D^-) and comprehensive evaluation index (S_i) obtained using entropy-TOPSIS under the treatment scenarios.

Treatments		D^+	D^-	S_i	Overall ranking
I_{100}	B_1N_H	1.639	1.954	0.544	4
	B_1N_M	1.082	2.079	0.658	2
	B_1N_L	2.277	1.323	0.367	6
	B_0N_M	2.212	1.123	0.337	7
I_{80}	B_1N_H	1.252	2.134	0.63	3
	B_1N_M	0.917	2.441	0.727	1
	B_1N_L	1.912	1.771	0.481	5
	B_0N_M	2.39	0.983	0.291	8

2022). Bai et al. (2024) found that irrigation and N application had significantly increasing effects on the WUE and IWUE of cotton under different water and N combinations. Kang et al. (2017) found reduced consumption rates following the application of deficit irrigation through the reduction of redundant evaporation, resulting in enhanced crop WUE. The results of this study showed an increasing-decreasing trend of the WUE with increasing N application rates at constant irrigation rates, reaching the highest value under the N_M treatment scenario. In addition, the WUE values under the I_{80} treatment were higher than those revealed under I_{100} at constant N application rates. The biochar application significantly increased the WUE, which might be due to the porous characteristic and large surface area of the applied biochar, effectively increasing the soil water holding capacity and reducing water evaporation and surface runoff (Akhtar et al., 2014; Faloye et al., 2017). In addition, the applied biochar might promote root growth, enhancing root water uptakes and, consequently, reducing the negative effects of drought events on winter wheat and effectively improving WUE (Li et al., 2023; Tripathi et al., 2016).

4.2. *Effects of the irrigation, biochar, and N fertilizer rates on the winter wheat N uptakes, soil N accumulation, N use efficiency, and NEEB*

Nitrate (NO_3^--N) was the main form of residual N in the soil in this study. Indeed, the observed NO_3^--N contents in the 1-m soil profile residue showed increasing trends with increasing N fertilizer rates, according to the following order: $N_H > N_M > N_L > N_0$. Cui et al. (2014) found a positive correlation between NO_3^--N leaching amounts from farmland soil and N application. In addition, they revealed a sharp increase in the NO_3^--N leaching amounts at N application rates exceeding a certain threshold. The results of this study indicated an increase in the NO_3^--N content with increasing soil depth under the I_{100} B_1 treatment scenarios when compared with that observed under the $I_{100}B_0$ treatment, reaching the highest content in the 50–60 cm soil layer. In contrast, higher NO_3^--N contents were observed under the B_0 treatment than those under B_1 in the deeper soil layers. These findings might be attributed to the positive effects of the applied biochar, improving soil structure, as well as the soil water and N retention capacity. The presence of polar functional groups and hydrogen bonds on the surface of biochar can further enhance the chemisorption process of soil nutrients (Spokas et al., 2012). On the other hand, the comparatively low biochar amounts in the deeper soil layers might negatively affect the water and N retention capacity of the experimental soil. Whereas the high irrigation rate (I_{100}) might enhance NO_3^--N leaching to the deeper soil layers. Xiao et al. (2017) highlighted an immediate and short-term increase in soil NH_4^+-N contents in dry-crop farmland following an N fertilizer application. In this study, the biochar application decreased the NH_4^+-N content in the 0–20 cm soil layer, which might be due to the promoting effect of the biochar addition on the nitrification process, converting NH_4^+-N to NO_3^--N. Furthermore, Zhang et al. (2024b) revealed an increased abundance of nitrification genes in soil following the application of biochar.

Crop N uptakes and utilization efficiency are key indicators of agricultural production (Vaziritabar et al., 2024). Indeed, investigating the main mechanisms controlling the effects of crop N uptake and utilization efficiency under different agricultural practices can contribute to the development of scientific and effective farm management programs. Wang et al. (2023) highlighted the restriction effects of water stress on root N uptakes. They showed lower translocation efficiency under a 60 % ET_c irrigation treatment than those under 80 % ET_c and 100 % ET_c irrigation treatments by 10.26 and 13.94 %, respectively. This finding showed higher N uptakes under the I_{100} treatment than those under the I_{80} treatment by 8.96 and 9.33 % in the 2020–2021 and 2021–2022 winter wheat growing seasons, respectively. Soil moisture is the main factor controlling nutrient transport in plants, as well as crop N partitioning and translocation (Koutroubas et al., 2012). Xiao et al. (2017) showed that biochar addition increased N uptakes and kernel N concentration through a three-year maize field experiment. These increases might be due to the translocation of excess N to the kernel after the silking period of crops, reducing the plant leaf N accumulation rates (Lee and Tollenaar, 2007). In addition, it was found that the biochar application could mitigate the negative effects of water stress on crop nutrient uptakes. Therefore, biochar could be an effective agricultural production strategy to mitigate the negative effects of water scarcity on plant growth.

The NHI is a key indicator for quantitatively assessing the translocation of N from vegetative parts of plants to harvested parts. In this study, the NHI showed an increasing-decreasing trend increasing N fertilizer rates under the different irrigation and biochar treatment scenarios. This finding further demonstrates the negative effects of excessive N fertilizer rates on crop yields due to imbalances between N supply and demand of crops (Cheng et al., 2023; Zhang et al., 2024a). On the other hand, the observed aNUE and NRE values under the different N fertilizer treatments followed the decreasing order of $N_M > N_H > N_L$, reaching the highest values at the N_M rate. This demonstrates the capacity of winter wheat to uptake and utilize N more efficiently at moderate N fertilizer levels. On the other hand, high N fertilizer rates may lead to N fertilizer losses. It is, therefore, essential to optimize N fertilizer management to effectively improve NUE, increase crop yields, and mitigate negative environmental effects. In this study, the biochar addition significantly improved the NUE of winter wheat, which is in line with results revealed in previous related studies. Indeed, Xiao et al. (2017) highlighted 10.2–14.2 % increases in the NUE in three-year maize growing seasons following the application of biochar at 20 and 30 t ha^{-1}. This finding might be attributed to the unique physical properties of the biochar, enhancing the adsorption and retention of soluble nutrients by the biochar alkaline groups. Moreover, the applied biochar might promote microbial activities involved in N cycling by increasing soil pH, thereby enhancing the N fixation capacity of the soil and, consequently, increasing root N uptakes and improving NUE (Ibrahim et al., 2020; Yuan et al., 2024).

Crop yields and economic efficiency are the main factors considered by farmers to select optimal agricultural practices and improve agricultural production (Xing et al., 2022). On the other hand, efficient use of resources is a key concern for agricultural policymakers. Rational use of resources can positively affect agricultural costs and promote environmental friendliness, thereby ensuring sustainable agriculture. Although the increases in the N fertilizer and irrigation rates improved the winter wheat yield and NEEB to some extent, they reduced the WUE and aNUE. However, there were no statistically significant differences in the winter wheat yield and NEEB between the N_H and N_M treatment scenarios. According to the TOPSIS results, the N_M rate in combination with the B_1 and I_{80} treatments was optimal for achieving high winter wheat yields, NUE, and economic efficiency. These findings provide an important reference for guiding future agricultural production practices.

4.3. Limitations of this study

In this study, we proposed optimal agricultural practices for winter wheat production through comprehensive assessments of crop growth indicators, water and N use efficiencies, and economic benefits. However, we did not investigate the GHG emissions under the different treatment scenarios over the winter wheat growing seasons, neglecting the potential GHG-related costs in the economic benefit calculations. In fact, numerous studies have demonstrated the effectiveness of deficit irrigation, N reduction, and biochar additions in reducing GHG emissions (Pei et al., 2023; Zhang et al., 2024b). Hence, the positive impacts of these agricultural practices on the NEEB might be underestimated in this study. This study only assessed the change in WUE of winter wheat under biochar application. However, it is still crucial to investigate the impacts of biochar applications on other crop species (e.g., rice) for water management purposes. Future studies on different crops are, therefore, needed to provide a scientific basis for achieving green and sustainable agriculture. In addition, the control group considered in this study consisted only of the biochar application at the moderate N fertilizer rate due to the limited number of experimental plots. Therefore, it is important to comprehensively assess the effects of biochar additions on winter wheat growth, WUE, and NUE through additional experimental groups under high and low N rates to provide detailed data support.

5. Conclusion

The optimization of farmland management practices can effectively increase crop yields, WUE, and NUE, thereby enhancing the economic benefits of agricultural production. The results of this study demonstrated the addition of biochar significantly enhanced the yield of winter wheat and optimized the nutrient partitioning of the plant, promoted the growth of nutrient organs, and effectively mitigated the potential negative effects of deficit irrigation on the yield of winter wheat. In addition, the biochar application increased the WUE, NPFP, aNUE, and NREvalues. Therefore, biochar can be used as an effective soil amendment for winter wheat production. The N_H treatment scenario increased the ADM, yield, N uptakes, and economic benefits of winter wheat to some extent. However, this treatment scenario reduced the WUE and NUE, resulting in wasted N and water resources. On the other hand, the I_{80} treatment scenario significantly increased the WUE in the two-year winter wheat growing seasons without causing a significant reduction in the crop yield. This finding demonstrated the importance of optimized irrigation regimes in achieving rational water use and conservation. In this study, the highest TOPSIS comprehensive score was obtained under the $I_{80}B_1N_M$ treatment scenario. This finding indicates that the application of deficit irrigation, moderate N rates, and biochar to winter wheat can effectively optimize WUE, NUE, and economic benefits while ensuring high yields. The results of this study provide important references for ensuring the sustainable development of agricultural production, efficient utilization of resources, and improved economic benefits.

CRediT authorship contribution statement

Huanjie Cai: Supervision, Funding acquisition. **Lianyu Yu:** Supervision. **Jiatun Xu:** Supervision. **Maodong Wang:** Investigation. **Pengyan Zhang:** Writing – original draft, Methodology.

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

The authors do not have permission to share data.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2024.109093.

References

Agegnehu, G., Nelson, P.N., Bird, M.I., 2016. Crop yield, plant nutrient uptake and soil physicochemical properties under organic soil amendments and nitrogen fertilization on Nitisols. Soil Tillage Res 160, 1–13. https://doi.org/10.1016/j.still.2016.02.003.

Akhtar, S.S., Li, G., Andersen, M.N., Liu, F., 2014. Biochar enhances yield and quality of tomato under reduced irrigation. Agric. Water Manag. 138, 37–44. https://doi.org/10.1016/j.agwat.2014.02.016.

Bai, Z., Xie, C., Yu, J., Bai, W., Pei, S., Li, Y., Li, Z., Zhang, F., Fan, J., Yin, F., 2024. Effects of irrigation and nitrogen levels on yield and water-nitrogen-radiation use efficiency of drip-fertigated cotton in south Xinjiang of China. Field Crop. Res. 308. https://doi.org/10.1016/j.fcr.2024.109280.

Bass, A.M., Bird, M.I., Kay, G., Muirhead, B., 2016. Soil properties, greenhouse gas emissions and crop yield under compost, biochar and co-composted biochar in two tropical agronomic systems. Sci. Total Environ. 550, 459–470.

Chai, Q., Gan, Y.T., Zhao, C., Xu, H.L., Waskom, R.M., Niu, Y.N., Siddique, K.H.M., 2016. Regulated deficit irrigation for crop production under drought stress. A review. Agron. Sustain. Dev. 36. https://doi.org/10.1007/s13593-015-0338-6.

Cheng, Y., Zhang, T., Hu, X., Liu, Z., Liang, Q., Yan, S., Feng, H., Siddique, K.H.M., 2023. Drip fertigation triggered by soil matric potential reduces residual soil nitrate content and improves maize nitrogen uptake and yield stability in an arid area. Eur. J. Agron. 150, 126932. https://doi.org/10.1016/j.eja.2023.126932.

Ciampitti, I.A., Vyn, T.J., 2011. A comprehensive study of plant density consequences on nitrogen uptake dynamics of maize plants from vegetative to reproductive stages. Field Crop. Res. 121, 2–18. https://doi.org/10.1016/j.fcr.2010.10.009.

Cui, Z., Wang, G., Yue, S., Wu, L., Zhang, W., Zhang, F., Chen, X., 2014. Closing the N-use efficiency gap to achieve food and environmental security. Environ. Sci. Technol. 48, 5780–5787. https://doi.org/10.1021/es5007127.

Ding, Y., Liu, Y.-X., Wu, W.-X., Shi, D.-Z., Yang, M., Zhong, Z.-K., 2010. Evaluation of Biochar Effects on Nitrogen Retention and Leaching in Multi-Layered Soil Columns. WATER AIR SOIL Pollut. 213, 47–55. https://doi.org/10.1007/s11270-010-0366-4.

Du, Y., Niu, W., Zhang, Q., Cui, B., Zhang, Z., Wang, Z., Sun, J., 2021. A synthetic analysis of the effect of water and nitrogen inputs on wheat yield and water- and nitrogen-use efficiencies in China. Field Crop. Res. 265, 108105. https://doi.org/10.1016/j.fcr.2021.108105.

El-Naggar, A., Lee, S.S., Rinklebe, J., Farooq, M., Song, H., Sarmah, A.K., Zimmerman, A. R., Ahmad, M., Shaheen, S.M., Ok, Y.S., 2019. Biochar application to low fertility soils: A review of current status, and future prospects. Geoderma 337, 536–554. https://doi.org/10.1016/j.geoderma.2018.09.034.

Fageria, N.K., Baligar, V.C., 2005. Enhancing Nitrogen Use Efficiency in Crop Plants. Advances in Agronomy. Academic Press, pp. 97–185.

Faloye, O.T., Alatise, M.O., Ajayi, A.E., Ewulo, B.S., 2017. Synergistic effects of biochar and inorganic fertiliser on maize (Zea mays) yield in an alfisol under drip irrigation. Soil Tillage Res 174, 214–220. https://doi.org/10.1016/j.still.2017.07.013.

Ghoneim, A.M., E.E, G., Osman, M.M.A., 2018. Effects of Nitrogen Levels on Growth, Yield And Nitrogen use Efficiency Of Some Newly Released Egyptian Rice Genotypes, 3, 310–318. https://doi.org/10.1515/opag-2018-0034.

Ghorbani, M., Amirahmadi, E., 2024. Biochar and soil contributions to crop lodging and yield performance - A meta-analysis. Plant Physiol. Biochem. 215, 109053. https://doi.org/10.1016/j.plaphy.2024.109053.

Hou, H., Yang, Y., Han, Z., Cai, H., Li, Z., 2019. Deficit irrigation effectively reduces soil carbon dioxide emissions from wheat fields in Northwest China. J. ence Food Agric. 99. https://doi.org/10.1002/jsfa.9800.

Ibrahim, M.M., Tong, C., Hu, K., Zhou, B., Xing, S., Mao, Y., 2020. Biochar-fertilizer interaction modifies N-sorption, enzyme activities and microbial functional abundance regulating nitrogen retention in rhizosphere soil. Sci. Total Environ. 739, 140065. https://doi.org/10.1016/j.scitotenv.2020.140065.

Jiang, Y., Li, T., Xu, X., Sun, J., Pan, G., Cheng, K., 2024. A global assessment of the long-term effects of biochar application on crop yield. Curr. Res. Environ. Sustain. 7, 100247. https://doi.org/10.1016/j.crsust.2024.100247.

Jin, Z., Chen, C., Chen, X., Hopkins, I., Zhang, X., Han, Z., Jiang, F., Billy, G., 2019. The crucial factors of soil fertility and rapeseed yield - A five year field trial with biochar addition in upland red soil, China. Sci. Total Environ. 649, 1467–1480. https://doi.org/10.1016/j.scitotenv.2018.08.412.

Jyolsna, T., Vashisht, B.B., Yadav, M., Kaur, R., Jalota, S.K., 2024. Field and simulation studies on yield, water and nitrogen dynamics and use efficiency in rice-wheat crops in sequence. Field Crop. Res. 311, 109366. https://doi.org/10.1016/j.fcr.2024.109366.

Kang, S., Hao, X., Du, T., Tong, L., Su, X., Lu, H., Li, X., Huo, Z., Li, S., Ding, R., 2017. Improving agricultural water productivity to ensure food security in China under changing environment: From research to practice. Agric. Water Manag. 179, 5–17. https://doi.org/10.1016/j.agwat.2016.05.007.

Kong, L., Xie, Y., Hu, L., Feng, B., Li, S., 2016. Remobilization of vegetative nitrogen to developing grain in wheat (Triticum aestivum L. Field Crop. Res. 196, 134–144. https://doi.org/10.1016/j.fcr.2016.06.015.

Koutroubas, S.D., Fotiadis, S., Damalas, C.A., 2012. Biomass and nitrogen accumulation and translocation in spelt (Triticum spelta) grown in a Mediterranean area. Field Crop. Res. 127, 1–8. https://doi.org/10.1016/j.fcr.2011.10.011.

Kumar, A., Rana, K.S., Choudhary, A.K., Bana, R.S., Sharma, V.K., Prasad, S., Gupta, G., Choudhary, M., Pradhan, A., Rajpoot, S.K., Kumar, A., Kumar, A., Tyagi, V., 2021. Energy budgeting and carbon footprints of zero-tilled pigeonpea–wheat cropping system under sole or dual crop basis residue mulching and Zn-fertilization in a semi-arid agro-ecology. Energy 231, 120862. https://doi.org/10.1016/j.energy.2021.120862.

Lee, E.A., Tollenaar, M., 2007. Physiological basis of successful breeding strategies for maize grain yield. Crop Sci. 47, S202–S215. https://doi.org/10.2135/cropsci2007.04.0010IPBS.

Li, X., Liu, H., Li, J., He, X., Gong, P., Lin, E., Li, K., Li, L., Binley, A., 2020. Experimental study and multi–objective optimization for drip irrigation of grapes in arid areas of northwest China. Agric. Water Manag. 232, 106039. https://doi.org/10.1016/j.agwat.2020.106039.

Li, Y., Song, H., Zhou, L., Xu, Z., Zhou, G., 2019b. Vertical distributions of chlorophyll and nitrogen and their associations with photosynthesis under drought and rewatering regimes in a maize field. Agric. For. Meteorol. 272-273, 40–54. https://doi.org/10.1016/j.agrformet.2019.03.026.

Li, D., Tian, M., Cai, J., Jiang, D., Cao, W., Dai, T., 2013. Effects of low nitrogen supply on relationships between photosynthesis and nitrogen status at different leaf position in wheat seedlings. Plant Growth Regul. 70, 257–263. https://doi.org/10.1007/s10725-013-9797-4.

Li, S., Wang, S., Shangguan, Z., 2019a. Combined biochar and nitrogen fertilization at appropriate rates could balance the leaching and availability of soil inorganic nitrogen. Agric. Ecosyst. Environ. 276, 21–30.

Li, Z., Wang, B., Liu, Z., Zhang, P., Yang, B., Jia, Z., 2023. Ridge-furrow planting with film mulching and biochar addition can enhance the spring maize yield and water and nitrogen use efficiency by promoting root growth. Field Crop. Res. 303. https://doi.org/10.1016/j.fcr.2023.109139.

Liu, P., Guo, X., Zhou, D., Zhang, Q., Ren, X., Wang, R., Wang, X., Chen, X., Li, J., 2023. Quantify the effect of manure fertilizer addition and optimal nitrogen input on rainfed wheat yield and nitrogen requirement using nitrogen nutrition index. Agric. Ecosyst. Environ. 345, 108319. https://doi.org/10.1016/j.agee.2022.108319.

Liu, X., Yin, B., Bao, X., Hou, X., Wang, T., Shang, C., Yang, M., Zhen, W., 2024. Optimization of irrigation period improves wheat yield by regulating source-sink relationship under water deficit. Eur. J. Agron. 156, 127164. https://doi.org/10.1016/j.eja.2024.127164.

Lu, J., Hu, T., Geng, C., Cui, X., Fan, J., Zhang, F., 2021. Response of yield, yield components and water-nitrogen use efficiency of winter wheat to different drip fertigation regimes in Northwest China. Agric. Water Manag. 255, 107034. https://doi.org/10.1016/j.agwat.2021.107034.

Ma, L., Zhang, X., Lei, Q., Liu, F., 2021. Effects of drip irrigation nitrogen coupling on dry matter accumulation and yield of Summer Maize in arid areas of China. Field Crop. Res. 274, 108321. https://doi.org/10.1016/j.fcr.2021.108321.

Major, J., Rondon, M., Molina, D., Riha, S.J., Lehmann, J., 2010. Maize yield and nutrition during 4 years after biochar application to a Colombian savanna oxisol. Plant Soil 333, 117–128. https://doi.org/10.1007/s11104-010-0327-0.

Mehmood, F., Wang, G., Gao, Y., Liang, Y., Chen, J., Si, Z., Ramatshaba, T.S., Zain, M., Shafeeq-ur-rahman, Duan, A., 2019. Nitrous oxide emission from winter wheat field as responded to irrigation scheduling and irrigation methods in the North China Plain. Agric. Water Manag. 222. https://doi.org/10.1016/j.agwat.2019.06.015.

National Bureau of Statistics of China, 2023. China Statistical Yearbook, p. 5.

Omondi, M.O., 2016. Quantification of biochar effects on soil hydrological properties using meta-analysis of literature data. Geoderma 274, 28–34. https://doi.org/10.1016/j.geoderma.2016.03.029.

Pei, Y., Chen, X., Niu, Z., Su, X., Wang, Y., Wang, X., 2023. Effects of nitrogen fertilizer substitution by cow manure on yield, net GHG emissions, carbon and nitrogen footprints in sweet maize farmland in the Pearl River Delta in China. J. Clean. Prod. 399, 136676. https://doi.org/10.1016/j.jclepro.2023.136676.

Spokas, K.A., Novak, J.M., Venter Ea, R.T., 2012. Biochar's role as an alternative N-fertilizer: ammonia capture. Plant Soil 350, 35–42.

Tripathi, M., Sahu, J.N., Ganesan, P., 2016. Effect of process parameters on production of biochar from biomass waste through pyrolysis: A review. Renew. Sustain. Energy Rev. 55, 467–481. https://doi.org/10.1016/j.rser.2015.10.122.

Ullah, S., Dahlawi, S., Naeem, A., Rangel, Z., Naidu, R., 2017. Biochar application for the remediation of salt-affected soils: Challenges and opportunities. Sci. Total Environ. 625, 320. https://doi.org/10.1016/j.scitotenv.2017.12.257.

Ullah, H., Santiago-Arenas, R., Ferdous, Z., Attia, A., Datta, A., 2019. Chapter Two - Improving water use efficiency, nitrogen use efficiency, and radiation use efficiency in field crops under drought stress: A review. In: Sparks, D.L. (Ed.), Advances in Agronomy. Academic Press, pp. 109–157.

Vaziritabar, Y., Frei, M., Yan, F., Vaziritabar, Y., Honermeier, B., 2024. Enhancing nitrogen use efficiency and plant productivity in long-term precrop/crop rotation and fertilization management. Field Crop. Res. 306. https://doi.org/10.1016/j.fcr.2023.109210.

Visconti, F., Salvador, A., Navarro, P., Miguel de Paz, J., 2019. Effects of three irrigation systems on 'Piel de sapo' melon yield and quality under salinity conditions. Agric. Water Manag. 226. https://doi.org/10.1016/j.agwat.2019.105829.

Wan, H., Wei, Z., Liu, C., Yang, X., Wang, Y., Liu, F., 2024. Biochar amendment modulates xylem ionic constituents and ABA signaling: its implications in enhancing water-use efficiency of maize (Zea mays L.) under reduced irrigation regimes. J. Integr. Agric. https://doi.org/10.1016/j.jia.2024.03.073.

Wang, X., Xiang, Y., Guo, J., Tang, Z., Zhao, S., Wang, H., Li, Z., Zhang, F., 2023. Coupling effect analysis of drip irrigation and mixed slow-release nitrogen fertilizer on yield and physiological characteristics of winter wheat in Guanzhong area. Field Crop. Res. 302. https://doi.org/10.1016/j.fcr.2023.109103.

Wu, B., Zhang, L., Tian, J., Zhang, G., Zhang, W., 2022. Nitrogen rate for cotton should be adjusted according to water availability in arid regions. Field Crop. Res. 285, 108606. https://doi.org/10.1016/j.fcr.2022.108606.

Xiao, Q., Zhu, L.-x, Tang, L., Shen, Y.-f, Li, S.-q, 2017. Responses of crop nitrogen partitioning, translocation and soil nitrogen residue to biochar addition in a temperate dryland agricultural soil. Plant Soil 418, 405–421. https://doi.org/10.1007/s11104-017-3304-z.

Xing, Y., Zhang, T., Jiang, W., Li, P., Shi, P., Xu, G., Cheng, S., Cheng, Y., Fan, Z., Wang, X., 2022. Effects of irrigation and fertilization on different potato varieties growth, yield and resources use efficiency in the Northwest China. Agric. Water Manag. 261, 107351. https://doi.org/10.1016/j.agwat.2021.107351.

Xu, X., Zhang, M., Li, J., Liu, Z., Zhao, Z., Zhang, Y., Zhou, S., Wang, Z., 2018. Improving water use efficiency and grain yield of winter wheat by optimizing irrigations in the North China Plain. Field Crop. Res. 221, 219–227. https://doi.org/10.1016/j.fcr.2018.02.011.

Yan, S., Wu, Y., Fan, J., Zhang, F., Zheng, J., Qiang, S., Guo, J., Xiang, Y., Zou, H., Wu, L., 2020. Dynamic change and accumulation of grain macronutrient (N, P and K) concentrations in winter wheat under different drip fertigation regimes. Field Crop. Res. 250, 107767. https://doi.org/10.1016/j.fcr.2020.107767.

Yi, Q., Tang, S., Fan, X., Mu, Z., Pang, Y., Huang, X., Huang, Q., Hui, D., 2017. Effects of nitrogen application rate, nitrogen synergist and biochar on nitrous oxide emissions from vegetable field in south China. Plos One 12, e0175325.

Yu, L., Zhao, X., Gao, X., Siddique, K.H.M., 2020. Improving/maintaining water-use efficiency and yield of wheat by deficit irrigation: A global meta-analysis. Agric. Water Manag. 228, 105906. https://doi.org/10.1016/j.agwat.2019.105906.

Yuan, X., Gu, X., Liang, R., Ban, G., Ma, L., He, T., Wang, Z., 2024. Comparing combined application of biochar and nitrogen fertilizer in paddy and upland soils: Processes, enhancement strategies, and agricultural implications. Sci. Total Environ. 933, 173160. https://doi.org/10.1016/j.scitotenv.2024.173160.

Zhang, H., Jing, W., Zhao, B., Wang, W., Xu, Y., Zhang, W., Gu, J., Liu, L., Wang, Z., Yang, J., 2021. Alternative fertilizer and irrigation practices improve rice yield and resource use efficiency by regulating source-sink relationships. Field Crop. Res. 265, 108124. https://doi.org/10.1016/j.fcr.2021.108124.

Zhang, Y., Lei, H., Zhao, W., Shen, Y., Xiao, D., 2018. Comparison of the water budget for the typical cropland and pear orchard ecosystems in the North China Plain. Agric. Water Manag. 198, 53–64. https://doi.org/10.1016/j.agwat.2017.12.027.

Zhang, P., Liu, J., Wang, M., Zhang, H., Yang, N., Ma, J., Cai, H., 2024a. Effects of irrigation and fertilization with biochar on the growth, yield, and water/nitrogen use of maize on the Guanzhong Plain, China. Agric. Water Manag. 295, 108786. https://doi.org/10.1016/j.agwat.2024.108786.

Zhang, P., Liu, J., Zhang, H., Wang, M., Xu, J., Yu, L., Cai, H., 2024b. Deficit irrigation interacting with biochar mitigates N2O emissions from farmland in a wheat–maize rotation system. Agric. Water Manag. 297, 108843. https://doi.org/10.1016/j.agwat.2024.108843.

Zhang, F., Niu, J., Zhang, W., Chen, X., Li, C., Yuan, L., Xie, J., 2010. Potassium nutrition of crops under varied regimes of nitrogen supply. Plant Soil 335, 21–34. https://doi.org/10.1007/s11104-010-0323-4.

Zhang, Q., Song, Y., Wu, Z., Yan, X., Gunina, A., Kuzyakov, Y., Xiong, Z., 2020. Effects of six-year biochar amendment on soil aggregation, crop growth, and nitrogen and phosphorus use efficiencies in a rice-wheat rotation. J. Clean. Prod. 242, 118435. https://doi.org/10.1016/j.jclepro.2019.118435.

Zhang, N., Ye, X., Gao, Y., Liu, G., Liu, Z., Zhang, Q., Liu, E., Sun, S., Ren, X., Jia, Z., Siddique, K.H.M., Zhang, P., 2023. Environment and agricultural practices regulate enhanced biochar-induced soil carbon pools and crop yield: A meta-analysis. Sci. Total Environ. 905, 167290. https://doi.org/10.1016/j.scitotenv.2023.167290.