Journal of Soil Science and Plant Nutrition (2023) 23:1576–1588
https://doi.org/10.1007/s42729-023-01223-5

ORIGINAL PAPER

Biochar Amendment Increases C and N Retention in the Soil–Plant Systems: Its Implications in Enhancing Plant Growth and Water-Use Efficiency Under Reduced Irrigation Regimes of Maize (*Zea mays* L.)

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Received: 25 November 2022 / Accepted: 21 March 2023 / Published online: 17 April 2023

Abstract
Biochar influences soilbiophysicochemical processes and nutrient availability, yet the effects of different biochar and soil water dynamics on carbon (C) and nitrogen (N) retention in the soil–plant systems remain unknown. Maize plants were grown in split-root pots filled with clay loam soil amended with wheat straw pellet biochar (WSP) and softwood pellet biochar (SWP) at 2% (w/w) and were either irrigated daily to 90% of water-holding capacity (FI) or irrigated with 70% volume of water used for FI to the whole root-zone (DI) or alternately to half root-zone (PRD) from the fourth leaf to grain-filling stage. Compared to the unamended controls, biochar amendment enhanced plant biomass and water-use efficiency, particularly when combined with PRD. Although the WSP amendment tended to decrease soil net N mineralization rate, it significantly increased C and N retention in the soil–plant systems. Compared to DI, PRD significantly increased soil respiration rate while lowering soil total organic C content. Moreover, PRD increased soil inorganic N content, which might be related to increased mineralization of soil organic C (SOC) and soil organic N (SON). Such effects might implicate that PRD outperformed DI in enhancing the mineralization of soil organic matter. Although PRD alone might not be a sustainable irrigation method because of greater C and N losses, biochar addition could alleviate these undesirable effects via depressing SOC and SON mineralization. Biochar amendment, especially WSP combined with PRD, could be a promising practice to increase maize growth and water-use efficiency while sustaining C and N retention in the soil–plant systems.

Highlights
- Effects of biochar addition and irrigation regimes on C and N retention in the soil–plant systems of maize were investigated.
- Biochar increased plant N retention and maize growth. Partial root-zone drying (PRD) irrigation increased soil respiration rate and soil organic C and N mineralization.
- Biochar addition combined with PRD improved maize growth, water-use efficiency, and sustained C and N retention in the soil–plant systems.

Keywords Biochar · Drying/wetting cycles · C and N retention · Isotope composition · Mineralization

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1 Introduction

Reducing greenhouse gas emissions while enhancing carbon (C) and nitrogen (N) retention during agricultural production has received increased attention (Lal and Stewart 2009). Among other field practices, proper irrigation water management has been confirmed to increase C and N retention in the soil–plant systems (Lal 2008; Agyarko-Mintah et al. 2017a, b). However, global climate change causes an increased frequency of extreme drought episodes in many places around the world, especially in arid and semi-arid regions, where freshwater resources are limited and insufficient to irrigate the crops to meet their maximum evapotranspiration demand. Consequently, reduced irrigation techniques that only partially compensate plant water consumption have become common practices in drought-prone areas. Deficit irrigation (DI) is most widely used as a conventional practice of reduced irrigation, a technique that uses less irrigation water than plant evapotranspiration to improve crop water productivity (English and Raja 1996). However, reducing irrigation volume under DI will inevitably decrease crop growth and yield (Agbna et al. 2017), hence reduce the C and N retention in the plant biomass. Therefore, novel irrigation techniques need to be developed to save irrigation water and improve plant water-use efficiency (WUE) while having minor impact on crop yield.

Partial root-zone drying (PRD) irrigation is a modification of DI that involves irrigating only part of the root system while allowing the rest of the roots experiencing soil drying, and the irrigation side is swapped in frequency depending on the soil moisture and crop water status (Kang and Zhang 2004). Studies on many crop species have shown that PRD could save irrigation water and outperform DI in terms of maintaining yields and improving WUE (Sepaskhah and Ahmadi 2010; Wang et al. 2012, 2017; Wan et al. 2023). Moreover, the drying/rewetting cycles of the soil under PRD could result in the "Birch effect" (Birch 1958), stimulating the mineralization of soil organic matter, thereby increasing soil N bioavailability and crop N uptake (Wang et al. 2010a, b, c; Wang et al. 2012). However, it could lead to significant losses of soil C and N by enhancing soil respiration and denitrification (Sun et al. 2013).

It is widely accepted that amending soil with biochar has the potential to sequester C, increase soil nutrient retention, improve nutrient availability to plants, and reduce the leaching loss of N (Smith et al. 2010). However, Ameloot et al. (2015) and Liu et al. (2021a, b) argued that due to the carbon-rich feature of biochar, it increased soil C/N ratio, which might depress N mineralization rate, and therefore reduced N bioavailability to plants and ultimately adversely affect plant growth and yields (Wang et al. 2010c; Akhtar et al. 2015). The controversial effects of biochar addition on crop N content found in different experimental studies might be attributed to various irrigation regimes and soil types combined with biochar (Guo et al. 2021). Further, biochar could provide a stable C source for microbial activity and reproduction (Farrell et al. 2013), thereby affecting the uptake, migration, cycling, and dynamics of C and N in the soil–plant systems (Chen et al. 2015; Nguyen et al. 2017a, b). Generally, biochar properties, including the porous nature and greater specific surface area, could increase the capacity of microbial C metabolism (Palansooriya et al. 2019). However, there are very few studies concerning the combined effects of biochar and PRD on N mineralization and total C and N retention in the soil–plant systems (Sun et al. 2013; Akhtar et al. 2014; Liu et al. 2022).

It is well established that the evolution of natural isotope signatures of ^{13}C and ^{15}N could reflect the C and N biogeochemical cycles in the environment. For instance, Ladd et al. (2009) reported that ^{13}C is intimately connected with the transformation of soil organic matter and the process of plant CO_2 assimilation. Generally, soil microbes decompose the lighter carbon (^{12}C) in the soil organic matter preferentially, and a greater ^{13}C composition ($\delta^{13}C$) is often associated with a high mineralization rate (Sun et al. 2013). Further, plant ^{15}N can be used as a proxy to evaluate the soil organic N (SON) mineralization rate due to soil microorganisms selecting towards ^{14}N during mineralization, immobilization turnover procedure, and denitrification, maintaining SON enriched in ^{15}N (Kerley and Jarvis 1996). Thus, the plants grown in soils with large organic N pool would be enriched in ^{15}N in biomass compared with plants that obtain N mainly from the inorganic chemical fertilizer N (Craine et al. 2009; Hobbie and Hogberg 2012). The modulation of ^{13}C and ^{15}N isotope compositions in soil and plant samples in response to PRD treatment or biochar addition has been well documented (Wang et al. 2010b; Sun et al. 2013; Chen et al. 2015). Yet, the combined effects of biochar and PRD on ^{13}C and ^{15}N isotope signatures as well as their inter-relationships to C and N dynamics in the soil–plant systems remain unexplored.

Therefore, the objective of this study was to explore the underlying mechanisms in the soil–plant systems regarding the combined effects of biochar addition and PRD on C and N retention in maize. We hypothesized that biochar amendment could ameliorate the negative impact of PRD on C and N retention, while PRD could enhance soil N mineralization, bioavailability, and crop WUE under biochar amendment; therefore, biochar addition combined with PRD could synergistically enhance crop WUE and C and N retention in the soil–plant systems.

2 Materials and Methods

2.1 Experimental Setup

The pot experiment was carried out in a greenhouse at the Northwest A&F University, Yangling, Shaanxi, China (34° 16'N, 108° 4° E), from April 5 to July 10, 2021. The experimental factors included biochar and irrigation. The maize (*Zea mays* L.) seeds were obtained from the College of Agronomy, Northwest A&F University. The seedlings were transplanted into the pots at the 4-leaf stage. The pot (18 cm length, 16 cm width, and 30 cm height) was filled with 9.0 kg biochar-soil mixtures at a 2% (w/w) ratio, with non-biochar soils serving as controls. The soil collected from the topsoil (10–30 cm depth) of the field in Yangling was sieved through a 5-mm sieve after air-drying. It had a 30.0% water-holding capacity, 5.0% permanent wilting point, and 1.30 g cm^{-3} bulk density. Either biochar of mixed softwood pellets (SWP) or wheat straw pellets (WSP) was produced by the UK Biochar Research Centre, UK. Both biochar materials were made in a pilot-scale rotary kiln pyrolysis unit with a nominal peak temperature of 550 ℃, which were generated at a heating rate of 78 ℃/min and 80 ℃/min, with the mean time at highest treatment temperature which was 3.9 min and 5 min, respectively. The pelletized biochar materials were crushed and passed through a 0.45-mm mesh. Plastic sheets were used to partition the pots evenly into two vertical compartments, preventing water interchange between the two compartments. From the upper center of the sheet where the maize seedling was transplanted, a short plastic piece (3 × 6 cm) was taken out. To ensure the nutrient requirement for plant growth during the experiment, 2 g N, 2 g P, and 0.22 g K (as urea, KH_2PO_4, and $KH_2PO_4 + K_2SO_4$, respectively) were applied before transplanting with irrigation water. The selected soil and biochar properties are shown in Table 1.

2.2 Irrigation Treatment

The experiment was a complete factorial randomized design involving 9 treatments, each with four replicates, three biochar treatments (non-biochar serving as controls, SWP, and WSP), and three irrigation regimes (full irrigation, FI; deficit irrigation, DI; partial root-zone drying PRD irrigation, PRD). During the first 30 days after planting, all containers were watered to 90% of their water-holding capacity. Subsequently, three irrigation treatments were imposed: FI, the whole pots were daily irrigated to 90% of water-holding capacity; DI, the whole pots were daily irrigated with 70% volume of water used in FI; and PRD, the amount of irrigation on one compartment is the same as the DI, and the irrigation was switched while the soil water content (SWC, vol. %) of the other compartment decreased to 10%–12%. The average SWC was measured using a time-domain reflectometer (TDR, TRASE, Soil Moisture Equipment Crop., Goleta, CA, USA) at 4:00 P.M. each day. At the onset of the irrigation treatments, a 2-cm layer of perlite was applied to the soil surface to minimize soil evaporation. The irrigation treatment lasted 9 weeks, during which each soil compartment of the PRD-treated plants was subjected to 3 drying/wetting cycles.

2.3 Measurement and Analysis

2.3.1 Plant Water Use, Dry Biomass, and Water-Use Efficiency

Plant water use (WU) during the irrigation period was calculated based on the amount of irrigation and changes of SWC in the pots. At the end of the irrigation treatment, the leaves, stalks, and roots were harvested separately. The plant samples were placed in an oven at 105 ℃ for 30 min and then dried at 75 ℃ for 48 h to constant weight to get total dry biomass (TDM). Plant water-use efficiency (WUE) was calculated as the ratio of TDM to WU during the irrigation treatment period.

2.3.2 Soil Respiration Rate and Soil Water Content

Soil respiration rate (SRR) was determined using the combination of the 6800–09 gas chamber and a portable photosynthetic system (LI-6800, Li-Cor, Inc., Lincoln, SEC, USA).

Table 1 Soil and biochar properties

Factor	Soil	SWP	WSP
Clay (< 0.002 mm, %)	8	-	-
Silt (0.05–0.002 mm, %)	85	-	-
Sand (2–0.05 mm, %)	7	-	-
pH	7.7	7.9	9.9
EC (μS cm^{-1})	360	90	1700
CEC (cmol + kg^{-1})	2.0	3.2	6.2
Total C (%)	1.8	85.5	68.3
Total N (%)	0.1	< 0.1	1.4
Total P[(c)] (%)	0.1	0.1	0.1
Total K[(c)] (%)	2.4	0.3	1.6
C:N	18	< 855.2	49.1
$H:C_{tot}$	-	0.4	0.4
$O:C_{tot}$	-	0.1	0.1
(O + N):C		< 0.1	0.1
$\delta^{13}C$	− 14.0	− 28.8	− 29.4
$\delta^{15}N$	5.0	4.0	− 0.7
Surface area (m^2 g^{-1})	-	26.4	26.4
Total ash[(a)] (%)	-	1.3	21.2
C stability[(b)] (%)	-	69.6	96.5

Note: [(a)]TGA, [(b)]Cross A, Sohi SP (2013), and [(c)]Aqua Regia digestion followed by ICP

One hundred grams of air-dried soil was placed in each nylon bag (140–150 microns, 8 × 6 × 1 cm) that prevented the effects of root respiration while allowing air and water to flow freely (Wang et al. 2010c). After transplanting, the bags were placed vertically into each soil compartment of the pots. All the top of the bags were covered with the surface of the soil, and the base of the bags was about 8–10 cm in depth. The SRR was measured 2–3 days before irrigation shifts in the PRD treatment. To measure SRR, the bag was removed from the pot and placed it in the Li-6800–09 gas chamber; the continuous measurement time was 90 s with three replicates. Subsequently, each nylon bag was weighed, and the soil water content (SWC) was determined to analyze the relationship between SSR and SWC. After measurement, the bags were reburied into the soil in each pot at the same position.

2.3.3 Soil Total Organic C Content

All soil samples were air-dried after harvesting the maize plants, then pulverized and passed through a 0.15-mm sieve. The soil total C and inorganic C were assessed by TOC-V_{Series} SSM-5000A (Solid Sample Measurement). The samples were placed in the ceramic boat and then pushed into a heated sample chamber (900 ℃) for total C determination. When determining inorganic C, the samples were placed in the ceramic boat and acidified, then rapidly propelled into a heating chamber (900 ℃) for determination. SOC_{tot} is the difference between the contents of the soil total C and inorganic C.

2.3.4 C, N content, and Stable Isotope Analysis

Oven-dried soil and plant samples were ground to a fine powder for C and N content analysis by the Dumas dry combustion method. The amounts of soil and plant C and N per pot were calculated accordingly. Then, the total amount of C and N retention in the soil–plant systems was estimated based on the sum of C and N in soils and plants, respectively. $^{13}C/^{12}C$ and $^{15}N/^{14}N$ ratios in the leaf and soil samples were measured with an Elemental Analyser System (vario PYRO cube, Elemental Analysensysteme GmbH, Germany) coupled to an Isotope Mass Spectrometer (Isoprime 100, Elemental Analysensysteme GmbH, Germany). Isotope compositions in [‰] are calculated as follows:

$$\delta = \left[\left(R_{sample}/R_{standard}\right) - 1\right]$$

where R_{sample} are the measured $^{13}C/^{12}C$ and $^{15}N/^{14}N$ ratios of the sample; $R_{standard}$ are the measured $^{13}C/^{12}C$ and $^{15}N/^{14}N$ ratios of the standard. $\delta^{13}C$ values are expressed relative to Pee Dee Belemnite (PDB). δ^{15} values are expressed based on the AIR-N_2 scale.

2.3.5 Soil Inorganic N Content and Apparent Net N Mineralization

On 0 and 66 days after treatment (DAT), the soil inorganic N was measured. Fresh soil samples were extracted in a shaker for 45 min with 1 M KCl (soil: extractant = 1:4) and then filtered and stored in a refrigerator of − 20 °C for analyzing. NO_3^- and NH_4^+ concentrations in the extract were measured by a continuous flow analyzer (Autoanalyzer 3, Bran + Luebbe GmbH, Norderstedt, Germany). The apparent net N mineralization was computed by subtracting the initial soil mineral N from the total amounts of plant biomass N and soil inorganic N at the end of the experiment. Notably, this method of calculating the apparent net N mineralization needs to account for the possible influence of ammonia volatilization. Therefore, the actual values of net N mineralization may vary from those stated below. Nevertheless, the method can be used to compare the effects of irrigation treatment and biochar amendment on soil N mineralization.

2.4 Statistical Analysis

All the data were analyzed by two-way analysis of variance (ANOVA) using IBM SPSS Statistics 23 (SPSS Inc., NY, USA). Tukey's multiple range test calculated the differences between treatments at a 5% significance level. The Shapiro–Wilk test was used to ensure that the data were typically spread, and Levene's test was used to check for homogeneity of variance. The significance of the correlation was assessed using Pearson's product-moment. The correlation between some of the observed values was determined using regression analysis. The variation in the relationship between soil respiration rate and soil water content in relation to biochar treatments was statistically analyzed by analysis of covariance (ANCOVA), with soil respiration rate as the dependent factor, soil water content as the independent variable, and the biochar treatments as the covariate.

3 Results

3.1 Soil Water Status

The changes in daily average volumetric SWC during the irrigation experiment under different biochar addition are shown in Fig. 1. We monitored daily the dynamics of soil moisture in four pots of each treatment. We found that compared to DI, PRD possessed a relatively greater daily average SWC, i.e., the average of dry and wet soil compartments.

3.2 Plant Water Use, Dry Biomass, and Water-Use Efficiency

The plants grown under biochar addition, especially with WSP, had greater WU than those grown under non-biochar controls. Predictably, reduced irrigation treatments (DI and PRD) decreased the WU in relation to FI (Table 2). The TDM of maize plant differed significantly among the biochar treatments (Table 2), being 1.5-fold greater in the biochar treatment than the non-biochar controls, particularly under WSP. Although TDM was not significantly affected by the irrigation treatment, PRD plants possessed slightly greater TDM (5.2%) than did DI (Table 2). The plants grown under reduced irrigation had greater WUE (34.5%) than FI plants, where PRD plants possessed 9.1% higher WUE than did DI (Table 2). Although biochar addition significantly increased WU compared to the non-biochar controls, the plants grown under biochar amendment possessed greater WUE (27.5%) than those grown under unamended soils regardless of the irrigation treatment, and the effect was more pronounced under WSP addition (Table 2).

3.3 Soil Respiration Rate, Soil Water Content, and Their Relationship

SRR was solely significantly affected by the irrigation treatment (Table 3), where reduced irrigation significantly decreased SRR compared to FI. In PRD, the SRR varied according to which soil compartment was being irrigated, and it was much greater in the wet compartment than that in the dry compartment. DI treatment possessed the lowest values of SRR except those with WSP addition. Compared to DI, PRD significantly increased SRR (Supplementary Table 1). SWC was affected by irrigation treatment (Table 3), where FI treatment possessed higher SWC compared to that of the reduced irrigation. The SWC of the irrigated side of the PRD pot was much greater compared to that of the dry side. Across the nine treatments, Tukey's multiple range test showed that the control-FI treatment had the highest SWC, followed by control-PRD treatment and WSP-PRD treatment as the lowest. When pooling all the data from the various biochar addition and irrigation treatment, SRR had a significant positive correlation with SWC, showing that SRR increased with increasing SWC (Fig. 2). Further, based on the results of the ANCOVA analysis, biochar addition positively influenced the relationship between SSR and SWC compared to the no biochar addition, and the difference between WSP and SWP was not statistically significant.

3.4 Soil Total Organic C, Inorganic N Content, and Net N Mineralization

SOC_{tot} was significantly affected by the biochar addition and irrigation treatment (Fig. 3). Regardless of irrigation treatment, biochar amendment significantly increased SOC_{tot} in relation to the non-biochar controls. Across the biochar treatment, reduced irrigation had higher SOC_{tot} compared to FI, which was slightly greater in DI than in PRD (Supplementary Table 1). There was a significant interaction between biochar and irrigation on SOC_{tot}, and across the nine treatments, WSP-DI possessed the highest SOC_{tot} and the control-FI as the lowest.

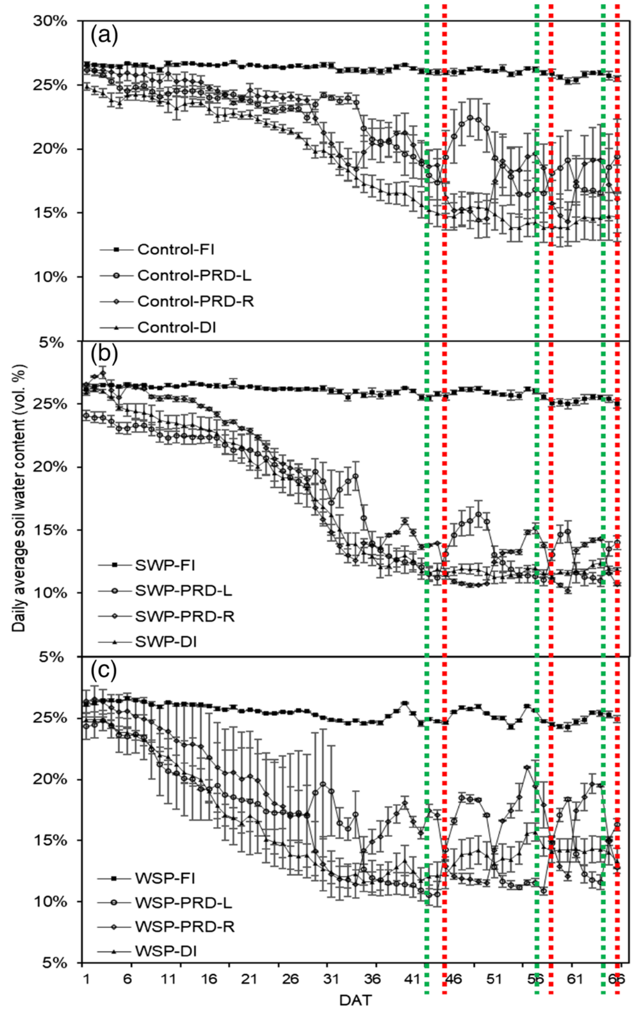

Fig. 1 Daily means of soil water content (θ, %) in the pots of maize plants exposed to different biochar (control, SWP, and WSP) and irrigation (FI, DI, PRD-L, and PRD-R) treatments. PRD-L and PRD-R represent the left and the right soil compartment of the PRD pots, respectively. Values are the mean ± standard error ($n = 4$)

Soil NH_4^+-N and NO_3^--N contents were significantly affected by the biochar and irrigation treatment as well as their interaction (Fig. 4a, b). For soil NH_4^+-N content, biochar addition possessed the lowest value compared to the unamended soils, and SWP addition significantly increased soil NH_4^+-N content than WSP. Among the three irrigation treatments, a greater NH_4^+-N content was found in FI than in reduced irrigation. For soil NO_3^--N content, SWP had the

Table 2 The effects of treatments and output of two-way ANOVA for plant water use (WU), total dry biomass (TDM), and water-use efficiency (WUE) of maize plants. The treatments are different biochar (control, SWP, and WSP) and irrigation (FI, DI, and PRD)

Biochar (B)	Irrigation (I)	WU (L plant^{-1})	TDM (g plant^{-1})	WUE (g L^{-1})
Control	FI	8.14 ± 1.15	22.32 ± 4.96	2.68 ± 0.22
	PRD	5.66 ± 0.00	24.99 ± 4.43	4.42 ± 0.78
	DI	5.62 ± 0.04	26.11 ± 2.12	4.64 ± 0.35
SWP	FI	10.65 ± 1.42	44.87 ± 3.30	4.36 ± 0.39
	PRD	7.23 ± 0.21	37.53 ± 3.88	5.15 ± 0.41
	DI	6.86 ± 0.58	31.65 ± 6.36	4.45 ± 0.66
WSP	FI	16.80 ± 0.38	71.2 ± 1.52	4.25 ± 0.15
	PRD	10.19 ± 0.91	64.22 ± 0.91	6.28 ± 0.55
	DI	11.75 ± 0.00	62.30 ± 2.78	5.44 ± 0.27
ANOVA				
Biochar (B)		***	***	**
Irrigation (I)		***	ns	**
B* I		ns	ns	ns

Values are the mean ± standard error (n = 4). ** and *** indicate significant levels at $P < 0.01$ and $P < 0.001$, respectively. ns indicates no statistical significance

Table 3 The effects of treatments and output of two-way ANOVA for soil respiration rate (SRR), soil water content (SWC), and SRR/SWC ratio of maize plants. The treatments are different biochar (control, SWP, and WSP) and irrigation (FI, DI, and PRD)

Biochar (B)	Irrigation (I)	SRR (mmol s^{-1} g^{-1})	SWC (vol. %)
Control	FI	1.31 ± 0.32	29.65 ± 1.87^{a}
	PRD-L	0.48 ± 0.08	27.35 ± 1.52^{ab}
	PRD-R	0.37 ± 0.03	15.20 ± 3.82^{bcd}
	DI	0.35 ± 0.04	15.58 ± 1.18^{bcd}
SWP	FI	1.06 ± 0.21	23.19 ± 3.54^{abcd}
	PRD-L	0.94 ± 0.05	22.03 ± 4.00^{abcd}
	PRD-R	0.50 ± 0.13	12.47 ± 1.38^{cd}
	DI	0.50 ± 0.06	12.40 ± 0.68^{cd}
WSP	FI	1.43 ± 0.19	25.10 ± 1.91^{abc}
	PRD-L	0.73 ± 0.09	22.43 ± 2.37^{abcd}
	PRD-R	0.36 ± 0.07	10.73 ± 2.36^{d}
	DI	0.67 ± 0.04	16.81 ± 1.29^{abcd}
ANOVA			
Biochar (B)		ns	ns
Irrigation (I)		***	***
B* I		ns	*

Values are the mean ± standard error (n = 4). * and *** indicate significant levels at $P < 0.05$ and $P < 0.001$, respectively. ns indicates no statistical significance. Different letters following the mean indicate significant differences between treatments at $P < 0.05$ level by the Tukey's test

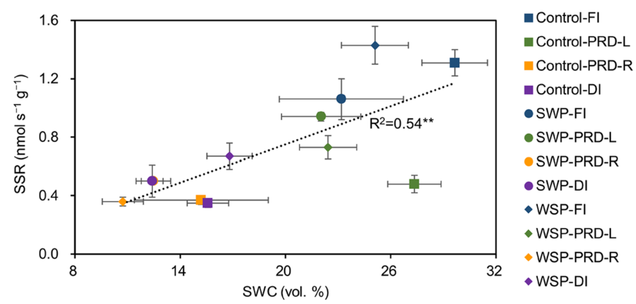

Fig. 2 Relationship between averaged soil respiration rate and soil water content of maize plants exposed to different biochar (control, SWP, and WSP) and irrigation (FI, DI, PRD-L, and PRD-R) treatments. PRD-L and PRD-R represent the left and the right soil compartment of the PRD pots, respectively. Values are the mean ± standard error (n = 4)

highest soil NO_3^--N content, followed by non-biochar controls, and WSP was the lowest irrespective of irrigation treatments. Across the SWP and non-biochar controls, FI treatment significantly increased soil NO_3^--N content compared to the reduced irrigation, and PRD had a higher value than that of DI treatment. Across the nine treatments, Tukey's multiple range tests showed that the control-FI had the highest NH_4^+-N content, followed by control-PRD and WSP-DI, the lowest; WSP-PRD had the highest NO_3^--N content, followed by control-FI plants, and WSP-FI plants had the lowest. Likewise, the response of soil inorganic N content (i.e., the sum of NH_4^+-N and NO_3^--N) to the biochar addition and irrigation treatment and their interaction showed a similar pattern of change as observed in NO_3^--N content (Fig. 4c). Net N mineralization was significantly affected by the biochar and irrigation treatments as well as their interaction (Fig. 4d). Across the three irrigation treatments, WSP application decreased net N mineralization by 20% on average compared to the non-biochar controls, whereas SWP application possessed the highest N mineralization, followed by the non-biochar controls. Under SWP addition and the non-biochar controls, FI led to significant greater net N mineralization in relation to the reduced irrigation, though

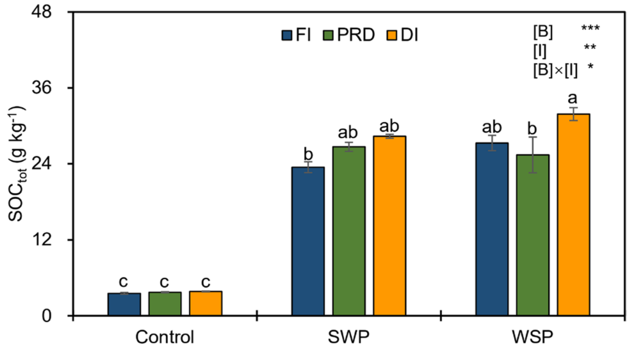

Fig. 3 Soil total organic C content (SOC_{tot}) of maize plants exposed to different biochar (control, SWP, and WSP) and irrigation (FI, DI, and PRD) treatments. Values are the mean ± standard error ($n = 4$). *, **, and *** indicate significant levels at $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively. ns indicates no statistical significance. Different letters in the bars indicate significant differences between treatments at $P < 0.05$ level by the Tukey's test

FI caused a lesser net N mineralization than did reduced irrigation under WSP addition. Interestingly, PRD possessed a higher net N mineralization than DI, disregarding the biochar treatments (Supplementary Table 1).

3.5 C and N Retention in the Soil–Plant Systems

Soil C and N retention varied among the biochar treatments, being separately 112.4% and 44.1% greater in the biochar-amended soils than that in the unamended soils (Table 4), and the increase in soil N retention was more evident upon WSP addition. There were significant interactions between biochar and irrigation on soil C and N retention; across the nine treatments, WSP-DI possessed the highest, and control-FI was the lowest (Table 4). WSP and SWP amendment possessed greater plant C and N retention by 171.6% and 118.6%, 56.6%, and 46.0% compared to the unamended controls, respectively (Table 4). The total amounts of C and N retention in the soil–plant systems were significantly affected by the biochar addition, where WSP and SWP addition significantly increased the total amounts of C and N retention by 118.8% and 73.1%, 107.0%, and 31.5% compared to the unamended controls, respectively. As there were significant interactions between biochar and irrigation on C and N retention in the soil–plant systems, Tukey's multiple range tests showed that the WSP-DI had the highest value followed by WSP-FI and the control-FI as the lowest. Although the irrigation did not significantly affect C and N retention in the plant-soil systems, PRD slightly decreased it as compared with DI (Table 4; Supplementary Table 1).

3.6 ^{13}C and ^{15}N Isotope Composition in the Soil and Leaf

$\delta^{13}C_{soil}$ and $\delta^{15}N_{soil}$ were solely significantly affected by the biochar addition (Fig. 5a, b), where the biochar addition possessed lower $\delta^{13}C_{soil}$ as compared with the unamended soils. Likewise, $\delta^{15}N_{soil}$ was significantly lower with biochar addition than the unamended soils. $\delta^{13}C_{leaf}$ was not affected by both biochar and irrigation treatment as well as their interaction (Fig. 5c), whereas $\delta^{15}N_{leaf}$ was significantly affected by the two factors (Fig. 5d). Across the three irrigation treatments, biochar addition had lower $\delta^{15}N_{leaf}$ compared to the non-biochar controls; while across the biochar amendments, reduced irrigation significantly decreased $\delta^{15}N_{leaf}$ in relation to FI treatment, and $\delta^{15}N_{leaf}$ was significantly higher in PRD than that in DI treatment (Fig. 5d; Supplementary Table 1).

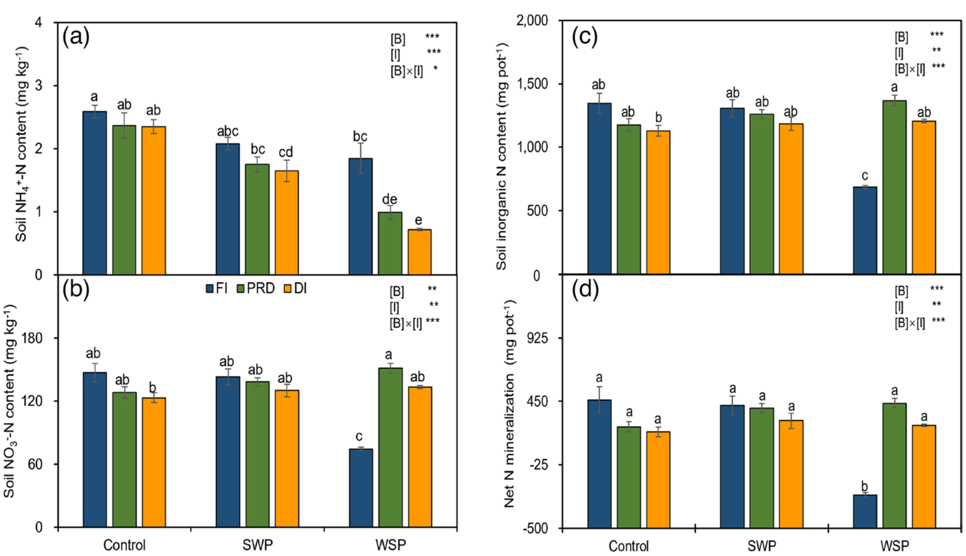

Fig. 4 a Soil NH_4^+-N content, **b** soil NO_3^--N, **c** soil inorganic N content, and **d** net N mineralization of maize plants exposed to different biochar (control, SWP, and WSP) and irrigation (FI, DI, and PRD) treatments. Values are the mean ± standard error ($n = 4$). *, **, and *** indicate significant levels at $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively. ns indicates no statistical significance. Different letters in the bars indicate significant differences between treatments at $P < 0.05$ level by the Tukey's test

Table 4 The effects of treatments and output of two-way ANOVA for plant C and N retention and soil C and N retention and the total amounts of C and N retention in the soil–plant systems. The treatments are different biochar (control, SWP, and WSP) and irrigation (FI, DI, and PRD)

Biochar (B)	Irrigation (I)	C retention (g pot^{-1})			N retention (g pot^{-1})		
		Plant	Soil	Plant + soil	Plant	Soil	Plant + soil
Control	FI	26.90 ± 6.27	175.87 ± 5.13^{c}	202.78 ± 5.53^{c}	1.39 ± 0.26	5.39 ± 0.16^{d}	6.78 ± 0.21^{d}
	PRD	30.01 ± 5.38	179.88 ± 4.44^{c}	208.89 ± 8.86^{c}	1.49 ± 0.24	5.42 ± 0.32^{d}	6.91 ± 0.56^{cd}
	DI	32.30 ± 2.65	183.49 ± 3.53^{c}	215.79 ± 5.97^{c}	1.58 ± 0.09	5.42 ± 0.02^{d}	7.00 ± 0.08^{cd}
SWP	FI	55.34 ± 4.11	379.91 ± 5.75^{ab}	435.26 ± 7.98^{ab}	2.53 ± 0.18	6.93 ± 0.13^{c}	9.46 ± 0.28^{b}
	PRD	46.13 ± 5.39	398.95 ± 8.69^{ab}	445.08 ± 13.81^{ab}	2.18 ± 0.23	7.05 ± 0.15^{c}	9.23 ± 0.24^{b}
	DI	38.25 ± 7.90	380.29 ± 4.71^{ab}	418.55 ± 8.72^{b}	1.80 ± 0.35	6.72 ± 0.25^{c}	8.52 ± 0.51^{bc}
WSP	FI	87.57 ± 1.63	371.45 ± 8.80^{ab}	459.02 ± 7.90^{ab}	3.50 ± 0.10	8.34 ± 0.18^{b}	11.84 ± 0.22^{a}
	PRD	75.97 ± 1.90	346.08 ± 28.12^{b}	422.05 ± 29.89^{b}	3.10 ± 0.10	8.22 ± 0.42^{b}	11.33 ± 0.49^{a}
	DI	77.84 ± 4.39	413.72 ± 9.21^{a}	491.56 ± 5.92^{a}	3.15 ± 0.18	9.50 ± 0.30^{a}	12.65 ± 0.17^{a}
ANOVA							
Biochar (B)		***	***	***	***	***	***
Irrigation (I)		ns	ns	ns	ns	ns	ns
B * I		ns	*	*	ns	*	*

Values are the mean ± standard error ($n = 4$). * and *** indicate significant levels at $P < 0.05$ and $P < 0.001$, respectively. ns indicates no statistical significance. Different letters following the mean indicate significant differences between treatments at $P < 0.05$ level by the Tukey's test

3.7 Regression Analysis Between Some Measured Variables

Significant linear relationships between TDM with WU and plant N content were observed (Fig. 6a, b), indicating that neither irrigation treatment nor biochar addition affected these relationships. In addition, there was a significant positive linear relationship between WUE and $\delta^{13}C_{leaf}$ across all treatments (Fig. 6c), implying that WUE was closely associated with $\delta^{13}C_{leaf}$.

4 Discussion

In the present study, biochar addition significantly increased the TDM of maize plants compared to the non-biochar controls regardless of irrigation treatment, especially with WSP addition (Table 2). The enhancement of TDM in the biochar treatments could be attributed to biochar and could improve soil physicochemical and hydrological properties in terms of bulk density, mineral elements, cation exchange capacity, and water retention

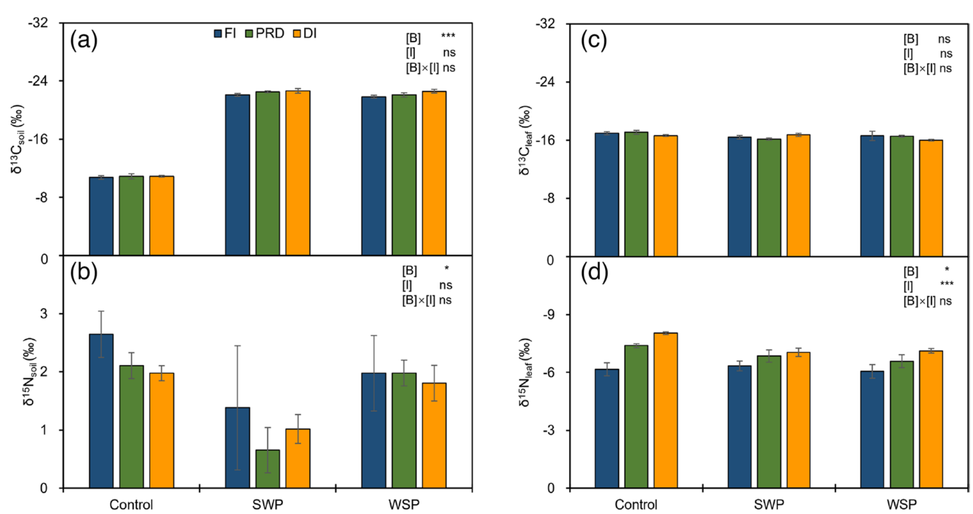

Fig. 5 a Soil carbon isotope composition ($\delta^{13}N_{soil}$), **b** soil nitrogen isotope composition ($\delta^{15}C_{soil}$), **c** leaf carbon isotope composition ($\delta^{13}C_{leaf}$), and **d** leaf nitrogen isotope composition ($\delta^{15}N_{leaf}$) of maize plants exposed to different biochar (control, SWP, and WSP) and irrigation (FI, DI, and PRD) treatments. Values are the mean ± standard error ($n = 4$). * and *** indicate significant levels at $P < 0.05$ and $P < 0.001$, respectively. ns indicates no statistical significance

capacity (Liu et al. 2021a). In addition, biochar application, particularly WSP, enhanced soil available nutrient pools. All these beneficial effects contributed to improved plant nutrient uptake and shoot growth consequently enhanced plant biomass accumulation (Wan et al. 2023). The greater TDM in the plants with biochar amended could be attributed to greater WU and WUE (Table 2). Such results were in accordance with our previous works (Guo et al. 2021), where plants grown in the biochar treatments possessed higher leaf gas exchange rates (e.g., stomatal conductance and transpiration rate) leading to greater WU, which contributed to the increase in TDM of maize plants (Fig. 6a).

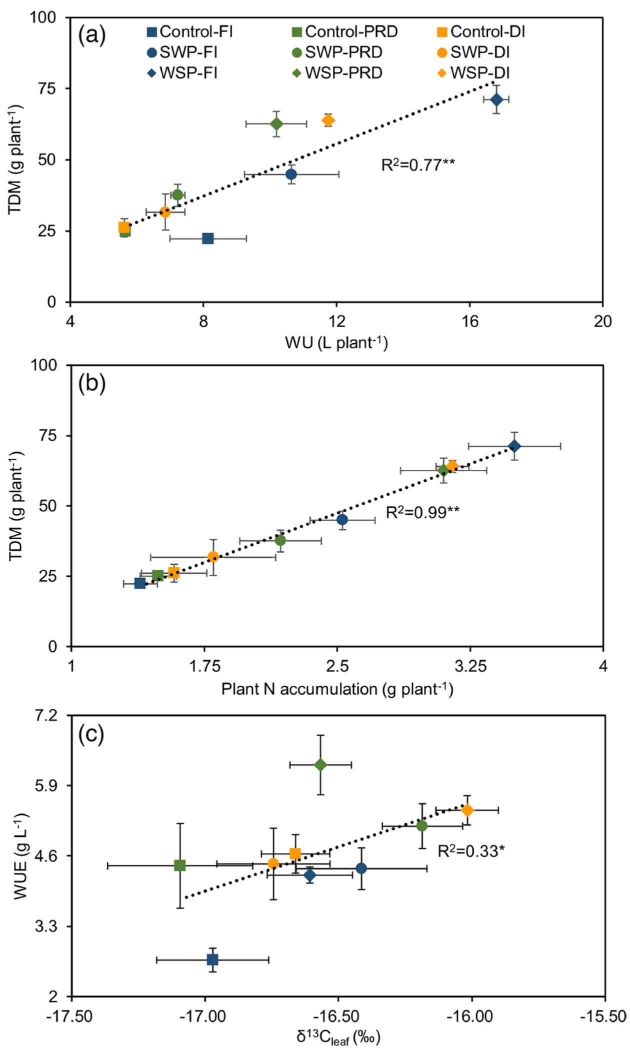

Fig. 6 Linear relationships between **a** plant water use (WU) and plant total dry biomass (TDM), **b** plant N retention and plant total dry biomass (TDM), and **c** leaf carbon isotope composition ($\delta^{13}C_{leaf}$) and plant water-use efficiency (WUE) of maize plants exposed to different biochar (control, SWP, and WSP) and irrigation (FI, DI, and PRD) treatments. Values are the mean ± standard error ($n=4$). * and ** indicate significant levels at $P<0.05$ and $P<0.01$, respectively

Although there was no statistically significant effect of the irrigation treatment on TDM, reduced irrigation treatments significantly increased the WUE compared to FI treatment (Table 2). Given the same amount of irrigation volume, PRD slightly increased TDM and WUE relative to DI though not statistically significant (Supplementary Table 1), affirming our earlier findings in potato (Sun et al. 2013) and maize (Wang et al. 2012). Nevertheless, in the present study, we found that PRD maintained better soil water content (SWC) than DI (Fig. 1; Table 3; Supplementary Table 1), probably due to PRD induced stronger root-to-shoot ABA signaling (Liu et al. 2021b); hence, more efficient in inducing partial stomatal closure and curtailing transpiration rate consequently sustained greater soil available water content leading to higher microbial activities and mineralization rate in the soil. For instance, Xiang et al. (2008) reported that drying/wetting cycles of the soil could lead to an increase in microbial activities and soil respiration rate (SSR). Indeed, our results revealed that PRD treatment had greater respiration rate and soil moisture compared to DI (Table 3; Supplementary Table 1), which might enhance decomposition of soil organic matter and potentially lead to increased soil C and N losses (Sun et al. 2013). As expected, a positive correlation between SRR and SWC was noticed in this study (Fig. 2), which to a certain extent indicated that greater soil water availability allows higher microbial activity, stimulating the decomposition of soil organic matter (Wang et al. 2010a). Such effect of soil drying/wetting cycles on soil organic matter turnover is known as the "Birch effect" (Birch 1958). Besides here, it was found that the application of biochar had little impact on soil C mineralization while the soil drying/wetting cycles are conducive to C mineralization (Table 3). Compared to DI, PRD significantly decreased soil total organic C content while increasing soil inorganic N content (Figs. 3 and 4a–c; Supplementary Table 1), which might be due to the fact that PRD increased SSR and microbial substrates availability, resulting in increased mineralization rate (Sun et al. 2013). Nonetheless, such difference in SRR between the two reduced irrigation regimes did not lead to significant difference in the C and N retention in the soil–plant systems (Table 4). As in Sun et al. (2013), it was noteworthy that the total amounts of C and N retention were slightly lower under PRD treatment than that of the DI (Table 4; Supplementary Table 1), indicating that PRD increased C and N losses in the soil–plant systems.

In addition, earlier findings have shown that the short-term priming effect of biochar amendment could promote the decomposition of soil organic carbon, facilitating a transitory increase in SSR and weakened C sequestration ability of biochar (Wardle et al. 2008). Sagrilo et al. (2015) also confirmed that in a short-term field trial, biochar application significantly enhanced SSR by about 28%. This was, however, not the case in the present study, where SSR seemed less responsive to biochar addition (Table 3). Nevertheless, the ANCOVA analysis revealed that biochar addition significantly altered the relationship between SSR and SWC compared to the non-biochar controls, implying that biochar could effectively stimulate microbial respiration at a given soil moisture condition. According to the findings of Castaldi et al. (2011) and Schimmelpfennig et al. (2014), the response of soil to biochar varies depending on the particle size and pyrolyzing temperature of the biochar. Generally, a finer biochar particle is more accessible for microorganisms to absorb and utilize, resulting in a greater SSR (Troy et al. 2013). Further, Sagrilo et al. (2015) revealed that when the pyrolysis temperature was higher than 350 ℃, SSR might not be affected by biochar amendment. A suitable ambient temperature and soil moisture are conducive to the reproduction and activity of microbial populations (Chan-Yam et al. 2019). Moreover, the amount of biochar added was also a major factor influencing SSR, with application rates that were positively correlated with SSR (Liang et al. 2010). Hence, the effects of biochar addition on SSR are closely related to the properties of biochar.

There are fewer studies on the effect of biochar addition on soil N mineralization than C mineralization. Our results reported that the application of biochar significantly decreased NH_4^+-N especially with WSP application regardless of the irrigation treatment (Fig. 4a), which resulted in reduced accumulation of mineral N (Fig. 4d). As previously reported by Dempster et al. (2012), where biochar addition significantly reduced the content of inorganic N pool, which was mainly due to that, biochar addition had a negative priming effect on the decomposition of soil organic matter and thus limited nitrification. Besides, the adsorption of N compounds by biochar is another mechanism to explain the lowered inorganic N content upon biochar amendment (Xu et al. 2016). It was reported that the free NH_4^+-N could be adsorbed by biochar, leading to a reduction in the amount of NH_4^+-N in the soil, weakening the nitrification of NH_4^+-N into NO_3^-N, and thus lessening NO_3^--N availability (Xu et al. 2016). It was notable that the soil added by WSP possessed lower soil NH_4^+-N content than did SWP (Fig. 4a). Also, the reduction of soil NO_3^--N content due to biochar addition occurred only with WSP, particularly for the WSP-FI treatment (Fig. 4b), which could be due to the fact that N mineralization rate is soil moisture dependent (Ding et al. 2018). These changes resulted in reduced inorganic N content and net N mineralization under WSP addition (Fig. 4c, d). The depressed net N mineralization would negatively affect soil N bioavailability and potentially reduce N content in plants (Ying et al. 2012). Contrary to this, in the present study, the C and N retentions in soil and plant were significantly increased in the biochar treatments, particularly with WSP (Table 4). And a significant linear relationship between TDM and plant N accumulation was observed, indicating that TDM was intimately related to plant N accumulation.

The enhanced mineralization of soil organic carbon and nitrogen under the PRD treatment would increase C and N losses in the soil–plant systems, resulting in reduced C and N retention (Sun et al. 2013), negatively influencing the environment. Thus, for sustainable crop production in water-limited climate, extra efforts for soil C and N management must be considered when applying the PRD technique in the long run. In the present study, the combined effects of biochar addition and PRD on soil C and N mineralization were further discussed via analyzing the ^{13}C and ^{15}N stable isotopic composition in the soil and leaf. The changes of $\delta^{13}C$ and $\delta^{15}N$ in plants are determined by the fractionation processes that occur during C and N exchanges in ecosystems (Gerschlauer et al. 2019). Here, biochar addition possessed lower $\delta^{13}C_{soil}$ as compared with non-biochar controls (Fig. 5a). It is based on the concept that soil microorganisms discriminate ^{13}C in the process of soil organic carbon decomposition, causing an enriched ^{13}C in the soil (Balesdent and Mariotti 1996). The lowered soil $\delta^{13}C$ upon biochar addition indicates that it decreased the decomposition of soil organic carbon due to the carbon-rich feature of biochar causing greater soil C:N ratio (Liu et al. 2021a, b), leading to a reduction of N mineralization (Robertson and Groffman 2007). Moreover, soil $\delta^{15}N$ under biochar addition was lower than that of the non-biochar controls (Fig. 5b), which further implied that biochar addition reduced soil organic N decomposition, in agreement with the results reported by Högberg (1997). Moreover, in the current study, $\delta^{13}C_{leaf}$ was not affected by both biochar and irrigation treatment (Fig. 5c); this differed from our previous results (Guo et al. 2021) and might be due to that, being a C4 plant, $\delta^{13}C_{leaf}$ of maize was less responsive to changes of growth environments. Nevertheless, there was a significant positive linear relationship between WUE and $\delta^{13}C_{leaf}$ across all treatments, implying that WUE was closely associated with $\delta^{13}C_{leaf}$. Likewise, Wang et al. (2010a) and Sun et al. (2013) found that, in tomato and potato plants, WUE was positively corrected with the shoot and plant $\delta^{13}C$. This further suggested that fine-tuned long-term stomatal control over the gas exchange in biochar and PRD plants contributed to improved WUE. Furthermore, biochar amendment significantly decreased $\delta^{15}N_{leaf}$ compared to the non-biochar controls (Fig. 5d), which confirmed that biochar addition might depress soil organic N mineralization. The present study has found that the PRD regime significantly increased $\delta^{15}N_{leaf}$ compared to DI (Fig. 5d; Supplementary Table 1), indicating that PRD outperformed DI in enhancing the mineralization of soil organic N (Sun et al.

2013). Therefore, biochar amendment combined with PRD irrigation could enhance the soil N bioavailability and its implications in improving the C and N retention in the soil–plant systems.

5 Conclusion

Our results demonstrated that adding biochar could increase carbon and nitrogen retention in the soil–plant systems, which could counteract some of the negative effects (e.g., C and N losses and biomass production) of alternate partial root-zone drying irrigation treatment. Although wheat straw biochar addition reduced the mineralization of soil organic carbon and nitrogen in a short-term pot experiment, the drying/wetting cycles under alternate partial root-zone drying irrigation effectively promoted the mineralization process. Biochar amendment, especially wheat straw biochar, significantly increased the plant N accumulation and consequently enhanced plant growth and water-use efficiency. Hence, wheat straw biochar addition could be a promising practice to improve maize seedling growth under alternate partial root-zone drying irrigation.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s42729-023-01223-5.

Acknowledgements Heng Wan would like to acknowledge the Chinese Scholarship Council (CSC) for funding the study at Soil Physics and Land Management group, University of Wageningen. We would like to thank the College of Agriculture, Northwest A&F University for providing seedlings in this experiment. We sincerely thank Dr. Loes van Schaik from the Soil Physics and Land Management group, University of Wageningen, for language, wording, paraphrasing, and sentence structure corrections to this manuscript.

Author Contribution Heng Wan: experiment design and execution, conceptualization, methodology, investigation, data curation, formal analysis, and writing—original draft preparation. Yiting Chen: reviewing and editing. Bingjing Cui: data collection. Xuezhi Liu: reviewing and editing. Jingxiang Hou: data analysis. ZhenhuaWei: experiment execution and funding acquisition. Jie Liu: reviewing and editing. Fulai Liu: supervision, conceptualization, methodology, data curation, funding acquisition, language editing, and validation.

Funding Open access funding provided by Royal Danish Library This work was funded by the Chinese Scholarship Council (no. 202206300064) and the National Natural Science Foundation of China (no. 51909220).

Data Availability All data are incorporated into the article and its online supplementary material.

Declarations

Competing Interests The authors declare no competing interests.

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