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Biochar effects on soil nitrogen retention, leaching and yield of perennial citron daylily under three irrigation regimes

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ABSTRACT

Biochar can serve as a soil amendment to immobilize soil nitrogen (N) and reduce N leaching from cropland without negative effect on crop yield. However, the interaction effect of biochar application and irrigation regimes on soil N status (N retention and N loss) and crop yield is rarely reported in the open perennial vegetable field. A two-years field trial (transplanting in first year and consecutive growth in second year) was conducted in citron daylily vegetable cropping system on a sandy brown alluvial soil. Two biochar application rates (0 and 30 t ha^{-1}) and three irrigation regimes (CDI, conventional drip irrigation; WSDI, water-saving drip irrigation with 80% of full irrigation quota; APRDI, alternate partial root-zone drip irrigation with 80% of full irrigation quota) were included. The response of crop yield and soil N status to both biochar application and irrigation regimes varied across planting years for perennial citron daylily. After the first planting year's harvest, APRDI enhanced flower bud yield by 18–28% compared to CDI and WSDI, likely due to improved nitrate use efficiency evidenced by lower soil nitrate retention in the surface soil (0–20 cm) post-harvest. However, biochar application resulted in a reduction of yield by 27% under APRDI. Additionally, WSDI with reduced yields, decreased soil TN in the sub-surface layer (20–50 cm) with 9–19% by comparison with other two irrigation regimes, resulting in higher TN concentration in the soil solution (14–28%) in and thus an increased risk for N leaching. However, after the second harvest year, there were no variations in crop yield induced by biochar application and irrigation regimes. Irrigation regimes exhibited limited influence on soil N status, while biochar application mitigated soil nitrogen decline in the 0–50 cm layer by enhancing organic nitrogen retention capacity for nearly 16–85%. Furthermore, the lowest TN concentration in the soil solution in the sub-surface layer (20–50 cm) with biochar application under APRDI suggested a reduced risk for N leaching. We conclude that combining biochar application with the APRDI regime could help retain soil N, decrease the risk of N leaching, and enhance crop yield in total for two consecutive planting years. Therefore, this approach is recommended for sustainable N management in long-term planting of perennial crops.

1. Introduction

Nitrogen (N) is one of essential nutrients for plant growth, and a substantial amount of N fertilizer is applied to arable land to enhance crop yield (Xu et al., 2024). However, instead of being effectively utilized by crops, the majority of agricultural N inputs are lost from arable land through leaching and gas emissions, causing a great risk of environmental deterioration (Chen et al., 2021; Harris et al., 2022; Qasim

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et al., 2022; Liang et al., 2019). Nitrate leaching from cropland can threaten the quality of groundwater (Gu et al., 2013; Guo et al., 2020) and emissions of ammonia (NH_3) and nitrous oxide (N_2O) pose risks to air quality (Lu et al., 2021; Xu et al., 2024). Therefore, achieving economic crop benefits and food efficiency while minimizing N pollution presents a challenge globally (Bodirsky et al., 2014). To date, efforts to mitigate N losses with increasing N use efficiency have primarily concentrated on annual crops, with relatively fewer studies assessing soil N management in long-lived perennial crops, despite their significance for dietary diversity and nutrition (Hong et al., 2020; Howe et al., 2023; Toensmeier et al., 2020). Perennial crops, planted only once and not replanted, are fully harvested annually to obtain goods (Ledo et al., 2020). Perennial vegetables are cultivating for their edible vegetative growth or reproductive structure, accounting for 33–56% of vegetable species and 6% of the world's vegetable land (Toensmeier et al., 2020). Different from annual vegetables that only grow within a few months, perennial vegetables exhibit continuous growth for an extended period, allowing for the development of mature root systems and vegetation cover throughout the year (Ledo et al., 2020; Smaje, 2015). Consequently, these differences may lead to variations in soil nitrogen status. Therefore, studying soil nitrogen balance in perennial crops under various N management practices is crucial for the world food economy, and global food and nutrition security.

Excessive N fertilization enhances the accumulation of N in the soil profile, but N leaching could occur with sufficient subsurface drainage induced by intensive rainfall or irrigation (Dai et al., 2016). N leaching could when sufficient subsurface drainage occurred induced by intensive rainfall or irrigation (Dai et al., 2016). Reducing N fertilization and applying water-saving irrigation can control N leaching effectively though may lead to a drop in crop yield (Chen et al., 2018; Duan et al., 2014). Thus, improving fertilizer using efficiency by soil amendments and developing innovative irrigation regimes are promising strategies to enhance nutrient availability (Haider et al., 2017; Sun et al., 2019). Biochar, as one of soil amendments, has been reported to have a positive effect on increasing soil N retention and mitigating N leaching (Blanco-Canqui et al., 2017; Liu et al., 2018; Sohi et al., 2010; Hossain et al., 2020). Biochar is characterized by high specific surface area with large bonding capacity for nutrients like N, and can improve soil aggregate stability to immobilize nutrients in soils (Blanco-Canqui et al., 2019; Mukherjee et al., 2014). In addition, the different microbial community in soils with biochar additions may be helpful to ease N leaching (Sheng and Zhu, 2018). It is well known that the combination of biochar amendment and N fertilization at appropriate rate could increase the nutrient supply capacity (Gul et al., 2016; Li et al., 2019), but whether biochar addition combines with reduced irrigation regimes could enhance soil N retention and reduce N leaching remains largely elusive. In fact, the effectiveness of biochar on N leaching is affected by water management (Zhang et al., 2020). Several studies showed that biochar could alleviate adverse effect on crop yield caused by drought stress as it improves soil water holding capacity (Faloye et al., 2019; Haider et al., 2017; Laird et al., 2010). Some innovation water-saving irrigation regimes, like alternate partial root-zone irrigation (APRI), could also ease the negative influence on crop growth induced by soil water deficits (Adu et al., 2018; Liu et al., 2020; Wang et al., 2019a). APRI alternates irrigation in space and time causing wet-dry cycles in two separate portions of the root system, which has been proven to save irrigation water by 20–30% without a significant reduction of crop yield (Liang et al., 2013; Mehrabi and Sepaskhah, 2019). In addition, APRI was reported to stimulate soil organic N mineralization and thus increase the N bioavailability and crop N uptake (Wang et al., 2012, 2017). Thus, the combination of biochar application with APRI may exert a synergistic effect on reducing N leaching while maintaining crop yield.

Perennial vegetables with higher economic and nutritional values have become popular with both farmers and consumer in China. The citron daylily (*Hemerocallis lilioasphodelus* Linn.) has medical health and ornamental value, which is widely grown in China, Malaysia, Japan and other Asia countries. The planting area of the crop was 5, 300 ha with the total value of 80 million yuan in Dali County in 2020 and more than 67, 000 ha citron daylily was cultivated in China in 2021 (http://www.shaanxi.gov.cn/xw/tpxw/202008/t20200806_1544869_wap.html). As a high-income crop, citron daylily becomes a popular choice for farmers to support "poverty alleviation program" in China. Therefore, the citron daylily was selected as the tested vegetable crop in this study.

The objective of this study is to investigate the effect of biochar application under three irrigation regimes on soil N status and crop yield of citron daylily. We hypothesize that (1) applying biochar to perennial vegetable fields would enhance soil nitrogen retention and reduce nitrogen leaching, (2) the impact of biochar on yield and soil N dynamics would vary depending on different irrigation regimes, and (3) the effects of biochar application and irrigation regimes on soil N status and crop yield would differ across different planting years on perennial vegetation land. The results of biochar application under different irrigation regimes could offer new insights into the strategic regulation of nitrogen management for sustainable crop yield production in perennial cropping systems.

2. Materials and methods

2.1. Study area

The field trial was conducted at the Institute of Shunyi Agricultural Science, Beijing, China (40°06'34″N, 116°52′57″E), which is located at downstream of the Chaobai River basin. The study area is characterized as temperate semi-humid continental monsoon climate with mean annual rainfall of 625 mm and mean annual temperature of 11.5 ℃ (1997–2016). The soil belongs to sandy brown alluvial soil (Xie et al., 2021). The area has been cultivated for more than 10 years, with wheat-corn crop rotation and vegetable cropping. Before starting the field trail, three soil cores were randomly collected in the experimental field at three soil depth profiles (0–20 cm, topsoil; 20–50 cm, subsoil; 50–100 cm, underlying soil) in March 2017 from the experimental area to analyze the soil physiochemical properties. The samples were transported to the laboratory immediately after collection and the plant residuals and debris were removed. The three soil samples from each layer were sufficiently mixed and were air dried at room temperature, passed through 2-mm sieve. Then a portion of the soil samples from each layer was taken for further analysis (Table 1).

2.2. Biochar

The biochar used in the experiment was made by tobacco residual with pyrolysis temperature of 450 ℃ for 8 h, purchased from Shanxi Yixin Bioenergy Technology Development Company. The biochar had a pH value of 9.98 and contained 724 g kg $^{-1}$ of TC, 6.2 g kg^{-1} of TN, 2.97 g kg^{-1} of TP, 10.08 g kg^{-1} of TK.

Table 1
Basic properties of soils for study area.

	Depth of soil profile (cm)		
	0–20	20–50	50–100
pH[†]	8.11	8.35	8.12
Bulk density (g cm^{-1})	1.25	1.67	1.64
TC (g kg^{-1})	9.15	4.58	5.00
TN (g kg^{-1})	1.22	0.55	0.63
TP (g kg^{-1})	1.57	1.18	1.33
TK (g kg^{-1})	13.18	14.05	11.19
C/N	7.50	8.33	7.94
NO_3^--N (mg kg^{-1})	28.29	15.86	23.22
NH_4^+-N (mg kg^{-1})	19.00	14.45	12.89

[†] pH, measured in water at a soil/water ratio of 1:2.5, TC, total carbon, TN, total nitrogen, TP, total phosphorous, TK, total potassium, NO_3^--N, nitrate nitrogen, NH_4^+-N, ammonium nitrogen.

2.3. Field experiment design

Citron daylily (*Hemerocallis lilioasphodelus* Linn.) was used in the experiments. Vigorous seedlings of 5-years old were purchased from Datong, Shanxi province, China. Seedlings were transplanted to fields on 1 April 2017. Then the field planting was conducted for 2 years from April 2017 to November 2018. The experiment included two factors, i.e., biochar application and irrigation regimes. There were six treatments with three replicates per treatment, and 18 plots (4 m × 5 m = 20 m^2) in total. Two biochar levels were applied at 0 (-B) and 30 t ha^{-2} (+B); and three irrigation regimes were included with conventional drip irrigation (CDI), water-saving drip irrigation with 80% of full irrigation quota (WSDI) and alternate partial root-zone drip irrigation with 80% of full irrigation quota (APRDI). In the +B treatment, the biochar was mixed into the 0–20 cm soil layer each year. The application rates of fertilizer and the quotas of irrigation water were applied based on the local farmer's practice. A total of 410 kg N ha^{-1} fertilizer (urea), 96 kg P_2O_5 ha^{-1} fertilizer (calcium superphosphate) and 270 kg K_2O ha^{-1} fertilizer (potassium sulfate) were applied to surface during the growth period of citron daylily in each year (From April to November). The fertilizers were divided for 4 equal portions and carried out for three times, i.e., on 20th June, 28th August and 15th October, respectively, at a ratio of 1:2:1 in 2017. In 2018, the fertilization times were on 15th June, 6th September and 30th October, respectively, also with a ratio of 1:2:1. Irrigation management was adjusted according to the precipitation and more details are shown in Table 2.

2.4. Sampling and analysis

The flower harvesting period of the citron daylily was started from the middle of June and ended at the middle of August. The flowers were picked and weighed every morning during the harvesting period, and then added up to total yield. Afterwards, flowers from each plot in a single year was mixed and then oven dried to a constant weight for analyzing the TN content. The TN content in the flower was determined using the Kjeldahl method (Sáez-Plaza et al., 2013).

In the field trial, Pressurized Soil Water Samplers (WS180, Hangzhou Huier Apparatus & Equipment Co., Ltd) were preset along the soil profiles at 0–20 cm, 20–50 cm, and 50–100 cm layers to collect the soil solution after heavy rains. The solution collected was filtered through 0.45 µm pore-size filters to analyze NH_4^+-N, NO_3^--N, and TN concentration. NH_4^+-N and NO_3^--N were determined by ultraviolet and visible spectrophotometry (Ding et al., 2010; Norman and Stucki, 1981). The TN in solution was determined by the alkaline potassium persulfate digestion- ultraviolet and visible spectrophotometry method (Ebina et al., 1983; Jia et al., 2021).

During the late growth period in December 2017 and 2018, soils were sampled from each treatment along the profile (0–20 cm, 20–50 cm, and 50–100 cm) by soil auger. The plant residuals and impurities were removed and then the soil samples were thoroughly mixed. Each fresh soil sample was divided into two parts. One part was air-dried at room temperature and then sieved through 2-mm and 0.15-mm mesh for the determination of soil pH, TN and TC. Another part was sieved through 2-mm mesh for analyzing the NH_4^+-N and NO_3^--N. Soil pH was measured in water at a soil/water ratio of 1:2.5 by a FE20-FiveEasy Plus pH meter (Mettler Toledo, Switzerland). TN and TC of the soil was measured using an Elemnetar Vario Max CN (Germany). NH_4^+-N and NO_3^--N in soils were extracted by 2 M KCl for 1 h at a soil/water ration of 1: 10. The concentrations of NH_4^+-N and NO_3^--N in KCl extracts were determined by ultraviolet and visible spectrophotometry (Ding et al., 2010; Norman and Stucki, 1981). The soil organic nitrogen (ON) was calculated by subtracting mineral N (NH_4^+-N and NO_3^--N) from TN (Wuest and Gollany, 2013).

2.5. Statistical analysis

Two-way analysis of variance (ANOVA) was performed to analyze the effects of biochar application (+B, -B) and irrigation regime (CDI, WSDI, APRDI) on the soil N concentration, N concentration in soil solution, flower buds yield, and accumulated N in the flower buds. Turkey's test at the 5% confidence level was followed to test for significant difference between the 6 treatments when there was significant interaction between the biochar and irrigation treatment. All statistical analyses were performed using the SPSS v22.0 software (IBM, USA). The relationship between the soil properties and the soil nutrients with nitrogen concentration in soil solution was conducted by using SPSS v22.0 (IBM, USA). All the figures were constructed by the Origin Pro v9.1 software (OriginLab, USA).

3. Results

3.1. Effects of biochar application on flower bud yield and N in flower bud under the three irrigation regimes

The flower yield of citron daylily was extremely higher in 2018 than that in 2017 (Fig. 1, Table S4). In 2017, the APRDI regime significantly enhanced flower yield, while biochar application resulted in a reduction of 27%. However, in 2018, no significant effects of biochar application or irrigation regimes on flower yield were detected (Fig. 1).

In 2017, biochar application showed no effect on N concentration in flower bud under the same irrigation regimes (Fig. 2a). Moreover, the WSDI regime significantly decreased the N concentration in flower buds. In 2018, however, neither irrigation regimes or biochar application had an impact the N concentration in flower buds (Fig. 2a). More N accumulated in flower buds of planting year in 2018, exceeding N accumulation in 2017 by two orders of magnitude (Fig. 2b). No significant variations of accumulated N in flower buds were detected among treatments in 2018. However, it is evident that biochar application and irrigation regimes altered nitrogen accumulation in flower buds in 2017 (Fig. 2b). Biochar application led to a decrease in nitrogen accumulation in flower buds, with a significant effect observed under both WSDI and APRDI regimes. Particularly, compared to the other two irrigation

Table 2
Details of irrigation regimes and biochar application during citron daylily growth period.

Irrigation regimes	Biochar application at surface layer (t ha^{-1})		Effective rainfall† (mm)		Irrigation amount (mm)		Irrigation times (No.)	
	2017	2018	2017	2018	2017	2018	2017	2018
CDI§	0	0	286	286	691	806	7	8
WSDI	0	0	286	286	553	645	7	8
APRDI	0	0	286	286	553	645	7	8
CDI	30	30	286	286	691	806	7	8
WSDI	30	30	286	286	553	645	7	8
APRDI	30	30	286	286	553	645	7	8

† Effective rainfall, the diurnal rainfall is >5 mm.
§CDI: Conventional drip irrigation, WSDI: water-saving drip irrigation (80% of conventional drip irrigation), APRDI: alternative partial root-zone drip irrigation (80% of conventional drip irrigation).

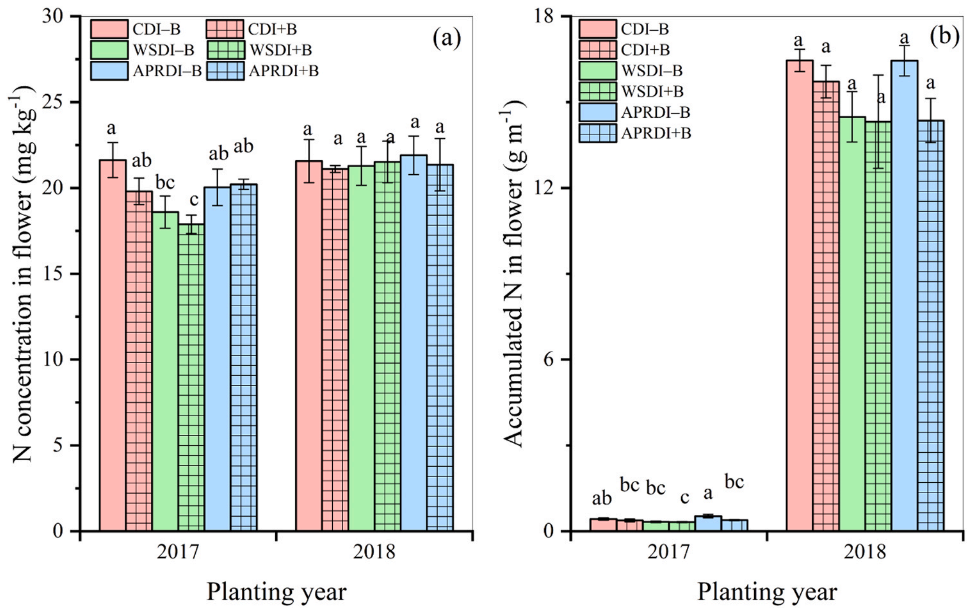

Fig. 1. Effects of biochar application on flower yield of citron daylily (t ha^{-1}) under three irrigation regimes in 2017 and 2018. The error bars represent the standard deviation of the mean (n = 3). Different letters indicate significant difference at $p < 0.05$ (*LSD*) for treatments.

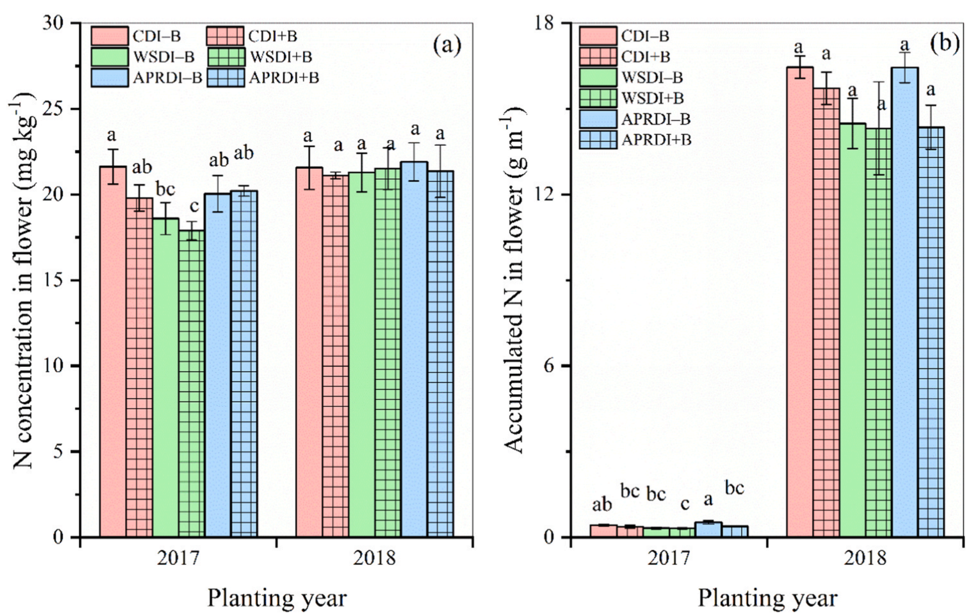

Fig. 2. Effect of biochar application on concentration and accumulated amount of nitrogen in flower of citron daylily during growing season in 2017 and 2018. The error bars represent the standard deviation of the mean (n = 3). Different letters indicate significant difference at $p < 0.05$ (*LSD*) for treatments.

regimes, WSDI significantly reduced nitrogen accumulation in flower buds in 2017 (Fig. 2b).

3.2. Soil N status affected by biochar application under three irrigation regimes

The planting year significantly influenced soil N status (Table S3). After harvest in 2017, the impact of biochar application and irrigation regimes on soil N (TN, NH_4^+-N, NO_3^--N) status varied depending on the profile depth (Table 3). Biochar application showed a limited effect on soil TN across the profile from 0 to 100 cm, whereas the WSDI regime induced a reduction of soil TN in the layer from 20 to 100 cm (Table 3). The biochar application generally tended to increase soil inorganic N pool (NO_3^--N and NH_4^+-N) in the surface layer (0–20 cm), with a significant increment of NH_4^+-N (Table 3, Table S2). Both NO_3^--N and NH_4^+-N along the profile (0–100 cm) responded more sensitively to irrigation regimes. In the surface soil layer (0–20 cm), the APRDI regime significantly decreased soil NO_3^--N and exhibited a tendency to decrease NH_4^+-N. However, the WSDI regime showed potential for increasing NO_3^--N levels both in the surface layer (0–20 cm) and the deeper layer (50–100 cm) (Table 3).

In contrast, following the harvest in 2018, biochar application exhibited a greater effect on soil nitrogen status compared to irrigation regimes (Table 3). No effect of irrigation regimes was observed. The positive effect of biochar application on soil TN concentration reached the level of significance in the surface (0–20 cm) ($p < 0.01$) and the sub-surface soil (20–50 cm) ($p < 0.05$) (Table 3). Consistently, biochar application significantly decreased both soil NH_4^+-N and NO_3^--N

Table 3
Effects of biochar application on soil NH_4^+-N, NO_3^--N, soil TN under three irrigation regimes during citron daylily growing season in 2017 and 2018.

Irrigation regimes	Biochar application	Soil depth(cm)	2017			2018		
			NH_4^+-N (mg kg^{-1})	NO_3^--N (mg kg^{-1})	TN (g kg^{-1})	NH_4^+-N (mg kg^{-1})	NO_3^--N (mg kg^{-1})	TN (g kg^{-1})
CDI§	-B	0–20	38.80±2.07bc‡	22.41±1.80c	1.18±0.08a	12.63±2.19ab	6.60±2.68a	0.66±0.01b
CDI	+B		50.87±5.28a	28.13±1.04b	1.22±0.05a	8.75±0.70b	4.11±0.52ab	1.03±0.06a
WSDI	-B		32.28±2.23c	35.61±2.89a	0.97±0.11a	13.59±2.29a	7.37±4.32a	0.64±0.02b
WSDI	+B		33.34±3.50c	29.07±2.31b	1.13±0.03a	9.37±1.18b	4.28±0.80ab	1.08±0.10a
APRDI	-B		34.86±4.95bc	16.98±1.32d	1.11±0.18a	11.96±2.69ab	3.86±1.86ab	0.54±0.03b
APRDI	+B		44.31±4.72ab	16.68±1.61d	1.14±0.17a	10.53±1.53ab	2.39±0.52b	0.99±0.09a
CDI	-B	20–50	27.23±4.29ab	36.70±2.57a	0.79±0.03a	2.96±1.19a	3.50±1.65a	0.39±0.05b
CDI	+B		30.54±4.70a	27.61±2.81b	0.71 ±0.04ab	2.17±1.46a	1.54±0.81a	0.44 ±0.02ab
WSDI	-B		26.47±3.18ab	18.89±3.81c	0.59±0.08b	1.94±0.32a	1.62±0.29a	0.34±0.02b
WSDI	+B		22.92±1.89b	21.90±1.37bc	0.62±0.15b	1.53±0.09a	2.08±1.01a	0.56±0.19a
APRDI	-B		29.26±5.25ab	26.71±2.51b	0.65 ±0.10ab	2.18±0.70a	3.20±1.46a	0.38±0.02b
APRDI	+B		32.12±2.02a	22.50±0.46bc	0.68 ±0.06ab	6.30±4.53a	2.63±1.92a	0.45 ±0.03ab
CDI	-B	50–100	24.71±4.15ab	34.90±2.43b	0.63 ±0.04ab	10.15±0.18a	2.09±0.54a	0.32±0.03a
CDI	+B		22.50±1.53b	26.18±1.69c	0.62 ±0.02ab	9.13±1.16a	2.14±2.25a	0.34±0.02a
WSDI	-B		20.89±4.41b	41.83±4.09a	0.53±0.07b	8.46±0.53a	2.82±3.98a	0.28±0.01a
WSDI	+B		24.45±0.44ab	17.87±0.97d	0.59 ±0.09ab	8.35±1.22a	1.28±0.57a	0.30±0.04a
APRDI	-B		30.49±5.90a	21.03±2.09 cd	0.69±0.04a	8.69±0.89a	0.50±0.38a	0.31±0.01a
APRDI	+B		30.39±2.84a	21.35±1.24 cd	0.73±0.04a	8.62±0.95a	1.33±1.21a	0.34±0.03a
	0–20	Irrigation regimes (I)	<0.001***	<0.001***	0.130	0.763	0.128	0.061
		Biochar application (B)	0.002**	0.690	0.171	0.004**	0.047*	<0.001***
		I×B	0.082	0.001***	0.578	0.406	0.826	0.508
	20–50	Irrigation regimes (I)	0.048*	<0.001***	0.040*	0.134	0.393	0.646
		Biochar application (B)	0.635	0.013*	0.790	0.326	0.282	0.012*
		I×B	0.253	0.004**	0.416	0.105	0.311	0.200
	50–100	Irrigation regimes (I)	0.006**	<0.001***	0.002**	0.078	0.510	0.051
		Biochar application (B)	0.816	<0.001***	0.327	0.368	0.813	0.062
		I×B	0.420	<0.001***	0.603	0.605	0.580	0.870

§CDI-Conventional drip irrigation, WSDI-water-saving drip irrigation (80% of conventional drip irrigation), APRDI-alternative partial root-zone drip irrigation (80% of conventional drip irrigation). Rates of biochar application in 0–20 cm soil: 0, and 30 t ha^{-1}.
‡The value was given as mean ± SD. Different letters indicates significant difference ($p < 0.05$) of treatments.
* indicates significant at $p < 0.05$, **indicates significant at $p < 0.01$, ***indicates significant at $p < 0.001$.

concentration in the surface soil (0–20 cm) (Table 3).

3.3. Average TN concentration in soil solution affected by biochar application under three irrigation regimes

Obvious differences of soil solution TN concentration were detected in different planting years (Fig. 3, Table S3). The TN concentration of soil solution throughout the profile was significantly higher in 2017 than that in 2018 (Fig. 3, Table S3). In the first planting year with less flower yield (Fig. 1), biochar application significantly enhanced the TN concentration of surface soil solution (0–20 cm) under WSDI and APRDI. In addition, biochar application also increased TN concentration of sub-surface soil solution (20–50 cm) under CDI (Fig. 3a). Compared with CDI regime, WSDI and APRDI showed more TN in soil solution of surface (0–20 cm) and sub-surface (20–50 cm) soil. In the second planting year with a large amount of flower buds yield (Fig. 1), biochar application showed a positive effect on TN concentration in soil solution through the profile under WSDI regime. However, a negative effect induced by biochar application on TN concentration in surface soil (0–20 cm) under CDI and in underlying soil (50–100 cm) under APRDI (Fig. 3b).

4. Discussion

4.1. Flower bud yield affected by biochar application under three irrigation regimes

The flower bud yield response of citron daylily to biochar application and irrigation regimes varied across different growing years (Table S1). In the 2017 planting year, the ARPDI regime without biochar application significantly enhanced flower bud yield of citron daylily (Fig. 1). However, there was no significant effect both of irrigation regimes and biochar application on harvest yield in 2018 (Fig. 1). These results were in accordance with the findings conducted by Akbarzadeh et al. (2022) on peppermint (a perennial herb) growth variability under APRDI conditions, which could be attributed to the maturity level of the roots. In the initial development stage of the transplanting year, the roots appear to be more sensitive to variations compared to the second year. Wang et al. (2022) also observed that the promotion effects of APRDI on root growth were more pronounced during earlier growth stages.

The flower bud yield of citron daylily was negatively correlated with nitrate levels in the surface soil (0–20 cm; Fig. S3). The lower nitrate concentration in the surface soil induced by the ARPDI regime (Table 3) may indicate higher plant N use efficiency, thereby increasing the yield. The APRDI has been reported to enhance crop yield by improving N use efficiency for several reasons: (i) it could stimulate soil N mineralization by enhancing microbial activities and soil respiration rate (Liu et al.,

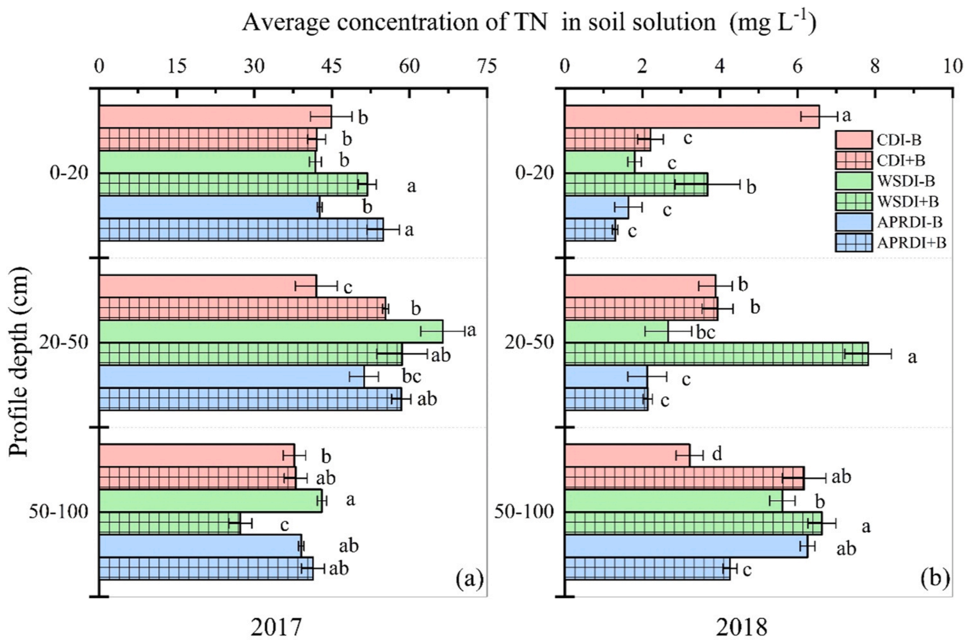

Fig. 3. Effects of biochar application on average concentration of TN (mg L^{-1}) in soil solution collected from soil profile (0–20, 20–50, 50–100 cm) under three irrigation regimes during citron daylily growing season in 2017 and 2018. The error bars represent the standard deviation of the mean (n = 3). Different letters indicate significant difference at $p < 0.05$ (*LSD*) for S treatments.

2020; Wang et al., 2010); (ii) it could promote root growth, leading to increased N adsorption, and subsequently improve the transfer of N from roots to shoots and fruits through elevated root vigor (Cheng et al., 2021; Wang et al., 2010, 2019a, 2019b).

Interestingly, under the ARPDI regime, biochar application reduced flower bud yield by 27%, while it showed no impact on flower yield under CDI and WSDI regimes in 2017 (Fig. 1). While most studies have been reported that biochar application could increase crop yield (Dai et al., 2020; Hussain et al., 2017; Purakayastha et al., 2019), some studies have observed no effect even negative influence on crop yield (Pokharel and Chang, 2019). This may be attributed to biochar application in alkaline soils, which can elevate pH, thereby increasing the risk of excessive soil salinity and reduced fertility due to nutrient precipitation (Brtnicky et al., 2021). However, our study found no effect of biochar application on soil pH (Table S1). The biochar-induced decline of yield in the study may be triggered with the nitrate capture by the increase of soil C/N ratio in the surface layer (0–20 cm) (Table S1). The higher C/N ratio resulted in soil microbial N immobilization and reduction of soil microbial activities, which may decrease N availability for plant growth (Bengtsson et al., 2003; Kirkby et al., 2014). Furthermore, biochar application can affect root growth (Farrar et al., 2021; Jones et al., 2012). Pokharel and Chang (2019) observed a reduction in root biomass with the application of woodchips biochar. Therefore, the reduction in root biomass caused by biochar application may be one mechanism contributing to the decrease in crop yield under the APRDI regime observed in our study.

4.2. Soil N status affected by biochar application under three irrigation regimes in 2017

Soil TN retention is ultimately determined by the balance between N input with fertilizer and outputs via plant N uptake, soil N leaching and gas emissions (Chen et al., 2021). After the initial harvest in 2017, neither biochar application nor irrigation regimes had any effect on soil TN concentration in the surface layer (0–20 cm). However, the WSDI regime significantly decreased soil TN concentration in deeper layers from 20 to 100 cm (Table 1). The WSDI regime resulted in the lowest yield of citron daylily and relatively lower accumulated TN in flower buds compared to the other two irrigation regimes (Fig. 1, Fig. 2). This indicates lower N use efficiency by plants under the WSDI regime. Correspondingly, the average concentration of TN in soil solution below 20 cm was relatively higher under the WSDI regime (Fig. 3), potentially leading to increased N leaching. Water-saving irrigation regimes, by maintaining conducive soil water status for nitrification and denitrification, may induce N_2O emissions (Bowles et al., 2018; Li et al., 2018). Furthermore, increased irrigation water quota could mitigate losses from NH_3 volatilization due to the NH_4^+-N dilution effect (Sun et al., 2023). The WSDI regime may consequently accelerate N losses through N_2O and NH_3 gas emission, further reducing N retention in the soil.

Soil inorganic N (IN, NH_4^+-N and NO_3^--N), as the main form of N available for direct plant uptake through the root system (Chen et al., 2021), was influenced by three irrigation regimes (Table 3). Compared to the CDI regime, the APRDI regime decreased the soil IN pool along the soil profile (0–100 cm) after the harvest of 2017 (Table S2). The APRDI may enhance microbial activities and soil respiration rate through soil drying and wetting cycles, resulting in the release of mineral N into the soil solution (Liu et al., 2020; Wang et al., 2010, 2017). This process increases plant N accumulation and consequently decreases the soil IN pool, which may be supported by the accumulated N in flower bud and the absence of reduction in TN concentration in the soil solution under the APRDI in our study (Fig. 2, Fig. 3). Furthermore, the APRDI decreased NO_3^-/ NH_4^+ ratio along the profile (0–100 cm), possibly as a result of significant nitrate depletion due to plant growth (Fig. 2). This finding contradicts the study conducted by Zhang et al. (2021), who reported that APRDI regimes enhanced the dominant form of soil NO_3^--N by reducing nitrate leaching.

The changes in soil inorganic nitrogen (IN) pool due to biochar application depended on irrigation regimes and profile depth (Table 3, Table S2). In the surface layer (0–20 cm), where crop roots are predominantly distributed and thus N uptake occurs during the first planting year, biochar application resulted in an increase in soil IN pool, with elevated levels of soil NH_4^+-N and NO_3^--N under CDI (Table 3, Table S2). Given the unaltered soil organic N (ON) pool (Table S2), biochar application enhanced the soil IN pool by reducing mineral N losses rather than increasing soil N mineralization rate (Gao et al., 2016). The decline trend of accumulated plant N and N concentration in the surface soil solution (Fig. 2, Fig. 3) may suggest reduced N depletion by plant uptake and N loss through leaching (Wei et al., 2020). Furthermore, biochar has the potential to reduce N_2O and NH_3 emission due to higher physical adsorption capacity (Ahmad et al., 2021), which may also contribute to the elevated soil IN pool.

4.3. Soil N status affected by biochar application under three irrigation regimes in 2018

Following the 2018 harvest year, biochar application increased soil TN concentration across the profile (0–100 cm) regardless of the irrigation regime. Consistently, the enhancement of soil ON in the layer from 0 to 50 cm due to biochar application (Table S2) suggested higher microbial immobilization of N in the soil. This finding was consistent with past studies indicating that biochar application can improve soil N immobilization (Ameloot et al., 2013; Bruun et al., 2012; Hossain et al., 2020). The soil with biochar application is more suitable for microbial colonization and growth due to the characteristics of biochar, including its fine porous structure, high surface area, hydrophilicity, and mineral nutrient content (Clough et al., 2013; Ghorbani et al., 2024; Gul and Whalen, 2016; Wang et al., 2021). In our study, the large labile C input due to biochar application enhance microbial activities as a nutrient source, facilitating immobilization (Bruun et al., 2012; Liu et al., 2017; Prayogo et al., 2014; Xu et al., 2021). A significant positive correlation between soil TC with soil ON in the layer from 0 to 50 cm supported the mechanism (Figure S1). Irrigation showed limited effect both on soil TN retention and IN pool in the second planting year may due to the maturity of root growth (Hussain et al., 2020; Wang et al., 2022). APRDI combined with biochar application demonstrated lower TN concentration in the soil solution from the deeper layer (50–100 cm), indicating a reduced risk for N leaching (Fig. 3). In comparison, biochar application under WSDI significantly increased TN concentration in the soil solution along the soil profile (0–100 cm), possibly indicating larger soil N leaching (Fig. 3).

4.4. Biochar application with irrigation regimes in N management for perennial crops

In the transplanting year of citron daylily (2017), plant growth was limited. During the transplanting year, the flower bud biomass accounts for no more than 10% of the above-ground biomass (Luo et al., 2017), whereas during normal production years, it averages around 28% (Zhang and Chen, 2008). Around 53 kg N ha^{-1} (5.3 kg ha^{-1} TN of flower bud, Fig. 2) was accumulated in the above-ground plant in our study, far lower than the applied N rate of 410 kg N ha^{-1}. The N loss via ammonia volatilization and N_2O emission was reported to account for 3–5% and around 1% of applied urea-N in calcareous fluvo-aquic soil, respectively (Zhang et al., 2011). Hence, considering the slight decline in soil N content (Table 1, Table 3), leaching appears to be a significant pathway for N loss during the initial year of citron daylily planting. Higher N leaching in the initial crop establishment phases of perennial systems such as grass crops or biofuel crops has been detected in previous studies (Díaz-Pinés et al., 2016; Hussain et al., 2020; Smith et al., 2013). Hussain et al. (2020) considered that crops hadn't yet reached their potential aboveground and belowground biomass in the first 1–2 years after planting, potentially leading to increased nitrogen leaching. As a result, the control of N leaching may be necessary to maintain the soil N in balance. Notably, irrigation exerted a more pronounced effect on both harvest yield and soil N status in comparison to biochar during the initial planting year (Fig. 1, Table 3). Water-saving irrigation regimes (WSDI and APRDI), are thus recommended to mitigate potential N leaching with minimal water usage. However, as discussed in 4.2, WSDI showed greater risk for N leaching, attributed to decreased soil N retention, increased N concentration in the soil solution, and reduced harvest yields (Fig. 1, Fig. 2, Fig. 3, Table 1). In contrast, APRDI may present optimal outcomes with lower soil nitrate levels, due to enhanced N use efficiency, thereby resulting in higher harvest yields. If the implementation of APRDI is unfeasible, biochar application under CDI is recommended, as it can maintain the soil mineral N pool without markedly impacting crop yields.

However, in the second planting year of 2018, the N uptake by citron daylily may be the major factor, as the accumulated N of flower buds was 36.8–44.8 higher than in 2017 (Fig. 2). With a significant amount of nitrogen being taken up by the plants, enhancing fertilizer use efficiency may become a priority. Interestingly, in contrast to the planting year of 2017, biochar application significantly influenced soil N status, while irrigation regimes showed limited effect on them, likely due to the maturation of roots. Biochar application under APRDI mitigated the decline in soil surface N levels through soil ON retention and decreased TN concentration in soil solution, demonstrating a greater potential for improving N use efficiency over long-term planting cycles, which is beneficial for perennial crops with long-term economic pursuits.

Our study primarily focuses on the long-term planting of perennial vegetables in the North Plain of China. The optimal nitrogen management strategies identified through the combination of biochar application and APRDI may have applicability to other temperate regions with perennial planting systems, particularly in Europe and the USA. Long-lived perennial crops, as highlighted by Hong et al. (2020), even account for 13% of the national total agricultural output in California. Moreover, perennial crops offer a broad range of ecosystem services that contribute to efforts to mitigate climate change (Howe et al., 2023; Ledo et al., 2020). Therefore, our findings contribute to the broader understanding of sustainable nitrogen management.

5. Conclusion

Obvious interannual variations were observed in bud yields of citron daylily (*Hemerocallis lilioasphodelus* Linn.) and soil N status from perennial vegetable land, thus confirming our third hypothesis. While biochar tended to diminish the enhancement of alternate partial-root zone irrigation (APRDI) on flower bud yield with limited effects on soil N retention in the first planting year of daylily, it showed no influence on flower bud yield in the second harvest year. Furthermore, the combination of biochar application with APRDI significantly alleviated soil N depletion after two years of planting, with reduced risk of nitrogen leaching. However, field experiments with longer durations are suggested to quantify the N response to the interaction of biochar application and APRDI, as perennial crops may require a longer time to establish a steady state for soil N balance.

Ethics approval and consent to participate

The manuscript is an original work that has not been published in other journals. The authors declare no experiments involving humans and animals.

CRediT authorship contribution statement

Xiaolei Sun: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Roland Bol:** Writing – review & editing, Supervision, Resources, Methodology, Conceptualization. **Zijian Xie:** Resources, Investigation, Data curation. **Fulai Liu:** Writing – review & editing, Supervision, Conceptualization. **Zhengyi Hu:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Xiaosong Yang:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation. **Zheng Sun:** Writing – review & editing, Methodology. **Meng Li:** Writing – review & editing, Resources, Data curation. **Guoxi Wang:** Investigation, Data curation. **Songyan Li:** Investigation, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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Consent for publication

All authors agreed to the publication.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2024.108788.

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