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ORIGINAL PAPER

Effects of nitrogen reduction on the agronomic characteristics, quality, and water and fertilizer use efficiency of tomato (*lycopersicon esculintum mill.*) between drip fertigation and negative-pressure fertigation

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Abstract

The aim of the study is to compare the agronomic characteristics, crop quality, water use efficiency (WUE), and fertilizer use efficiency (FUE) of tomato (*Lycopersicon esculintum Mill.*) between drip fertigation (DI) and negative-pressure fertigation (NPI). Four treatments were evaluated in a greenhouse plot experiment for their effects on soil moisture and soil available nitrogen and plant photosynthetic, nitrogen uptake, fruit quality, yield, irrigation water use efficiency (WUE_i), and FUE: (1) NPI fertigation with no nitrogen fertilization (NPI-$F_{0.00}$); (2) NPI fertigation with 75% conventional fertilization (NPI-$F_{0.75}$); (3) DI fertigation with no nitrogen fertilization (DI-$F_{0.00}$); and (4) DI fertigation with 100% conventional fertilization (DI-$F_{1.00}$). Compared with those under NPI fertigation, the sugar-acid ratio (30%), vitamin C content (34%), soluble solids content (20%), and nitrate concentration (34%) of tomato fruits under DI fertigation decreased. In addition, the WUE across treatments significantly decreased in the order of NPI-$F_{0.75}$ > NPI-$F_{0.00}$ > DI-$F_{1.00}$ > DI-$F_{0.00}$; notably, compared with NPI, water consumption increased twofold-fold, and WUE decreased by 47% under DI. The apparent recovery efficiency of applied nitrogen, partial factor productivity from applied nitrogen, and agronomic efficiency of applied nitrogen under NPI-$F_{0.75}$ were greater than those under DI-$F_{1.00}$. Both DI and NPI were able to maintain a relatively high tomato yield, but NPI performed slightly better. The yield percentage increase from the soil fertility contribution under NPI and DI was greater than 90%. Compared with DI fertigation, NPI fertigation reduced the amount of fertilizer needed without reducing yield or fruit quality and improved WUE and FUE, resulting in better overall use of soil nutrients by tomato plants.

Keywords Negative-pressure irrigation · Drip irrigation · Photosynthetic parameters · Nitrogen uptake · Fruit quality · Fruit yield · Plant growth

Introduction

Developing countries with large populations, such as China, face serious pressure to food security crisis, freshwater scarcity and environmental deterioration. Improving the utilization efficiency of water and fertilizer and reducing the emission of harmful substances in agricultural production are ever-growing needs. These challenges have prompted farmers, farm managers, and planners to adopt better irrigation management strategies that can create an optimal soil–water–plant relationship and can conserve water while maintaining productivity and crop quality (JeetBahadur et al. 2021).

Drip irrigation (DI) is a very efficient practical irrigation technology, and DI fertigation specifically provides for comprehensive management of water and fertilizer (Fan et al. 2020; Wang et al. 2020; Yaghi et al. 2013). DI coupled with nitrogen (N) fertigation has the potential to save irrigation water, increase the use efficiencies of both water and nitrogen fertilizers, and reduce the loss of nitrogen to the

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environment (Liu et al. 2020; Lv et al. 2019). For example, an irrigation and fertilization regime of 75% evaporation and 250 kg N ha^{-1} was found to provide the optimal combination of tomato yield, fruit quality, and water use efficiency (WUE), which was the best water and nitrogen management strategy for the tomato production in the drip-irrigated greenhouse (Du et al. 2017; Ankush et al. 2018; Nut et al. 2019). DI fertigation combined with the application of soluble organic and chemical fertilizers for top-dressing increased fruit yield (75 180 kg ha^{-1}) and plant dry matter (10 449 kg ha^{-1}) and enhanced plant nutrient uptake, nitrogen recovery efficiency (39%), nitrogen agronomic efficiency (177 kg kg^{-1}), and soluble solids content, vitamin C content and lycopene content in tomato fruits (Wu et al. 2020; Hu et al. 2021).

Negative-pressure irrigation (NPI) has received increasing attention in recent years, especially in the greenhouse production of several crops, such as peppers (*Capsicum annuum L.*; Nalliah et al. 2009; Nalliah and Ranjan 2010), tomatoes (*Lycopersicon esculintum Mill.*; Abidin et al. 2014); spinach (*Spinacia oleracea L.*; Bian et al. 2018); Bok Choy (*Brassica napus L.*; Zhao et al. 2017a); rapeseed (*Brassica chinensis L.*; Zhao et al. 2019); cucumber (*Cucumis sativus L.*; Zhao et al. 2017b); and crown daisy (*Glebionis coronaria L.*; Yang et al. 2020). The ability of NPI to supply water directly to the crop root zone ensures that optimum water and nutrient conditions are maintained throughout the reproductive period of the plant (Ashrafi et al. 2002; Abu-Zreig et al. 2006; Moniruzzaman et al. 2011a, b; Khan et al. 2013; Zheng et al. 2013; Wang et al. 2016, 2017, 2019). Supplying water directly to the crop root zone improved crop growth, quality, yield and water use efficiency (WUE) for a variety of crops (Wang et al. 2007; Agrawal et al. 2018; Cakir and Cebi 2010; Cakir et al. 2017; Li et al. 2021; Nalliah et al. 2009). For example, tomato plant height, yield, and WUE under NPI were found to be greater than those under drip irrigation (Li et al. 2017a). The use of NPI for growing red pepper plants has been found to save 35% more water, and the water use efficiency increased by 12–125% compared to that of normal irrigation (Nalliah and Ranjan., 2010; Li et al. 2017b). Additionally, a greenhouse NPI pot experiment with red pepper plants resulted in improved nutrient (e.g., nitrogen, phosphorus, potassium) accumulation in a single plant compared with that under normal irrigation, and the yield improved by 14% from the color turning stage to the ripe red stage (Li et al. 2017b).

The tomato (*Lycopersicon esculintum Mill.*) is cultivated mainly in greenhouses during the spring and autumn seasons in China, and fertigation technology, mostly DI fertigation, is widely used. Farmers commonly apply excessive nitrogen fertilizer in pursuit of high yield and profit, with annual nitrogen application rates reaching 2000–4000 kg N ha^{-1}; such rates far exceed crop demand (Wu et al. 2020) and inevitably lead to soil nutrient enrichment. Undoubtedly, fertilizer reduction in agricultural production not only decreases costs and increases benefits but is also conducive to improving soil quality and reducing environmental risks.

While previous research has shown that the irrigation effect of NPI is better than that of DI, little research has compared fertilizer reduction under NPI versus DI, especially under greenhouse-grown and soil-based matrix conditions with high fertility. The objectives of our study were to investigate the differences between NPI fertigation and DI fertigation on soil nutrients, plant growth, and water or fertilizer use efficiency in tomato plants, especially under reduced nitrogen application conditions, and to determine a more efficient system for managing water and fertilizer.

Materials and methods

Field site

Our field experiment was carried out in a solar greenhouse in Heshunxin village in Ningxia, China (38°21′44″N, 106°09′32″E), between July 2017 and January 2018. The greenhouse for this experiment has a six-year history of vegetable cultivation, and the soil texture is sandy loam from 0 to 40 cm and loamy sand from 40 to 60 cm. The bulk density and pH were 1.35 g cm^{-3} and 8.27, respectively, in the 0–20 cm layer of soil; other basic physical and chemical properties of the soil are shown in Table 1. The soil fertility is very high, with organic matter reaching grade 2 (National Soil Census Office., 1992; grade 1 is the highest among the six grades), total nitrogen reaching grade 3, available nitrogen reaching grade 2 or grade 3, Olsen phosphorus reaching 2.88 times that of grade 1, and available potassium reaching grade 4.

Irrigation system

NPI system

A new type of NPI device (Patents, China ZL201310554433.7) was used in this experiment, which consists of four parts: capillary water emitters, a water delivery pipe, a negative pressure water bucket, and a negative pressure generator. The system design is shown in Fig. 1 (Yang et al. 2020). There were 12 emitters connected to the irrigation system in this experiment. According to the results of suitable negative pressure for tomato growth, the irrigation water pressure was controlled at −3.0 kPa using a heavy liquid (mercury)-type negative pressure valve (Patents, China ZL201310554435.6) during the entire irrigation process.

Table 1 The basic physical and chemical properties of the soil

Soil layer	Total salt (g kg^{-1})	OM[1] (g kg^{-1})		TN (g kg^{-1})	AN (mg kg^{-1})	OP (mg kg^{-1})	AK (mg kg^{-1})
0–20 cm	0.52	32.8		1.30	119.0	115.2	85
	Field water capacity		*Soil mechanical composition (%)*[1]			*Texture*	
			Clay [≤2 μm]	*Silt [2–50 μm]*	*Sand [50–2000 μm]*		
0–20 cm	21.79%		3.65	30.80	65.55	Sandy loam	
20–40 cm	18.95%		2.72	32.73	64.55	Sandy loam	
40–60 cm	16.35%		2.55	21.01	76.44	Loamy sand	

[1] Values in brackets refer to soil particle size. OM, organic matter; TN, total nitrogen; AN, available nitrogen; OP, olsen phosphorus; AK, available potassium

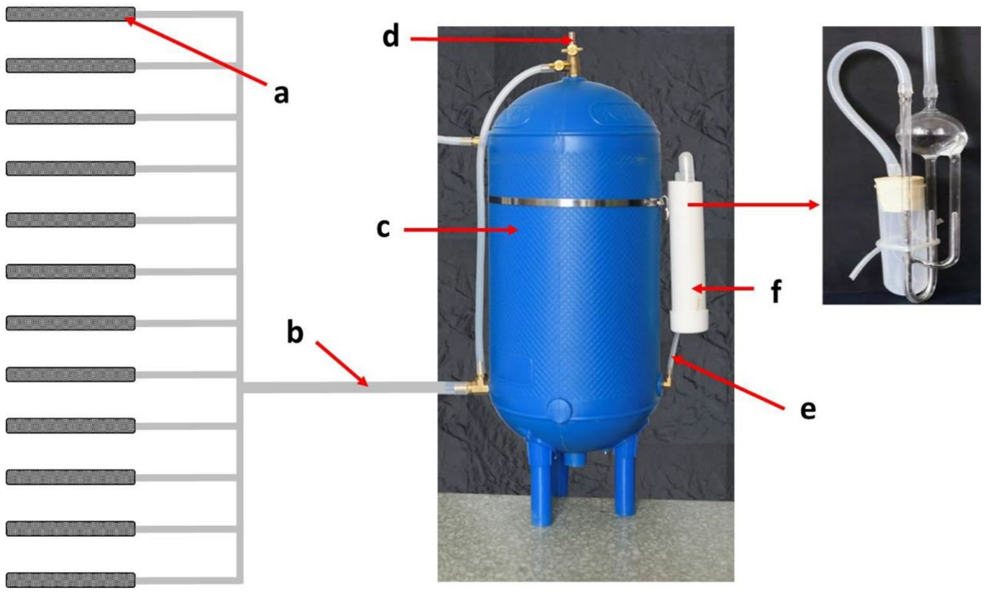

Fig. 1 The negative pressure irrigation system used in this experiment. *Note* "**a**" is capillary water emitter, "**b**" is a water delivery pipe, "**c**" is a negative pressure water bucket, "**d**" is water inlet, "**e**" is connecting pipe, and "**f**" is heavy liquid (mercury)-type negative pressure valve

DI system

The components of a multistation fertilizer applicator for DI consisted of a water source pump, pressure tank, fertilizer application machine, fertilizer solution barrel, main pipe, branch pipe, multiple manual switches, water meter and emitter (Fig. 2). The fertilizer solution barrel was equipped with a stirrer, and the irrigation water pressure was controlled at a range of 0.2–0.3 MPa using a pressure tank during the irrigation process.

Experimental design

Experimental treatment

A two-factor complete randomized design was used with three replicates per treatment. Factor one was the water supply method: negative-pressure irrigation (NPI) and drip irrigation (DI). Factor two was fertilizer application: $F_{0.00}$ (no nitrogen (N) fertilization), $F_{0.75}$ (75% conventional fertilization), and $F_{1.00}$ (100% conventional fertilization).

We conducted a preliminary survey of fertilizer amounts applied by farmers in previous years and found that local farmers were accustomed to drip irrigation and high fertilization rates that result in a highly profitable yield. (1) We determined that treatment $F_{1.00}$ (conventional fertilization, which was recognized by farmers as the amount of fertilizer that could maximize their economic benefits) would be 900 kg N ha^{-1}, 450 kg P_2O_5 ha^{-1}, and 600 kg K_2O ha^{-1}. (2) Previous studies have shown that NPI can improve FUE (Yang et al. 2020; Li et al. (2017b) reported that NPI fertilization could reduce fertilizer amounts by 11–24% compared to the DI of greenhouse tomato plants grown on the North China Plain. We inferred that reducing fertilizer amounts by 25% under NPI was equivalent to the full fertilizer amount under DI; thus, the fertilizer amount ($F_{0.75}$) under NPI was 675 kg N ha^{-1}, 337.5 kg P_2O_5 ha^{-1}, and 450 kg K_2O ha^{-1}. (3) To study nitrogen fertilizer reduction under the two irrigation fertilization methods, no nitrogen treatment ($F_{0.00}$) was used.

Thus, there were four treatments: NPI-$F_{0.75}$, NPI-$F_{0.00}$, DI-$F_{1.00}$, and DI-$F_{0.00}$. NPI-$F_{0.00}$ and NPI-$F_{0.75}$ are NPI fertilization with no nitrogen fertilization and 75% conventional

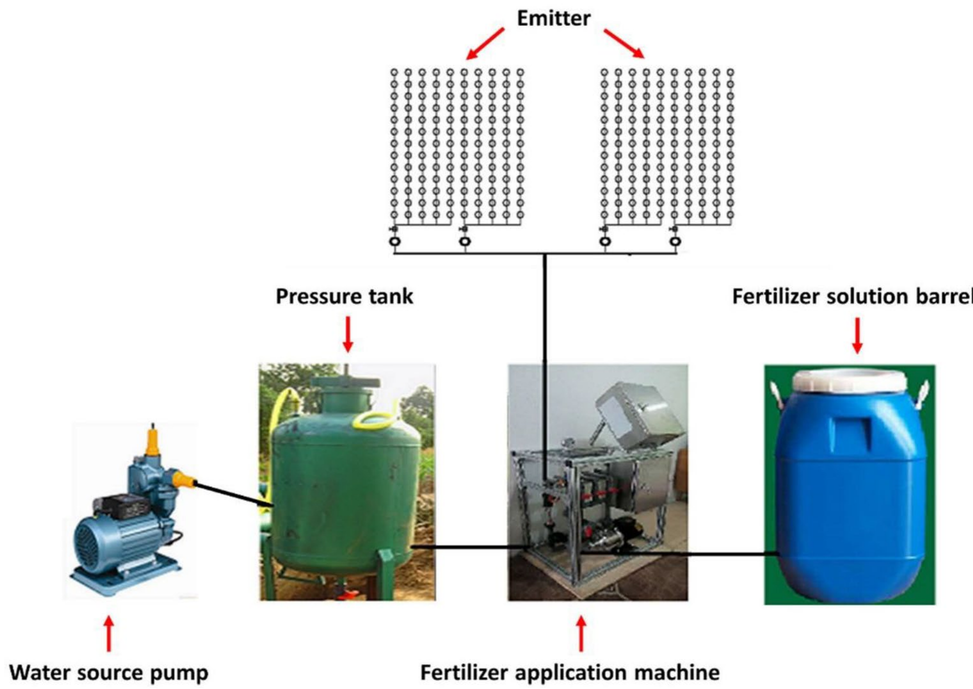

Fig. 2 Design of the multistation fertilizer applicator for drip irrigation

Table 2 Fertilizing amount under different treatments

Treatment	Fertilization (kg ha^{-1})		
	N	P_2O_5	K_2O
NPI-$F_{0.00}$	0	337.5	450
NPI-$F_{0.75}$	675	337.5	450
DI-$F_{0.00}$	0	450	600
DI-$F_{1.00}$	900	450	600

NPI-$F_{0.00}$, negative-pressure irrigation with no nitrogen fertilization; NPI-$F_{0.75}$, negative-pressure irrigation with 75% conventional fertilization; DI-$F_{0.00}$, drip irrigation with no nitrogen fertilization; DI-$F_{1.00}$, drip irrigation with 100% conventional fertilization

fertilization, respectively; DI-$F_{0.00}$ and DI-$F_{1.00}$ are DI fertilization with no nitrogen fertilization and 100% conventional fertilization, respectively. The fertilizer amount for each treatment is shown in Table 2.

Plot design

Each plot was composed of three 6 m long and 1.41 m wide ridges, with a total of 25.38 m^2 and 84 plants. The plot was separated by a guard row.

Fertilization and irrigation methods

Fertilizer application included urea (N, 46%), heavy superphosphate (P_2O_5, 42%) and potassium sulfate (K_2O, 50%). Phosphate fertilizer, 40% nitrogen fertilizer, and 40% potassium fertilizer were applied as basal fertilizers, and the remaining fertilizer was applied in six batches during the critical season (11 and 28 August, 16 September, 8 and 26 October and 15 November). Before tomato transplanting, 22.5×10^3 kg ha^{-1} organic fertilizer (organic matter, 260.6 g kg^{-1}; total N, 6.8 g kg^{-1}; total P, 3.7 g kg^{-1}; total K, 8.6 g kg^{-1}) was applied as base fertilizer.

An automatic intelligent irrigation control system was used in the drip irrigation (DI) treatment, with water supplied at for 3–6 days intervals depending on the weather, temperature in the greenhouse, soil moisture and plant growth conditions and for 2–3 h each time.

Tomato plant

The tomato plants were transplanted on July 30, 2017, and the plants were uprooted after the fruits were harvested on January 5, 2018. The whole growth period was 155 days. The tomato plant spacing and row spacing were 40 cm and 70 cm, respectively. The fields were managed in accordance with conventional local greenhouse management practices.

Measurements

Water parameters

The soil moisture was calculated using the oven-drying method (Bao 2000) in the 0–20 cm, 20–40 cm and 40–60 cm layers of each treatment was recorded throughout the production period on October 5, October 25, November 15, December 5, and December 25. Water application under NPI and DI was measured at the seedling stage (July 31–September 29), flowering and fruit-setting stage (September

30–October 21), fruit-bearing peak stage (October 22–December 11) and fruit-bearing late stage (December 11–January 1). Tomato irrigation water use efficiency (WUE_i, kg m^{-3}) was estimated as the amount of product produced per unit water consumption and was calculated with the following equation: where Y is the fruit yield (kg ha^{-1}) and I is the irrigation volume (m^3 ha^{-1}).

$$WUEi = Y/I \tag{1}$$

Soil and plant nitrogen parameters

Soil and plant samples from each treatment were collected after harvest, soil available nitrogen was determined by the alkaline hydrolysis diffusion method, and the concentration of total N in the whole plant was determined by the Kjeldahl method. The detailed methods used were previously described by Bao (2000). The uptake of N was calculated as follows (Zhao et al. 2017a):

$$N\ uptake = N\ concentration \times biomass \tag{2}$$

Nutrient availability parameters

The apparent recovery efficiency of applied N (RE_N, %), partial factor productivity from applied N (PFP_N, kg kg^{-1}), and agronomic efficiency of applied N (AE_N, kg kg^{-1}) reflect the utilization efficiency of fertilizer nitrogen in the soil and were calculated as follows (Kaur et al. 2018; Li et al. 2018; Olk et al. 1999):

$$RE_N = (U - U_0)/F \times 100 \tag{3}$$

$$PFP_N = Y_N/F \tag{4}$$

$$AE_N = (Y_N - Y_0)/F \tag{5}$$

where U (kg ha^{-1}) and U_0 (kg ha^{-1}) are the total amount of N absorbed by the whole plant at harvest with fertilization and without fertilization, respectively; Y_N (kg ha^{-1}) and Y_0 (kg ha^{-1}) are the fruit yields with fertilization and without fertilization, respectively; and F (kg ha^{-1}) is the total nitrogen fertilizer supply.

The percentage of soil fertility contribution (PSFC, %) reflects the soil nutrient supply in farmland and was calculated as follows (Xu et al. 2015):

$$PSFC = Y_0/Y_N \times 100 \tag{6}$$

Photosynthetic parameters

The net photosynthetic rate (P_n), stomatal conductance (G_s), intercellular CO_2 concentration (C_i), and transpiration rate (T_r) of the tomato leaves were measured using a portable photosynthetic measurement system (LI-6400, LI-COR Biosciences Inc., USA) at the peak stage of tomato fruit bearing (November 29). On November 20, the SPAD value of the tomato leaves was determined by a chlorophyll content analyzer (SPAD-502 Plus, Konika-Minolta Inc., Tokyo, Japan).

Fruit quality parameters

Three representative fruits were randomly collected from each plot at harvest to determine fruit quality parameters. Fruit height and equatorial diameter were measured by a caliper, and the fruit shape index was calculated from the fruit height and equatorial diameter. Hardness was measured by a fruit durometer (GY-1, Yiwu Hot Electronic Co., Ltd, China). The sugar-acid ratio, vitamin C content, soluble solids content, and nitrate concentration were analyzed per Cemeroğlu (2010) and Kacar (2010). The titratable acidity and total sugar content of the fruit juice samples were determined via NaOH titration and thermal titration with Pilling's reagent, respectively. The soluble solid content was measured using a handheld digital refractometer (ATC 0–90% brix, Interworld Highway, LLC, USA). The vitamin C content was determined by using 2,6-diclorofenol indophenol dye. Total N was analyzed by the Dumas method (Thompson et al. 2004).

Statistical analysis

Correlation analysis and variance analysis of different indicators were performed using IBM SPSS Statistics (IBM Corp., Armonk, NYC), and other statistical analyses were performed using SigmaPlot 12.5 (Systat Software Inc., San Jose, CA).

Results

Effects of nitrogen reduction on soil moisture under drip fertigation and negative-pressure fertigation

The soil moisture profiles and water application under NPI and DI are shown in Fig. 3. Compared with that under DI, the mean soil moisture in the 0–40 cm soil layer under NPI was greater, especially in the surface soil layer (0–20 cm), where the soil moisture was more stable. At the 40–60 cm soil depth, the soil moisture increased with time and finally

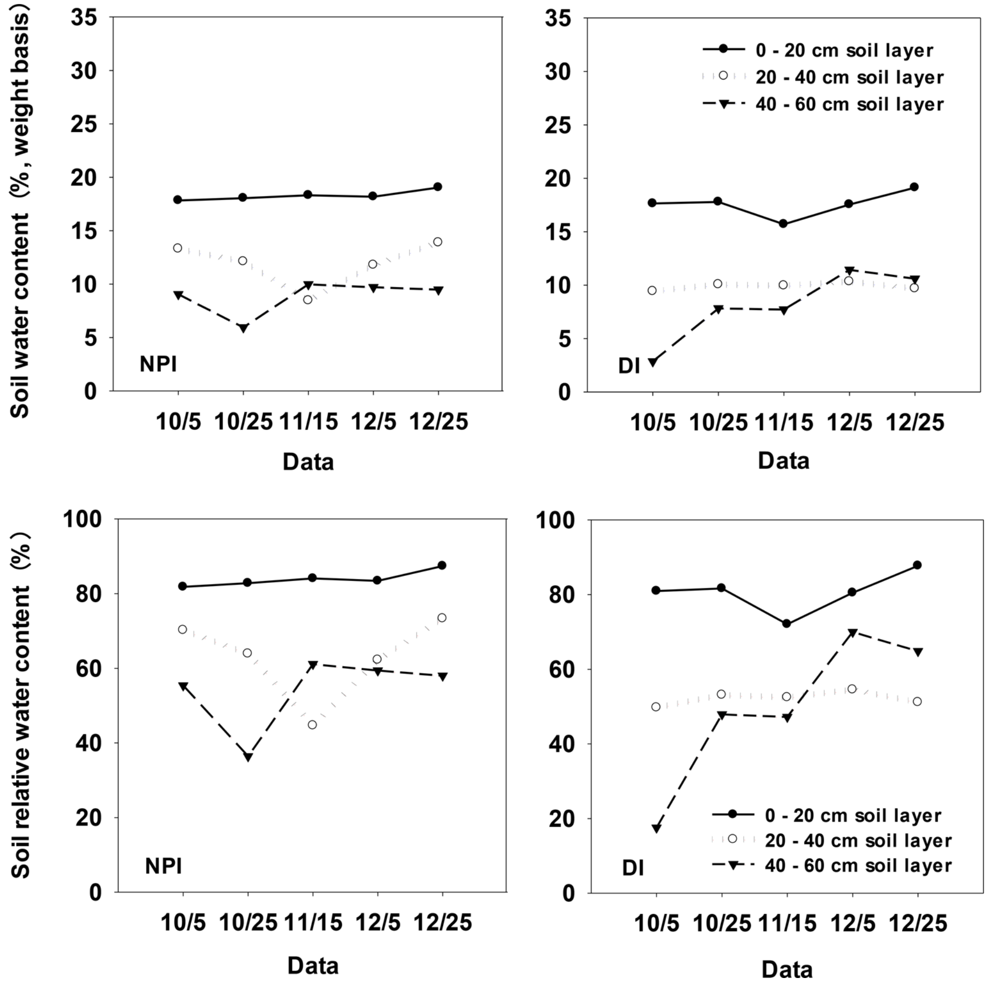

Fig. 3 Soil moisture under negative-pressure irrigation (NPI) and drip irrigation (DI)

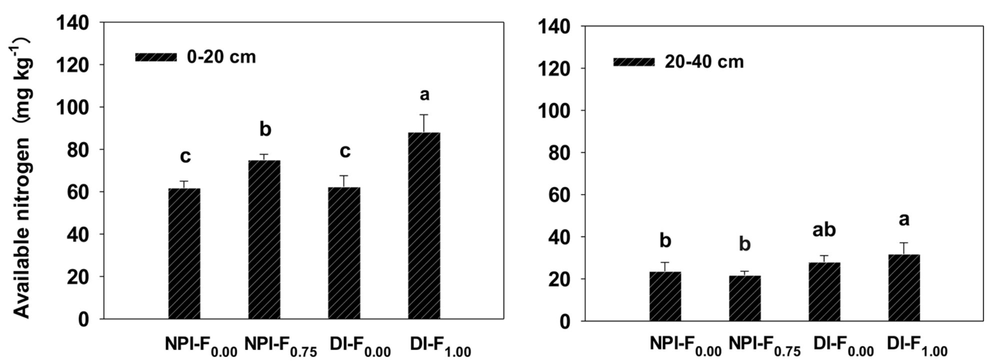

Fig. 4 Soil available nitrogen under negative-pressure irrigation (NPI) and drip irrigation (DI) after harvest time. Note: NPI-$F_{0.00}$ and NPI-$F_{0.75}$ are negative-pressure fertilization with no nitrogen fertilization and 75% conventional fertilization, respectively; DI-$F_{0.00}$ and DI-$F_{1.00}$ are drip fertilization with no nitrogen fertilization and 100% conventional fertilization, respectively

reached the highest level, but the highest level of NPI was lower than the highest level of DI. Soil texture differences between depths (in our case, a loam above a sand layer) are beneficial for retaining soil irrigation water in the plow layer under NPI (Wang et al. 2017).

Effects of nitrogen reduction on soil nutrients under drip fertigation and negative-pressure fertigation

Nitrogen application significantly increased the available nitrogen at the soil surface (Fig. 4). We observed the relationship DI-$F_{1.00}$ > NPI-$F_{0.75}$ > DI-$F_{0.00}$ = NPI-$F_{0.00}$ in this layer, and the differences in available nitrogen among the $F_{0.00}$, $F_{0.75}$, and $F_{1.00}$ treatments were significant. In the subsurface soil (20–40 cm), the relationships were DI-$F_{1.00}$ > DI-$F_{0.00}$ > NPI-$F_{0.00}$ > NPI-$F_{0.75}$, and the differences between

Table 3 Interaction of irrigation method and fertilization on soil available nitrogen

	AN* (0–20 cm)		AN (20–40 cm)	
Source	F	Sig.	F	Sig.
Irrigation method	0.02	0.90	2.02	0.19
fertilization	23.14	0.00	0.90	0.44
Irrigation method * fertilization	4.31	0.07	1.61	0.24
N (kg ha^{-2})	*Mean (mg kg^{-1})*	*significance*		
0	62.10	Cc		
675	75.10	Bb		
900	88.20	Aa		

AN, available nitrogen; N, nitrogen application

DI-$F_{1.00}$ and NPI-$F_{0.75}$ were significant and between DI-$F_{1.00}$ and NPI-$F_{0.00}$ were significant. Our results indicate that the nitrogen applied to the soil is more likely to be washed into the subsoil by irrigation water under DI, while it is mostly reserved in surface soil under NPI. The interaction effect between irrigation method and fertilization on soil available nitrogen was not significant, and both had an independent effect on available soil nitrogen (Table 3).

Effects of nitrogen reduction on photosynthesis in tomato plants under drip fertigation and negative-pressure fertigation

Our ANOVA results indicated that there was no interaction effect between irrigation method and fertilization on the photosynthetic parameters (Table 4). Tomato fertilizer application may enhance photosynthesis under both irrigation methods (Li et al. 2003), especially by influencing stomatal conductance (G_s) and SPAD. Based on the SPAD values, reducing nitrogen application decreased the chlorophyll content, and there were significant differences among the $F_{1.00}$, $F_{0.75}$, and $F_{0.00}$ treatments. Compared with $F_{0.00}$, $F_{0.75}$ increased by 13% under NPI, and $F_{1.00}$ increased by 15% under DI. Moreover, NPI fertigation increased stomatal conductance (G_s). The G_s of the NPI-$F_{0.75}$ treatment was greater than that of the other treatments and was significantly different from that of the $F_{0.00}$ treatment under both irrigation methods. Previous research has shown that N fertilizer application significantly increased the electron donor and acceptor performance of the photosystem II reaction center, which led to an increase in chlorophyll and net photosynthesis rates (Yang et al. 2018; Heidari et al., 2020).

Effects of nitrogen reduction on the nitrogen concentration and nitrogen uptake by tomato plants under drip fertigation and negative-pressure fertigation

Under the two irrigation methods, the nitrogen concentration and nitrogen uptake of each tissue were affected by the amount of fertilizer applied, and the effects of fertilization were significantly greater than those of reduced nitrogen fertilization; the effects of NPI were similar to those of DI (Table 5). Under NPI, the nitrogen uptake of the whole plant under NPI-$F_{0.75}$ was approximately 24% greater than that under NPI-$F_{0.00}$. Under DI, the nitrogen uptake of the whole plant under DI-$F_{1.00}$ was approximately 27% greater than that under DI-$F_{0.00}$. There was no interaction effect between irrigation method and fertilization (Table 5). The irrigation method had a significant effect on the nitrogen concentration in the fruit, and under DI, the nitrogen concentration was significantly greater than that under NPI, but the increase was only 0.048 g kg^{-1} (3.6%).

Effects of nitrogen reduction on fruit quality parameters of tomato plants under drip fertigation and negative-pressure fertigation

The tomato acid-sugar ratio, vitamin C content, soluble solids content, and nitrate concentration were significantly affected by irrigation method and fertilization application

Table 4 Photosynthetic parameters of tomato plants under different irrigation and fertilization treatments

Treatment	P_n (μmol m^{-2} s^{-1})		G_s (mol m^{-2} s^{-1})		C_i (μmol mol^{-1})		T_r (mmol m^{-2} s^{-1})		SPAD	
NPI-$F_{0.00}$	12.63 ± 1.52a		0.21 ± 0.02 b		333.43 ± 35.04a		2.14 ± 0.18a		34.83 ± 1.53c	
NPI-$F_{0.75}$	13.96 ± 1.45a		0.30 ± 0.05 a		332.18 ± 23.05a		2.28 ± 0.08a		39.28 ± 0.33b	
DI-$F_{0.00}$	11.45 ± 0.08a		0.18 ± 0.03 b		349.46 ± 43.64a		2.25 ± 0.08a		36.12 ± 1.17c	
DI-$F_{1.00}$	11.56 ± 2.11a		0.24 ± 0.05 ab		337.33 ± 23.34a		2.11 ± 0.12a		41.36 ± 0.60a	
Source	*F*	*Sig.*	*F*	*Sig.*	*F*	*Sig.*	*F*	*Sig.*	*F*	*Sig.*
Irrigation method	0.94	0.36	1.16	0.31	0.37	0.56	1.17	0.31	2.39	0.16
fertilization	0.61	0.57	6.01	0.03	0.11	0.90	1.97	0.20	33.91	0.00
Irrigation method * fertilization	0.50	0.50	0.60	0.46	0.08	0.78	3.94	0.08	0.45	0.52

NPI-$F_{0.00}$, negative-pressure irrigation with no nitrogen fertilization; NPI-$F_{0.75}$, negative-pressure irrigation with 75% conventional fertilization; DI-$F_{0.00}$, drip irrigation with no nitrogen fertilization; DI-$F_{1.00}$, drip irrigation with 100% conventional fertilization. P_n, net photosynthetic rate, G_s, stomatal conductance, C_i, intercellular CO_2 concentration, T_r, transpiration rate, SPAD, chlorophyll

Table 5 The nitrogen concentration and nitrogen uptake by tomato plants under drip fertigation and negative pressure fertigation

Treatment	Nitrogen concentration (g 100 g^{-1})				Nitrogen uptake (kg ha^{-1})					
	Dried fruit		Dried Rootstems and leaves		Fruit		Rootstems and leaves		Whole plant	
NPI-$F_{0.00}$	1.26 ± 0.03c		1.84 ± 0.08b		70.50 ± 0.15b		51.15 ± 4.05b		121.65 ± 4.20b	
NPI-$F_{0.75}$	1.41 ± 0.03a		2.07 ± 0.12a		87.30 ± 3.15a		63.60 ± 4.95a		150.75 ± 4.80a	
DI-$F_{0.00}$	1.32 ± 0.03b		1.85 ± 0.06b		72.30 ± 2.10b		50.25 ± 2.10b		122.40 ± 3.90b	
DI-$F_{1.00}$	1.45 ± 0.04a		2.13 ± 0.10a		87.45 ± 2.70a		67.50 ± 6.15a		154.95 ± 8.70a	
Source	*F*	*Sig.*	*F*	*Sig.*	*F*	*Sig.*	*F*	*Sig.*	*F*	*Sig.*
Irrigation method	6.50	0.03	0.00	0.87	1.00	0.36	0.10	0.80	0.00	0.86
fertilization	32.90	0.00	11.00	0.01	73.30	0.00	16.30	0.00	43.10	0.00
Irrigation method * fertilization	0.70	0.42	0.20	0.68	0.40	0.54	0.90	0.37	0.20	0.63
Nitrogen fertilization	*Mean*	*significance*	*Mean*	*significance*	*Mean*	*significance*	*Mean*	*significance*	*Mean*	*signifi-cance*
0 kg ha^{-1}	1.29	Bb	1.85	Bb	71.4	Bb	50.7	Bb	122.1	Bb
675 kg ha^{-1}	1.41	Aa	2.07	Aa	87.3	Aa	63.6	Aa	150.75	Aa
900 kg ha^{-1}	1.45	Aa	2.13	Aa	87.45	Aa	67.5	Aa	154.95	Aa
Irrigation method	*Mean*	*significance*								
NPI	1.34	Bb								
DI	1.38	Aa								

NPI-$F_{0.00}$, negative-pressure irrigation with no nitrogen fertilization; NPI-$F_{0.75}$, negative-pressure irrigation with 75% conventional fertilization; DI-$F_{0.00}$, drip irrigation with no nitrogen fertilization; DI-$F_{1.00}$, drip irrigation with 100% conventional fertilization. NPI, negative-pressure irrigation; DI, drip irrigation

Table 6 The quality of tomato under different irrigation and fertilization treatment

Treatment	Sugar-acid ratio	Vitamin C (mg 100 g^{-1})	Soluble solid (g 100 g^{-1})	Nitrate (mg kg^{-1})
NPI-$F_{0.00}$	8.18	22.30	5.4	126
NPI-$F_{0.75}$	7.00	19.70	5.4	158
DI-$F_{0.00}$	7.50	20.60	5.1	100
DI-$F_{1.00}$	4.89	13.00	4.3	104
Compared NPI-$F_{0.75}$with DI-$F_{1.00}$				
DI-$F_{1.00}$	-30	-34%	-20	-34%

NPI-$F_{0.00}$, negative-pressure irrigation with no nitrogen fertilization; NPI-$F_{0.75}$, negative-pressure irrigation with 75% conventional fertilization; DI-$F_{0.00}$, drip irrigation with no nitrogen fertilization; DI-$F_{1.00}$, drip irrigation with 100% conventional fertilization

(Table 6). Nitrogen reduction treatment increased the acid-sugar ratio, vitamin C content and soluble solids content. Compared with those under NPI-$F_{0.75}$, the sugar-acid ratio, vitamin C content, soluble solids content, and nitrate concentration of the tomato fruits under DI-$F_{1.00}$ decreased by 30%, 34%, 20%, and 34%, respectively. Our results also demonstrated that less irrigation water applied with 75% conventional fertilization also produced a higher quality tomato. The nitrate concentration in tomato did not exceed the national food safety limit standard, and the tomato is thus safe to eat (Ministry of Health of the People's Republic of China, 2012).

The irrigation and fertilization treatments affected fruit size (Table 7). The height and equatorial diameter of the tomato fruits in the NPI-$F_{0.75}$ and DI-$F_{1.00}$ treatments were greater than those in the NPI-$F_{0.00}$ or DI-$F_{0.00}$ treatments. Our ANOVA results indicate that there was no significant interaction effect between irrigation method and fertilization on the height diameter, equatorial diameter, fruit shape index, or hardness of tomato plants. Fertilization and no nitrogen fertilization significantly affected the height diameter and equatorial diameter of the fruits.

Effects of nitrogen reduction on tomato fresh fruit yield, irrigation volume, and WUE under drip fertigation and negative-pressure fertigation

There was no significant interaction effect between irrigation method and fertilization on fresh fruit yield, irrigation volume, or WUE_i (Table 8). The irrigation method had a significant effect on the irrigation volume and WUE_i. The irrigation volume under NPI was significantly lower than that under DI, and the WUE_i was significantly greater than that under DI. During the entire growth period of tomato plants, the total irrigation volume under DI was approximately 4446 m^3 ha^{-1}, while that under NPI was nearly half that under DI. Fertilization had a significant effect on yield and WUE_i. No nitrogen supply led to a decrease in WUE_i or yield under the same irrigation method. The yields of NPI-$F_{0.75}$ and DI-$F_{1.00}$ were 10% greater than those of NPI-$F_{0.00}$ and DI-$F_{0.00}$, respectively.

Because the WUE_i was affected by the fertilizer and irrigation method independently at the same time and the WUE_i under fertilization includes the influence of the irrigation method, as shown in Table 8, the effect of the irrigation method needs to be removed. The water use efficiency of fertilizer sources (WUE_f) is the difference in WUE_i between fertilization and no nitrogen fertilization; therefore, $WUE_f =$ 0 kg m^3 under no extra nitrogen fertilizer. We found that fertilization can improve WUE_i, but when fertilization exceeds a certain amount, WUE_f decreases (Table 9). Moreover, the WUE_f was much lower than the WUE_i and accounted for only 7.5–9.7% of the WUE_i.

Table 7 The fruit size and fruit shape index under different irrigation and fertilization treatment

Treatment	Height diameter (mm)		Equatorial diameter (mm)		Fruit shape index		Hardness	
NPI-$F_{0.00}$	65.17 ± 0.70b		71.87 ± 2.86b		0.91 ± 0.04a		9.07 ± 0.11a	
NPI-$F_{0.75}$	73.41 ± 3.22a		82.51 ± 3.50a		0.89 ± 0.03a		9.10 ± 0.20a	
DI-$F_{0.00}$	64.58 ± 1.79b		73.27 ± 1.77b		0.88 ± 0.04a		9.16 ± 0.10a	
DI-$F_{1.00}$	74.36 ± 2.84a		81.96 ± 2.86a		0.91 ± 0.02a		9.19 ± 0.11a	
Source	*F*	*Sig.*	*F*	*Sig.*	*F*	*Sig.*	*F*	*Sig.*
Irrigation method	0.09	0.77	0.37	0.56	0.93	0.36	0.61	0.46
fertilization	22.13	0.00	17.86	0.00	0.68	0.54	0.06	0.95
Irrigation method * fertilization	0.32	0.59	0.36	0.57	1.31	0.29	0.00	1.00
Nitrogen fertilization	*Mean*	*significance*	*Mean*	*significance*				
0 kg ha^{-1}	64.90	Bb	72.60	Bb				
675 kg ha^{-1}	73.40	Aa	82.50	Aa				
900 kg ha^{-1}	74.40	Aa	82.00	Aa				

NPI-$F_{0.00}$, negative-pressure irrigation with no nitrogen fertilization; NPI-$F_{0.75}$, negative-pressure irrigation with 75% conventional fertilization; DI-$F_{0.00}$, drip irrigation with no nitrogen fertilization; DI-$F_{1.00}$, drip irrigation with 100% conventional fertilization

Table 8 Yield and water use efficiency of tomato under different irrigation and fertilization treatments

Treatment	Fresh fruit yield (kg ha^{-1})		Irrigation volume (m^3 ha^{-1})		WUE_i (kg m^{-3})	
NPI-$F_{0.00}$	101946.45 ± 2224.20b		2343.00 ± 75.90b		43.52 ± 0.96b	
NPI-$F_{0.75}$	112251.00 ± 2297.10a		2386.50 ± 60.90b		47.04 ± 0.67a	
DI-$F_{0.00}$	99544.20 ± 1432.50b		4455.00 ± 33.00a		22.34 ± 0.31d	
DI-$F_{1.00}$	109856.85 ± 1625.70a		4438.50 ± 32.25a		24.75 ± 0.21c	
Source	*F*	*Sig.*	*F*	*Sig.*	*F*	*Sig.*
Irrigation method	2.30	0.17	2301.10	0.00	1685.00	0.00
fertilization	42.70	0.00	0.50	0.60	34.20	0.00
Irrigation method * fertilization	0.00	1.00	0.90	0.37	2.40	0.16
Nitrogen fertilization	*Mean*	*significance*	*Mean*	*significance*	*Mean*	*significance*
0 kg ha^{-1}	100745.33	Bb			32.90	Bb
675 kg ha^{-1}	112251.00	Aa			47.00	Aa
900 kg ha^{-1}	109856.85	Aa			24.70	Cc
Irrigation method			*Mean*	*significance*	*Mean*	*significance*
NPI			2364.75	Bb	45.30	Aa
DI			4446.75	Aa	23.50	Bb

NPI-$F_{0.00}$, negative-pressure irrigation with no nitrogen fertilization; NPI-$F_{0.75}$, negative-pressure irrigation with 75% conventional fertilization; DI-$F_{0.00}$, drip irrigation with no nitrogen fertilization; DI-$F_{1.00}$, drip irrigation with 100% conventional fertilization. WUE_i, water use efficiency of irrigation source

Table 9 Water use efficiency of fertilizer source (WUE_f) no fertilization and fertilization treatments

Nitrogen fertilization (kg ha^{-2})	WUE_f (kg m^{-3})
0	0.00c
675	3.53 a
900	2.41 b

WUE_f, water use efficiency of fertilizer source

Table 10 Fertilizer use efficiency (FUE) of tomato and percentage of soil fertility contribution under different irrigation and fertilization treatment

Treatment	RE_N (%)	PFP_N (kg kg^{-1})	AE_N (kg kg^{-1})	PSFC (%)
NPI-$F_{0.00}$	—	—	—	—
NPI-$F_{0.75}$	4.33 ± 0.12	166.30 ± 2.78	15.27 ± 1.54	91.00 ± 0.82
DI-$F_{0.00}$	—	—	—	—
DI-$F_{1.00}$	3.60 ± 0.73	122.07 ± 1.48	11.46 ± 1.35	90.67 ± 1.25

NPI-$F_{0.00}$, negative-pressure irrigation with no nitrogen fertilization; NPI-$F_{0.75}$, negative-pressure irrigation with 75% conventional fertilization; DI-$F_{0.00}$, drip irrigation with no nitrogen fertilization; DI-$F_{1.00}$, drip irrigation with 100% conventional fertilization. RE_N, recovery efficiency of applied nitrogen; PFP_N, partial factor productivity from applied nitrogen; AE_N, agronomic efficiency of applied nitrogen; PSFC, percentage of soil fertility contribution

Effects of nitrogen reduction on tomato fertilizer use efficiency (FUE) under drip fertigation and negative-pressure fertigation

Fertilization significantly affected FUE (Table 10). The apparent recovery efficiency of applied nitrogen (RE_N), partial factor productivity from applied nitrogen (PFP_N), and agronomic efficiency of applied nitrogen (AE_N) of NPI-$F_{0.75}$ were 19%, 37%, and 33% greater than those of DI-$F_{1.00}$, respectively. The percentage of soil fertility contribution (PSFC) was more than 90% in both treatments, indicating that the soil was very fertile. Therefore, we conclude that, compared with drip fertilization, negative-pressure fertilization can improve tomato fertilizer use efficiency. Although the water and fertilizer supplies of the tomatoes were lower under NPI than under DI, they did not affect yield but instead increased irrigation water and fertilizer use efficiency.

Nitrogen balance analysis

There was no significant interaction between the irrigation method and fertilization, which worked independently of each other, as seen in the nitrogen storage changes and the ratio of nitrogen uptake to nitrogen loss in the system (Table 11). Under NPI and DI, irrigation method and fertilization played independent roles, respectively. Fertilization treatment had a significant effect on the nitrogen storage change and the ratio of nitrogen uptake to nitrogen loss in the system. Tomato growth led to a decrease in soil nitrogen storage under NPI and DI, and the reduction in nitrogen storage at the 0–20 cm soil depth decreased with increasing fertilizer application. Under the condition of no nitrogen fertilizer application, approximately 80% of the nitrogen loss in the production process was absorbed and utilized by tomato plants.

Correlation analysis

A significant negative correlation was detected between WUE and available nitrogen at the 20–40 cm soil depth,

Table 11 Nitrogen balance under different irrigation and fertilization treatment

Treatment	Nitrogen uptake / system nitrogen loss		0–20 cm nitrogen storage reduction (kg ha^{-1})		Nitrogen ineffective loss (kg ha^{-1})	
NPI-$F_{0.00}$	78.90 ± 6.70	Aa	154.50 ± 8.70	Aa	33.00 ± 11.70	Cc
NPI-$F_{0.75}$	19.00 ± 0.78	Bb	118.50 ± 6.90	Bb	643.50 ± 11.7	Bb
DI-$F_{0.00}$	80.70 ± 10.17	Aa	153.00 ± 14.10	Aa	30.00 ± 17.85	Cc
DI-$F_{1.00}$	15.80 ± 1.24	Bb	82.50 ± 21.90	Bc	828.00 ± 30.45	Aa
Source	*F*	*Sig.*	*F*	*Sig.*	*F*	*Sig.*
Irrigation method	0.05	0.84	5.12	0.05	66.25	0.00
fertilization	310.95	0.00	41.97	0.00	3915.82	0.00
Irrigation method * fertilization	0.49	0.50	4.31	0.07	69.71	0.00
Nitrogen fertilization	*Mean*	*significance*	*Mean*	*significance*		
0 kg ha^{-1}	79.80	Aa	153.75	Aa		
675 kg ha^{-1}	19.00	Bb	118.50	Bb		
900 kg ha^{-1}	15.80	Bb	82.50	Cc		

NPI-$F_{0.00}$, negative-pressure irrigation with no nitrogen fertilization; NPI-$F_{0.75}$, negative-pressure irrigation with 75% conventional fertilization; DI-$F_{0.00}$, drip irrigation with no nitrogen fertilization; DI-$F_{1.00}$, drip irrigation with 100% conventional fertilization

and the same relationship was detected between WUE and irrigation volume (Table 12). Stepwise regression revealed that the P_n and available nitrogen at the 20–40 cm soil depth could be excluded from the regression model, and there was a significant positive correlation between WUE and P_n. Our results indicate that DI and NPI fertilization under high soil fertility conditions result in fertilization factors that are not high enough to cause variations in WUE, and irrigation volume is thus not enough to cause variations in tomato growth, development, and photosynthetic characteristics; however, an excessive water supply can significantly reduce WUE.

There was a significant positive correlation between irrigation volume and available nitrogen at the 20–40 cm soil depth, indicating that under high basal fertility, excessive irrigation would cause nitrogen leaching from the upper soil to this layer.

The available nitrogen at the 0–20 cm soil depth was highly significantly correlated with the fresh fruit yield, dry matter of the root stems and leaves, nitrogen concentration of the dry fruit, nitrogen concentration of the dry root stems and leaves, nitrogen uptake of the fruit, nitrogen uptake of the root stems and leaves, stem diameter, fruit height diameter, fruit equatorial diameter and SPAD. Our results showed that the nitrogen absorbed by tomato plants mainly came from the 0–20 cm soil layer.

Discussion

Interaction effect of irrigation method and fertilization on WUE_i

WUE_i decreased as nitrogen fertilizer use decreased under the different irrigation methods, and WUE_i under NPI was greater than that under DI for both fertilization treatments. Our results showed that an appropriate irrigation method can increase fertilizer efficiency and improve WUE_i. We also found that G_s promoted the regulation of plant WUE_i under fertigation. Wang (2018) concluded that reduced soil water regimes under N fertigation caused partial closure of stomata via decreased plant water status and intensified root-to-shoot ABA signaling, resulting in improved intrinsic WUE (WUE_i). Our results and those of Wang (2018) suggested that there was a positive relationship between appropriate irrigation methods and fertilization, supporting the notion that water promotes fertilizer use and that fertilizer use promotes water use. Moderate soil water regimes with reasonable N additions are recommended for fertigation in terms of achieving high fresh fruit yield, WUE, and nutrient uptake.

Analysis of fertilizer use efficiency (FUE) differences between NPI and DI during tomato growth

The RE_N, PFP_N, and AE_N of NPI-$F_{0.75}$ were greater than those of DI-$F_{1.00}$. Fertilization and irrigation methods significantly affected FUE. Although the water and fertilizer supplied to the tomatoes decreased under NPI, they did not reduce the yield and instead increased the FUE. Our results show that compared with drip irrigation, NPI can reduce fertilization needs without affecting the yield or quality of tomatoes.

The PSFC for crops is generally 50–80%, and the RE_N is 30–40% according to previous studies (Dobermann et al., 2005; Liang et al. 2019; Rasool et al. 2020). Comparatively, we found that the RE_N is smaller and the PSFC is larger. Our results may be due to excess nitrogen application or a sufficient original soil nitrogen concentration.

In another study, even without nitrogen application, tomato yield was greater than that with optimized

Table 12 Correlation analysis of different indicators

	Fresh fruit Yield	Roots, stem and leaves dry matter	*N* concentration		*N* uptake		Plant height	Stem diameter	Fruit				photosynthesis					AN		Irrigation volume	WUE	Whole plant *N* uptake	0–20 cm *N* storage reduction	*N* ineffective loss	*N* uptake / system *N* loss
			Fruit	Root, stem and leaves	Fruit	Root, stem and leaves			Height diameter	Equatorial diameter	Shape index	Hardness	SPAD	P_n	G_s	C_i	T_r	0–20 cm	20–40 cm						
Fresh fruit Yield	1																								
Root, stem and leaves dry matter	0.81**	1																							
Fruit N concentration	0.77**	0.77**	1																						
Root, stem and leaves N concentration	0.86**	0.88**	0.80**	1																					
Fruit N uptake	0.93**	0.84**	0.95**	0.88**	1																				
Root, stem and leaves N uptake	0.86**	0.97**	0.81**	0.97**	0.89**	1																			
Plant height	-0.07	0.10	0.30	-0.16	0.13	-0.03	1																		
Stem diameter	0.56	0.76**	0.75**	0.65*	0.70*	0.72**	0.44	1																	
Fruit height diameter	0.90**	0.84**	0.80**	0.92**	0.91**	0.91**	0.02	0.65*	1																
Fruit equatorial diameter	0.92**	0.84**	0.86**	0.95**	0.95**	0.92**	-0.10	0.63*	0.90**	1															
Fruit shape index	-0.01	0.01	-0.11	-0.05	-0.06	-0.01	0.25	0.04	0.25	-0.20	1														
Hardness	0.12	-0.14	0.17	0.14	0.16	-0.00	0.00	-0.07	0.11	0.21	-0.21	1													
SPAD	0.76**	0.76**	0.91**	0.79**	0.89**	0.80**	0.34	0.81**	0.83**	0.78**	0.14	0.16	1												
P_n	0.41	-0.01	0.03	0.12	0.23	0.06	-0.20	-0.22	0.33	0.26	0.18	0.08	0.02	1											
G_s	0.78**	0.39	0.41	0.52	0.62*	0.46	-0.12	0.27	0.65*	0.60*	0.15	0.22	0.54	0.64*	1										
C_i	-0.04	0.12	0.08	0.25	0.02	0.19	-0.35	0.05	-0.07	0.15	-0.49	-0.23	0.06	-0.31	-0.17	1									
T_r	0.07	0.01	-0.06	0.14	0.00	0.08	-0.45	0.01	0.08	0.21	-0.29	0.09	-0.29	0.14	-0.01	-0.07	1								
0–20 cm AN	0.77**	0.90**	0.87**	0.90**	0.88**	0.93**	0.12	0.68*	0.86**	0.87**	-0.02	0.11	0.83**	0.01	0.30	0.14	-0.09	1							
20–40 cm AN	-0.01	0.30	0.31	0.32	0.18	0.34	0.30	0.25	0.18	0.18	-0.01	0.19	0.28	-0.57	-0.41	0.29	-0.16	0.47	1						
Irrigation volume	-0.20	0.03	0.31	0.14	0.07	0.09	0.45	0.39	0.03	0.06	-0.09	0.39	0.31	-0.55	-0.45	0.19	-0.10	0.30	0.73**	1					
WUE	0.34	0.09	-0.18	-0.00	0.07	0.04	-0.43	-0.28	0.11	0.08	0.08	-0.36	-0.18	0.59*	0.56	-0.18	0.13	-0.18	-0.70*	-0.99**	1				
Whole plant N uptake	0.92**	0.93**	0.90**	0.96**	0.97**	0.97**	0.05	0.73**	0.94**	0.96**	-0.04	0.08	0.87**	0.15	0.55	0.11	0.04	0.93**	0.27	0.09	0.06	1			
0–20 cm N storage reduction	-0.77**	-0.90**	-0.87**	-0.90**	-0.88**	-0.93**	-0.12	-0.68*	-0.86**	-0.87**	0.02	-0.11	-0.83**	-0.01	-0.30	-0.14	0.09	1.00**	-0.46	-0.30	0.18	-0.93**	1		
N ineffective loss	0.88**	0.87**	0.90**	0.84**	0.95**	0.88**	0.27	0.79**	0.91**	0.86**	0.13	0.17	0.93**	0.12	0.59*	-0.14	-0.13	0.88**	0.21	0.13	0.00	0.94**	-0.88**	1	
N uptake / system N loss	-0.90**	-0.83**	-0.87**	-0.81**	-0.94**	-0.84**	-0.26	-0.74**	-0.92**	-0.84**	-0.20	-0.14	-0.90**	-0.22	-0.68*	0.22	0.06	-0.81**	-0.12	-0.02	-0.12	-0.92**	0.81**	-0.98**	1

* indicate significant correlation ($P<0.05$); ** indicate very significant correlation ($P<0.01$)

fertilization according to Wu et al. (2020). Wu et al. (2020) carried out their experiment under medium and low soil fertility and concluded that water-fertilizer integration technology could better utilize basic soil fertility and provide higher yields. Our results showed that NPI water-fertilizer combination was more effective than DI water-fertilizer combination.

Analysis of fruit quality differences between DI Fertigation and NPI fertigation

NPI can maintain the stability of soil moisture and help ensure that there is sufficient water for tomato growth during the whole growth period. Compared with DI, NPI increased the sugar-acid ratio, vitamin C content, and soluble solids content; improved fruit quality; and reduced water demand. We found that negative-pressure fertigation not only maintained a high fruit yield but also significantly increased WUE_i and FUE, indicating a great advantage in terms of water and fertilizer savings compared with DI; similar conclusions were drawn by Li et al. (2018) and Gao et al. (2019). The photosynthetic parameters, nitrogen concentration, nitrogen uptake, fruit size, fruit hardness, and yield differed little between NPI and DI under reduced fertilization or conventional fertilization. This is very different from the results obtained by Li et al. (2017a) and is possibly due to the pressure of the water supply or fertilizer application method under NPI.

The values for fruit quality parameters under the nitrogen reduction and NPI water regimes were similar or even greater than those under conventional fertilization under the DI water regime. However, this was not observed by Azizedogan and Ustun (2017), who showed that a water regime to reduce water supply decreased quality parameter values (i.e., titratable acidity, vitamin C, height diameter, and equatorial diameter) compared to conventional irrigation. Our results and those of Azizedogan and Ustun (2017) demonstrate that irrigation and fertilization have an interaction effect on fruit quality parameters and that fertilization may have a greater impact than does irrigation.

Conclusions

In the greenhouse, and in response to changes in soil moisture and water uptake by crop roots, we found that NPI can meet the water demand of tomato plants during different growth periods. The crop active irrigation mode not only reduces water consumption but also promotes crop growth, improves fruit quality, achieves greater yield and improves WUE.

Overall, compared with those under negative-pressure fertigation, the sugar-acid ratio, vitamin C content, soluble solids content, and nitrate concentration of tomato fruits under drip fertigation decreased by 30%, 34%, 20% and 34%, respectively; the water consumption increased twofold-fold, the WUE decreased by 47%, and the FUE decreased.

There was no significant difference between reduced fertilization (75%) and conventional fertilization in terms of the photosynthetic parameters of tomato plants, nitrogen concentration, nitrogen uptake, fruit size, hardness, or yield under the two kinds of irrigation. No nitrogen fertilization results in a reduced tomato fruit size and thus reduced yield. Reduced fertilization (75%) and no nitrogen fertilization will reduce the soil nutrient concentration at the end of the crop growth period. Compared with that under no nitrogen fertilization, the chlorophyll content under reduced fertilization (75%) under NPI and conventional fertilization under DI increased by 13% and 15%, the nitrogen uptake of the whole plant increased by 24% and 27%, respectively, and the yield increased by approximately 10%. The best quality tomato fruits were subjected to optimized fertilization under NPI.

Therefore, we recommend the adoption of NPI when planting tomatoes in greenhouses and the application of fertilizer according to the soil nutrient content and nutrient demand of the crop.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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