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Interactive effect of irrigation and polymer-coated potassium chloride on tomato production in a greenhouse

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ABSTRACT

As a main crop cultivated in greenhouses, tomato (*Solanum lycopersicum* L.) has become one of the most popular vegetables in the world. Tomato is water and nutrient demanding. Although effects of irrigation and nitrogen nutrition management on tomato growth have been widely investigated, few studies have been conducted on the interactive effects of irrigation and potassium (K) fertilizers, especially those of irrigation and polymer-coated potassium chloride (PCPC). In this study, a pot experiment was conducted with three PCPC application rates (F_{100}, F_{80}, and F_{60}) and three irrigation levels (I_{100}, I_{80}, and I_{60}) in 2018 and repeated again in 2019. The results showed higher soil available K, endogenous hormone contents, antioxidant enzyme activities, photosynthetic rate, and tomato yield, lower lipid peroxidation, and better root morphology and tomato quality in the $F_{80}I_{80}$ treatment. Compared with the other treatments, the $F_{80}I_{80}$ treatment increased tomato yield by 5.3–18.1 %, vitamin C content by 7.3–26.6 %, leaf rubisco activity from the fruit enlargement stage to the fruit ripening stage by 4.7–18.1 %, and photosynthetic rate by 4.5–17.8 %. Adjusting PCPC application rate and irrigation level to meet tomato growth requirements could not only save water and fertilizers, but also increase tomato yield and protect the environment.

1. Introduction

Drought is an abiotic stress that affects plant growth and development and causes yield loss (Waraich et al., 2011). In the past decades, moderate to severe water scarcity has become a worldwide concern, especially in semi-arid and arid regions (Li and Guo, 2015). Increasing domestic water demand due to rapid population growth, which competes with industrial water usage, has exacerbated the water shortage issue in China (Su et al., 2018). Flood irrigation using groundwater is a conventional irrigation method used in greenhouse production in China. However, this irrigation method is not water-saving and favorable for crop quality (Chen et al., 2013). In addition to groundwater over-exploitation, this irrigation method may also lead to soil nutrients loss to the deeper soil layers (Li et al., 2017). Consequently, groundwater would be polluted and human health would be threatened (Haj-Amor et al., 2017). Therefore, it is important to develop better irrigation strategies to improve water use efficiency (WUE) but without compromising crop yield and quality (Yang et al., 2020). In order to achieve this goal, different irrigation strategies have been developed and assessed. Drip irrigation is one of the most popular irrigation methods in the world. It is well known that drip irrigation has the advantages of high WUE, high fertilizer use efficiency, and environmentally friendly. However, its high cost hinders its wide adoption in China. Deficit irrigation is another good method that improves soil water exploitation by plant roots (Ćosića et al., 2015; Qin et al., 2013; Coyago-Cruz et al., 2019). Although deficit irrigation decreases tomato yield to some extent, it improves tomato quality and WUE (Patanè et al., 2011a,b; Chen et al., 2013). Nangare et al. (2016) reported that tomato fruit quality was improved in such as color, hardness, acidity, soluble solids, and ascorbic acid considerably with deficit irrigation at 80 % of conventional irrigation level. Besides, stable tomato yield and high water productivity (19.2 kg m^{-3}) were achieved. Inmaculada et al. (2016) reported that deficit irrigation (75 % etc) reduced water use efficiency by an average of 28.2 % but increased tomato soluble solids by 8.4 % and Hunter a/b ratio by 2.4 %. Long-term water deficit stress restricts tomato growth and reduces its yield. Therefore, it is necessary to develop fertilization strategies to offset the negative effect of drought stress on tomato yield.

An essential element for tomato growth and reproduction, potassium (K) plays an important role in plant water metabolism and

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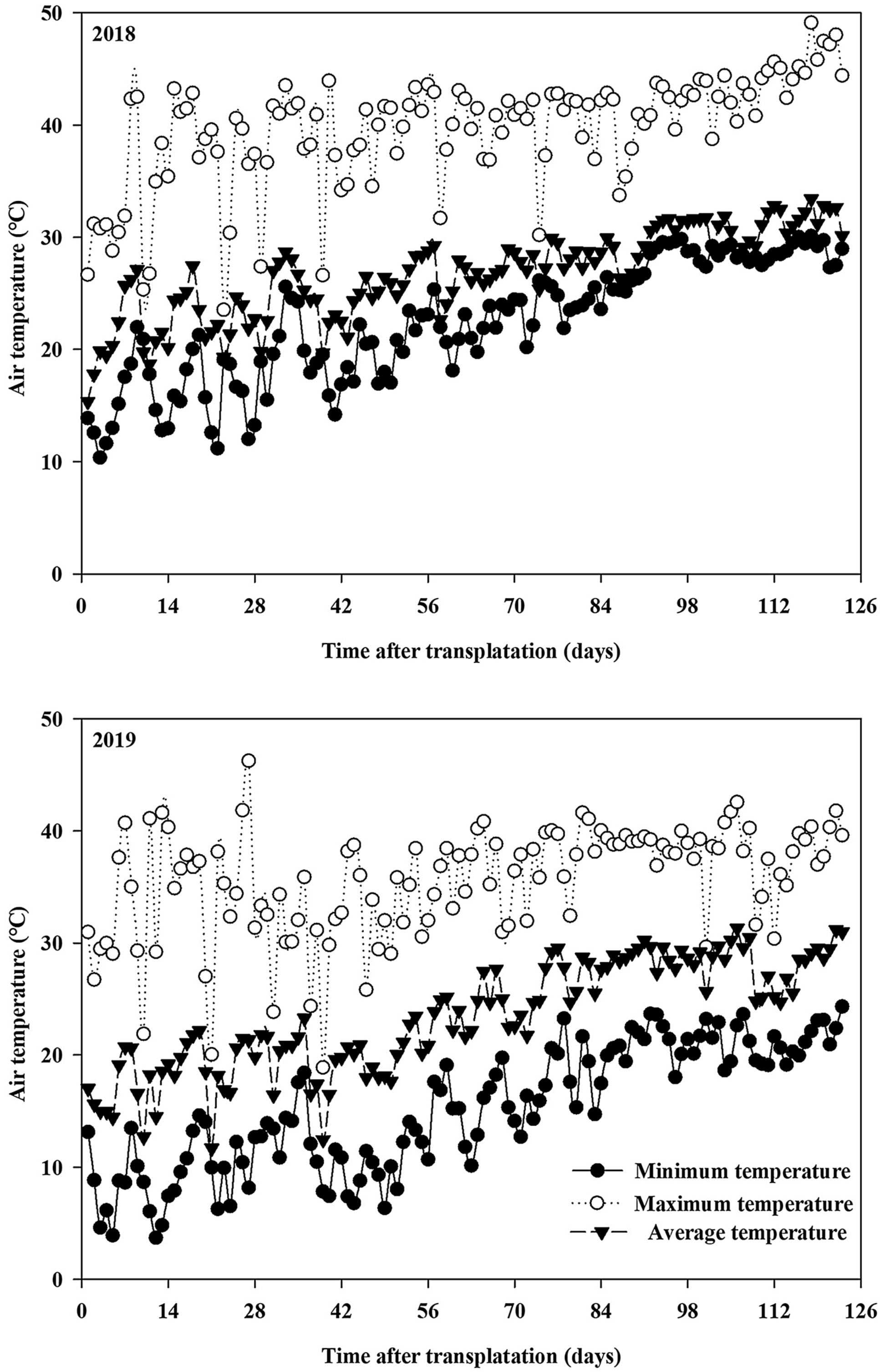

Fig. 1. Changes in air temperature after tomato seedling transplantation during the 2018 and 2019 growing seasons.

stress-tolerance (Behboudian and Anderson, 1990; Besford and Maw, 1975). Appropriate K application not only meets crops' K need but also enhances crops' draught-resistance as K increased leaf turgor potential under water stress (Premachandra et al., 2008). Therefore, proper K application can avoid tomato yield decrease caused by deficit irrigation. However, to maximize crop yield and economic benefits, farmers apply excessive fertilizers, particularly K fertilizers in greenhouse tomato production (Fan et al., 2014). Massive application of K fertilizers not only decreases tomato yield and quality, but also increases the risk of water pollution (Zhang et al., 2013; Tieman et al., 2017; Kuscu et al., 2014). Therefore, methods to reduce available K loss and improve K use efficiency (KUE) should be developed (Bertol et al., 2007). Polymer coated potassium chloride (PCPC) as a novel K fertilizer was developed by the National Engineering Laboratory for Efficient Use of Soil and Fertilizer Resources in China. It is a controlled-released K fertilizer. Its K release rate closely matches crops' K demand, thereby reducing unnecessary K loss at the initial stage of fertilization and increasing K supply at the peak of crop K demand (Yang et al., 2017), and reducing

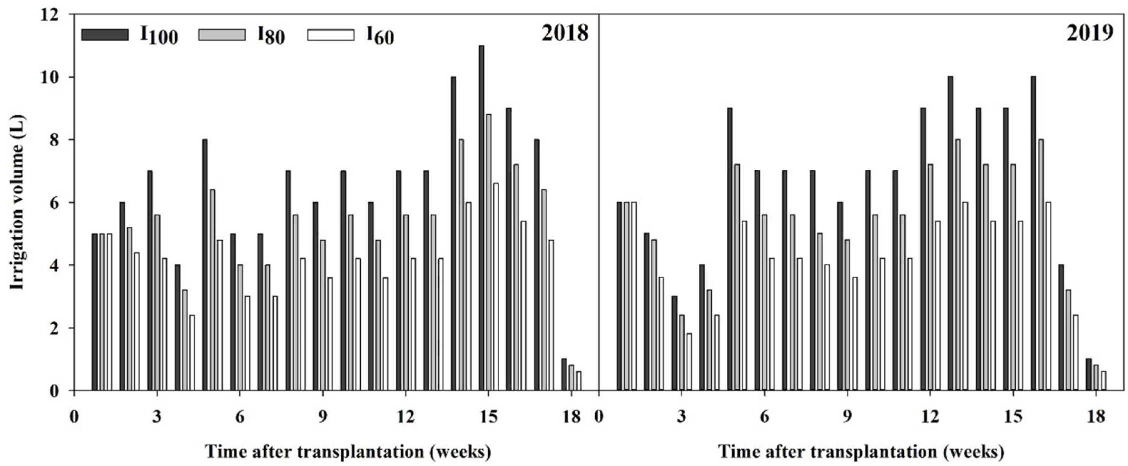

Fig. 2. Changes in weekly irrigation volume after tomato seedling transplantation during the 2018 and 2019 growing seasons.

labor input associated with top dressing application compared with conventional K fertilization (20 % of potassium chloride (KCl) was applied as base fertilizers, while the rest 80 % was applied water soluble fertilizer as topdressing). Therefore, optimizing the input of K fertilizer is of great significance not only to meet the K demand of crops, but also to reduce environmental pollution. At the same time, suitable K application rates improve crop yield, quality and KUE. Chapagain et al. (2003) found that glucose and total soluble solids in the tomato fruits were slightly higher with increasing KCl application in the treatment solution, and the percentage of rotten and blotchy fruits was significantly decreased. The research of Yang et al. (2016) on cotton revealed that PCPC application not only increased cotton lint yield (by 11.2–32.1 %) and improved cotton quality, but also increased K recovery efficiency (by 24.3–33.8 %) in comparison with conventional K fertilizer application. Tian et al. (2017) demonstrated that the application significantly increased cotton lint yield by 8.1–32.7 % and KUE by 15.5–54.8 % compared with KCl application. Therefore, PCPC has great potential for increasing tomato yield and improving KUE.

Water and K managements play significant roles in tomato growth and yield formation in greenhouse. Currently, few studies have been conducted on the interactive effects of PCPC application rate and irrigation level on tomato. Therefore, pot experiments were conducted in this study to learn the best combination of PCPC application rate and irrigation level so as to maximize the synergy between PCPC and water.

2. Materials and methods

2.1. Experimental site and materials

A pot experiment was conducted in 2018 and repeated again in 2019 in a greenhouse (36°9′39″ N, 117°9′47″ E) of the National Engineering Laboratory for Efficient Utilization of Soil Fertility Resources at Shandong Agricultural University of Tai'an City, Shandong Province, China. The site had a temperate continental monsoon climate with a mean annual temperature of 13.2℃. During the experiment, air temperature was recorded with a recorder (HOBO MX2301, USA). The test soil was brown soil (sub-category) and was classified as Typic Hapli-Udic Argosols according to the Chinese soil classification system (CRGCST, 2001) and Typic Hapludalf according to USDA "Soil Taxonomy" (Soil Survey Staff, 1999). The soil had 13.2 % clay, 52.4 % silt, and 34.4 % sand. Soil water content at field capacity (-0.3 bar) was 22.8 % and the wilting point (-15 bar) was 10.3 %. The physical and chemical properties of the soil were as follows: pH (7.65 at soil: water ratio of 1:2.5), organic matter content (13.52 g/kg), nitrate content (68.86 mg/kg), ammonium content (7.82 mg/kg), available phosphorus (23.20 mg/kg), and available K (68.53 mg/kg).

Urea (46 % N), triple superphosphate (46 % P_2O_5), and KCl (60 % K_2O) were obtained from local fertilizer distributors. The PCPC (54 % K_2O) was provided by the National Engineering & Technology Research Center for Slow and Controlled-Release Fertilizers, China. The PCPC is round particles with smooth surface.

Tomato variety was "Luo la", which is widely cultivated in the North China Plain. To each clay pot (30 cm in diameter and 36 cm in height, with a drainage hole in the bottom), 5 kg of sand was added first and then approximately 30 kg of the above soil were added. Tomato was transplanted into the pots on Apr. 13, 2018 and harvested on Aug. 13, 2018 and transplanted on Mar. 20, 2019 and harvested on Jul. 20, 2019. At the flowering stage, topping was performed for better tomato fruit yield, and tomato fruit on each plant was thinned to five bunches for better fruit marketability according to local farmers' experience. Weed and pest control was performed based on standard practices of local growers. (Fig. 1)

2.2. Experimental design and management

Three irrigation levels were set up including low irrigation (I_{60}, 54–60 % soil water content), medium irrigation (I_{80}, 72–80 % soil water content) and high irrigation (I_{100}, 90–100 % soil water content). Manual irrigation was performed, and irrigation frequency is shown in Fig. 2. Three PCPC application rates were set up including conventional application rate (F_{100}), 80 % of conventional application rate (F_{80}), and 60 % of conventional application rate (F_{60}). The experiment adopted a randomized block design and included 11 treatments and four replicates: $F_{100}I_{100}$, $F_{100}I_{80}$, $F_{100}I_{60}$, $F_{80}I_{100}$, $F_{80}I_{80}$, $F_{80}I_{60}$, $F_{60}I_{100}$, $F_{60}I_{80}$, $F_{60}I_{60}$, CK (convention irrigation level but without K fertilization), and CF (conventional irrigation and KCl application). In all the treatments, urea and triple superphosphate were used as N and P fertilizers, respectively. In all the treatments except CK and CF, PCPC was used as K fertilizer, while in CF, KCl was used as K fertilizer. For better experiment results, the convention fertilizer application rate used in this study (*i.e.*, 15.07 g N pot^{-1}, 16.54 g P_2O_5 pot^{-1}, and 21.26 g K_2O pot^{-1}) was 1.5 times that used by local formers in the field (*i.e.*, N-P_2O_5-K_2O of 380-417 – 536 kg/ha). For urea, 50 % was applied as base fertilizers and the rest was split into four topdressing applications (10 % at seedling stage, 10 % at flowering stage, 20 % at fruit enlargement stage, and 10 % at fruit ripening stage). Triple superphosphate was applied once as base fertilizers. For KCl in the CF treatment, 20 % was applied as base fertilizer, and the rest 80 % was applied as topdressing during four stages (seedling stage 10 %, flowering stage 30 %, fruit enlargement stage 30 %, and fruit ripening stage 10 %). In the treatments where PCPC was used as K fertilizer, it was applied once as base fertilizer.

After tomato seedlings were transplanted, all the pots were immediately irrigated to 100 % of field capacity with tap water. Seven days later (April 20th, 2018 and March 27th, 2019), the pots were irrigated according to their respective irrigation treatments. Soil water content was measured with a TDR300 soil moisture meter and maintained every day with tap water during the experimental period when needed (TDR values I_{100} 44.3 %–46.7 %volumetric water content (VWC); I_{80} 40.5 %–42.1 % VWC; I_{60} 36.9 %–38.2 % VWC). Totally, 119 L, 96.6 L, and 74.2 L of tap water were used in the I_{100}, I_{80}, and I_{60} treatments, respectively, in 2018, and 120 L, 97.4 L, and 74.8 L, respectively, in 2019.

2.3. Sampling and measurements

2.3.1. Plant sampling and analyses

Healthy fruit was harvested whenever its color changed from green to pink. Single fruit fresh weights were recording and fruit yield of each pot was calculated. For each treatment, three tomato fruit samples of similar size and color were selected, crushed, and passed through a 0.8 mm mesh sieve to separate seeds and epidermis from the juice.

Lycopene content, vitamin C (Vc) content, soluble sugar, and soluble solids in tomato fruit were measured using the homogenized juice. Lycopene content was determined using the spectrophotometer method at the wavelength of 474 nm. Vc content was measured using the 2, 6-dichloroindophenol titrimetric method. The contents of soluble sugar and soluble solids were determined using the anthrone method and with a hand refractometer, respectively (Li et al., 2000).

Chlorophyll content was measured with a chlorophyll meter (SPAD-502; Minolta, Tokyo, Japan). Ten plant leaves were randomly selected from each treatment on a sunny day during the fruit enlargement stage (May 28, 2019). Leaf photosynthesis parameters including net photosynthetic rate, stomatal conductance, and transpiration rate were determined at the fruit enlargement stage using a LI-6400XT portable photosynthesis system (LI-Cor, Lincoln, NE, USA) between 09:00 to 11:00 a.m. also on a sunny day. The average air temperature was 30.6℃ and 30.2℃ in 2018 and 2019, respectively, when the photosynthesis parameters were measured. RhizoScan software (WinRHIZO Tron125 MF 2015) was used to analyze and record root surface area, volume, and average diameter at the fruit ripening stage (August 13 in 2018 and July 20 in 2019). Meanwhile, leaf and root samples were collected during the fruit enlargement stage (May 28, 2019) and at the fruit ripening stage (July 20, 2019). Auxin (IAA), gibberellin (GA), malondialdehyde (MDA) and hydrogen peroxide (H_2O_2) contents, catalase (CAT), peroxidase (POD), superoxide dismutase (SOD) and rubisco activities were estimated using an ELISA kit (Shanghai Hengyuan Biological Technology Co. Ltd., Shanghai, China).

At the end of the experiment on August 13 in 2018 and July 20 in 2019, plants were randomly selected from each treatment, washed with water, oven-dried first at 105 °C for 30 min and then at 85 °C to constant weight, and pulverized with a small mill pulverizer. The dried samples were digested with a mixture of H_2SO_4 and H_2O_2, and K concentration was determined using a flame photometer. Fruit K concentration was also quantified with a flame photometer. K uptake rate was calculated as the product of K concentrations in the aboveground parts of tomato and the biomass of the above-ground parts (Silva et al., 2013).

2.3.2. Soil sampling and analyses

Soil samples were taken at the flowering stage (May 7 in 2018 and April 15 in 2019), fruit enlargement stage (June 3 in 2018 and May 15 in 2019), and fruit ripening stage (July 10 in 2018 and June 15 in 2019) and at the end of the experiments (August 13 in 2018 and July 20 in 2019). For each sampling time, two soil samples were collected at the 0 – 20 cm layer from each pot and mixed thoroughly.

The soil samples were air dried, ground, and sieved through a 2 mm sieve, and analyzed for soil available K content. Soil sample (2.5 g) was extracted with 1 mol/L CH_3COONH_4 (pH 7.0) at soil: solution ratio of 1:10, shaken for 0.5 h, filtered and analyzed for soil available K concentration using a flame photometer (Li et al., 2020; Lu et al., 2017; Yang et al., 2016).

2.3.3. Characterization of K release from PCPC

K release characteristics of PCPC (HG/T4215-2011) were investigated both in water and in soil. K release characteristics of PCPC in water were studied using the national standard method of China for slow release fertilizers (Liu et al., 2009). Briefly, 10 g PCPC were put in a glass bottle containing 200 ml distilled water and placed in an incubator at 25℃. Solution in the bottle was sampled at day 1, 7, 14, 21, 35, 49, 63, 77, 91, 105, and 119 and analyzed for K concentration by flame photometer method. Nutrient release characteristics of PCPC in soil were investigated using the buried bag method (Yang et al., 2012). On the day (April 13, 2018) tomato plants were transplanted, 39 mesh bags (1 mm mesh size) with PCPC inside were buried into the soils with 3 pots. On day 1, 7, 14, 21, 35, 49, 63, 77, 91, 105, and 119, 3 bags were collected each time. Fertilizer granules were removed from the bag, rinsed with distilled water to remove soil, and then placed in a vacuum oven at 60℃ for 48 h. K release rate was calculated based on fertilizer weight changes (Wilson et al., 2009).

2.4. Calculations and statistical analyses

KUE (%) = (plant K uptake in K application treatment − plant K uptake in no K application treatment)/K application amount × 100 %

Evapotranspiration (ET, kg) was calculated using the water balance method (Andreu et al., 1997):

$$ET = IL + \Delta W$$

where IL is irrigation amount (kg) and ΔW is change in soil water storage (kg).

WUE was calculated as follows (Ertek et al., 2006):

$$WUE = Y/ET$$

where Y is fruit yield (g pot^{-1}) and ET is water consumption (or plant evapotranspiration, kg pot^{-1}).

Statistical analyses were conducted using analyses of variance (ANOVA) and Duncan's test ($P < 0.05$) of SAS software (SAS 2010, SAS Institute, Cary, NC, USA). Data were processed and figures were generated using Microsoft Excel 2016 software. Bars in the figures represent standard errors.

3. Results

3.1. K release characteristics of PCPC

The K release characteristics are key indicators of PCPC field application performance. Nutrient release rate of PCPC is mainly affected by temperature and soil moisture. Within a certain range, K release rate of PCPC increases with the increases in temperature and soil moisture. In the laboratory, no marked K release from PCPC was observed during the first 21 days, with only 12.1 % of total K being released (Fig. 3). However, from day 21–91, 69.4 % of total K was released. Then, from day 92 on, K release decelerated. After 119 days, 74.4 % of total K was released from PCPC. In the field, during the first 21days, 19.0 %, 13.4 %, and 8.8 % of total K were released from PCPC in the I_{100}, I_{80}, and I_{60} conditions, respectively. The K release rate accelerated from day 35–77 in I_{100}, from day 35–91 in I_{80}, and from day 35–105 for I_{60}. At the end of the experiment, 96.5 %, 87.3 %, and 76.6 % of total K had been released from PCPC under the I_{100}, I_{80}, and I_{60} conditions, respectively.

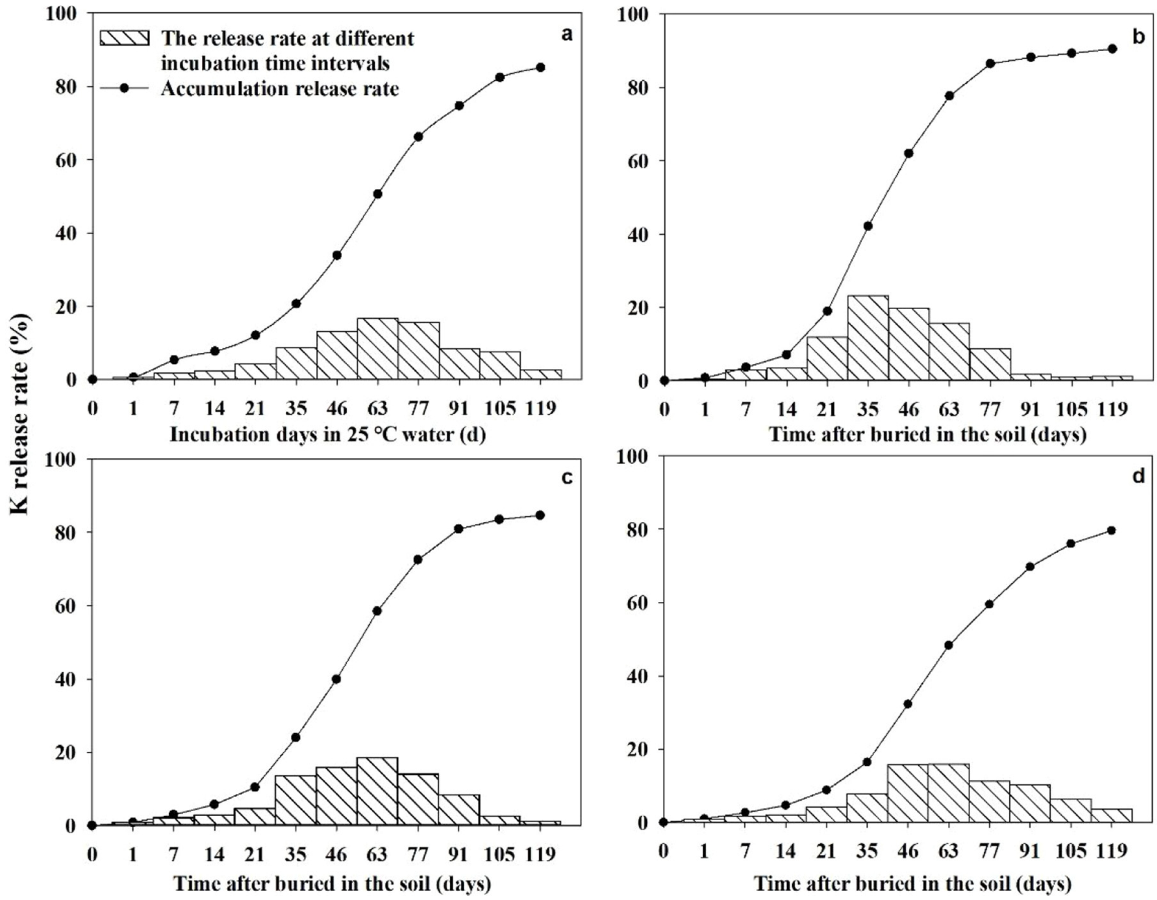

Fig. 3. Potassium release rate of PCPC under different conditions, a) incubation in 25℃ water; b) buried in soil with 100 % irrigation level; c) buried in soil with 80 % irrigation level; d) buried in soil with 60 % irrigation level.

3.2. Interactive effects of irrigation and PCPC application on tomato yield, KUE, and WUE

The results indicated that tomato yield, KUE, and WUE were significantly affected by PCPC application rate ($P < 0.01$) and irrigation level ($P < 0.01$) in both 2018 and 2019 (Table 1). The PCPC application rate and irrigation level had significant interactive effects on tomato yield ($P < 0.01$), WUE ($P < 0.05$), and KUE ($P < 0.05$) in 2019 (Table 1). The F_{80} and I_{80} treatments presented higher tomato yield, KUE, and WUE in comparison with other treatments. In 2018, the F_{80} treatments increased tomato yield by 3.9–6.3 %, 2.9–7.3 %, and 8.0–8.7 % compared with the CF, F_{100}, and F_{60} treatments, respectively, and increased WUE by 25.4–27.6 %, 6.4–7.6 %, and 9.9–11.5 %, respectively. KUE increased with decrease in PCPC application rate. The F_{80} treatments increased KUE by 10.8–10.9 % and 11.0–11.7 % compared with the CF and F_{100} treatments, respectively. In both years, tomato yield was improved by 4.8–5.0 %, 4.3–4.9 %, and 7.7–8.7 % in the I_{80} treatments compared with that in the CF, I_{100} and I_{60} treatments, respectively, and KUE by 12.3–16.5 %, 3.8–5.1 %, and 6.0–8.3 %, respectively. Similarly, the I_{80} treatments increased WUE by 21.3–22.8 % and 21.7–22.5 % compared with the CF and I_{100} treatments, respectively. The $F_{80}I_{80}$ treatment resulted in the greatest yield, which was 5.3–18.1 % greater than those in the others K fertilization treatments in 2018 and 2019, while increasing KUE and WUE.

3.3. Effects of irrigation and PCPC coupling on tomato quality

The contents of lycopene, Vc, soluble sugar, and soluble solids are important indexes of the nutritive value of tomatoes. Lycopene, Vc, soluble sugar, and soluble solid contents were significantly affected by PCPC application rate ($P < 0.01$) and irrigation level ($P < 0.01$) in both 2018 and 2019 (Table 2). PCPC application rate and irrigation level had significant interactive effects on Vc ($P < 0.01$) and soluble solids ($P < 0.01$) in 2018 and 2019 and on soluble sugar ($P < 0.01$) in 2018. In both years, fruit lycopene, Vc, soluble sugar, and soluble solid contents were higher in the F_{80} treatments than in the CF, F_{100}, and F_{60} treatments. The I_{80} treatments also had the higher lycopene, Vc, soluble sugar, and soluble solid contents than CF, I_{100}, and I_{60} treatments. The $F_{80}I_{80}$ treatment significantly improved tomato fruit quality compared with other K fertilization treatments, increasing fruit lycopene, Vc, soluble sugar, and soluble solid contents by 2.3–22.3 %, 7.2–30.4 %, 1.0–25.4 %, and 2.5–18.7 %, respectively.

3.4. Effects of irrigation and PCPC coupling on leaf SPAD value, rubisco activity, and photosynthesis indicators

Leaf SPAD values were considerably affected by PCPC application rate and irrigation level, as well as their interaction (Fig. 4A). Treatments with PCPC application significantly improved leaf SPAD value compared with the CK treatment. In particular, the F_{80} treatments showed better effects than the F_{100} and F_{60} treatments in increasing leaf SPAD value.

Rubisco is one of the most important enzymes in plants that affect photosynthesis in leaves. Rubisco enzyme was significantly affected by PCPC application rate ($P < 0.01$) and irrigation level ($P < 0.01$) as well as their interaction in both the fruit enlargement stage and the fruit ripening stage (Fig. 4 B). Photosynthetic rate, stomatic conductance and transpiration rate were significantly affected by PCPC application rate ($P < 0.01$) and irrigation level ($P < 0.01$) (Table 3). Photosynthetic rate and transpiration rate were also significantly ($P < 0.05$) affected

Table 1
Yield, potassium use efficiency and water use efficiency of tomato in different treatments during the 2018 and 2019 growing seasons.

Treatment	2018			2019		
	Yield (g pot^{-1})	KUE (%)	WUE (g kg^{-1})	Yield(g pot^{-1})	KUE (%)	WUE (g kg^{-1})
F × I						
CK	2542.9h	–	21.24g	2487.1f	–	20.58h
CF	3165.3cd	30.3d	26.55e	3030.0cd	30.3de	25.06g
$F_{100}I_{100}$	3207.2c	28.9d	26.52e	3057.0bcd	30.4de	24.79g
$F_{100}I_{80}$	3297.9b	32.1d	33.62d	2995.8cd	31.9de	31.40e
$F_{100}I_{60}$	3081.8e	27.6d	39.82b	2942.7cde	28.0e	39.70b
$F_{80}I_{100}$	3269.4b	40.2bc	27.72e	3181.8b	41.7cd	26.58f
$F_{80}I_{80}$	3482.7a	45.6ab	35.15c	3483.5a	46.9c	35.14d
$F_{80}I_{60}$	3125.4de	37.8c	43.95a	3033.5cd	34.8d	42.09a
$F_{60}I_{100}$	3002.5f	47.3a	24.98f	2913.3de	50.2b	24.06g
$F_{60}I_{80}$	3188.8c	50.3a	32.44d	3086.7bc	61.6a	30.85e
$F_{60}I_{60}$	2899.4g	44.5ab	38.82b	2852.0e	52.7b	37.01c
PCPC application rate						
F_{100}	3195.6b	29.5c	33.32b	2998.5b	30.1c	31.97b
F_{80}	3292.5a	41.2b	35.60a	3232.9a	41.1b	34.61a
F_{60}	3030.2c	47.3a	32.08c	2950.7b	55.7c	30.64c
Irrigation level						
I_{100}	3159.7b	38.8b	26.41c	3050.7b	41.7b	25.15c
I_{80}	3323.1a	42.6a	33.74b	3188.7a	46.8a	32.47b
I_{60}	3035.5c	36.6b	40.86a	2942.7c	38.5c	39.60a
Source of variance						
F	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
I	< 0.0001	0.0045	< 0.0001	< 0.0001	< 0.0001	< 0.0001
F × I	< 0.0001	0.9214	0.0486	0.0041	0.0479	0.0412

Note: Means followed by the same lowercase letters within a same column of each item are not significantly different at the 5% level, "-"no valid value.

by the interaction between PCPC application rate and irrigation level. Rubisco activity and photosynthetic rate were higher in the F_{80} treatments than in the CF, F_{100}, and F_{60} treatments, and higher in the I_{80} treatments than in the CF, I_{100}, and I_{60} treatments. Moreover, compared with the other K fertilization treatments, the $F_{80}I_{80}$ treatment increased rubisco activity by 4.7–18.1 % during the fruit enlargement stage and the fruit ripening stage, and increased photosynthetic rate by 4.5–17.8 % in the two year. Stomatal conductance and transpiration rate increased with the increase in irrigation level. In both years, compared with the other K fertilization treatments, the $F_{80}I_{100}$ treatment markedly increased stomatal conductance and transpiration rate by 3.3–41.3 % and 3.3–40.9 %, respectively.

3.5. Effects of irrigation and PCPC coupling on tomato root morphology

PCPC application rate and irrigation level significantly *($P < 0.01$)* affected root surface area, volume, and average diameter (Table 4). The interaction between PCPC application rate and irrigation level significantly *($P < 0.01$)* affected root surface area, but did not significantly affect root volume and average diameter. Under a same irrigation level, root surface area, volume, and average diameter first increased and then decreased with increase in PCPC application rate. Compared with the CF, F_{100}, and F_{60} treatments in the two years, the F_{80} treatments increased root surface area by 38.9–48.5 %, 3.8–11.5 %, and 14.9–21.5 %, respectively, increased root volume by 39.5–48.7 %, 4.4–10.9 %, and 17.6-17.6 %, respectively, and increased root average diameter by 13.9–17.4 %, 3.2–4.4 %, and 8.9–11.6 %, respectively. Under a same PCPC application rate, root surface area, volume, and average diameter decreased with increase in irrigation level. In the two years, compared with the CF, I_{100}, and I_{80} treatments, the I_{60} treatments had 27.0–44.3 %, 21.3–26.2 %, and 11.4–17.5 %, respectively, higher root surface area, 38.5–49.5 %, 13.8–18.3 %, and 8.0–8.8 %, respectively, higher root volume, and 12.8–18.0 %, 7.7–10.3 %, and 3.9–5.8 %, respectively, higher root average diameter. The $F_{80}I_{60}$ treatment resulted in the most favorable root morphology compared with the other K fertilization treatments in both years.

3.6. Effects of irrigation and PCPC coupling on available K content in topsoil

Soil available K in topsoil was significantly affected by PCPC

Table 2
Tomato fruit quality in different treatments during the 2018 and 2019 growing seasons.

Treatment	2018				2019			
	Lycopene (mg kg^{-1})	Vc (g 100 g^{-1})	Soluble sugar (g 100 g^{-1})	Soluble solids mass rate(%)	Lycopene(mg kg^{-1})	Vc (g 100 g^{-1})	Soluble sugar (g 100 g^{-1})	Soluble solids mass rate(%)
F × I								
CK	21.65f	8.67h	2.17h	4.17g	22.00e	7.43f	2.01f	3.98i
CF	26.15e	12.51f	2.59g	4.36e	22.90e	11.64d	2.42e	4.19g
$F_{100}I_{100}$	31.98abc	13.30de	2.86e	4.48d	25.08cd	12.13c	2.72c	4.39c
$F_{100}I_{80}$	32.28abc	15.46b	3.29b	5.06b	27.35b	13.68b	3.09a	4.46b
$F_{100}I_{60}$	30.29cd	12.54f	2.75f	4.29ef	23.34de	11.26e	2.45e	4.23fg
$F_{80}I_{100}$	32.75ab	14.61c	3.16c	4.53d	26.11bc	13.91b	2.93b	4.49b
$F_{80}I_{80}$	33.53a	16.68a	3.47a	5.19a	29.48a	15.86a	3.12a	4.71a
$F_{80}I_{60}$	31.53bcd	12.96ef	3.03d	4.28ef	25.35c	12.19c	2.75c	4.25ef
$F_{60}I_{100}$	30.07bcd	13.56d	2.78f	4.31ef	24.94cd	11.77d	2.69cd	4.28de
$F_{60}I_{80}$	32.64abc	14.33c	3.21c	4.71c	25.14cd	13.57b	2.92b	4.31d
$F_{60}I_{60}$	28.21d	11.61g	2.63g	4.22g	23.25de	11.12e	2.54de	4.12h
K application rate								
F_{100}	31.52ab	13.77b	2.97b	4.61a	25.26b	12.35b	2.75b	4.36b
F_{80}	32.61a	14.75a	3.22a	4.67a	26.98a	13.99a	2.93a	4.38a
F_{60}	30.31b	13.16c	2.87c	4.41b	24.44b	12.16b	2.72b	4.24c
Irrigation level								
I_{100}	31.60a	13.82b	2.93b	4.43b	25.38b	12.61b	2.78b	4.38b
I_{80}	32.82a	15.49a	3.32a	4.98a	27.33a	14.37a	3.04a	4.49a
I_{60}	30.01b	12.37c	2.81c	4.26c	23.98b	11.52c	2.58c	4.20c
Source of variance								
F	0.0085	< 0.0001	< 0.0001	< 0.0001	0.0034	< 0.0001	0.0012	< 0.0001
I	0.0020	< 0.0001	< 0.0001	< 0.0001	0.0004	< 0.0001	< 0.0001	< 0.0001
F × I	0.4111	< 0.0001	0.0017	0.0007	0.2892	0.0006	0.1903	< 0.0001

Note: Means followed by the same lowercase letters within a same column of each item are not significantly different at the 5% level, "-"no valid value.

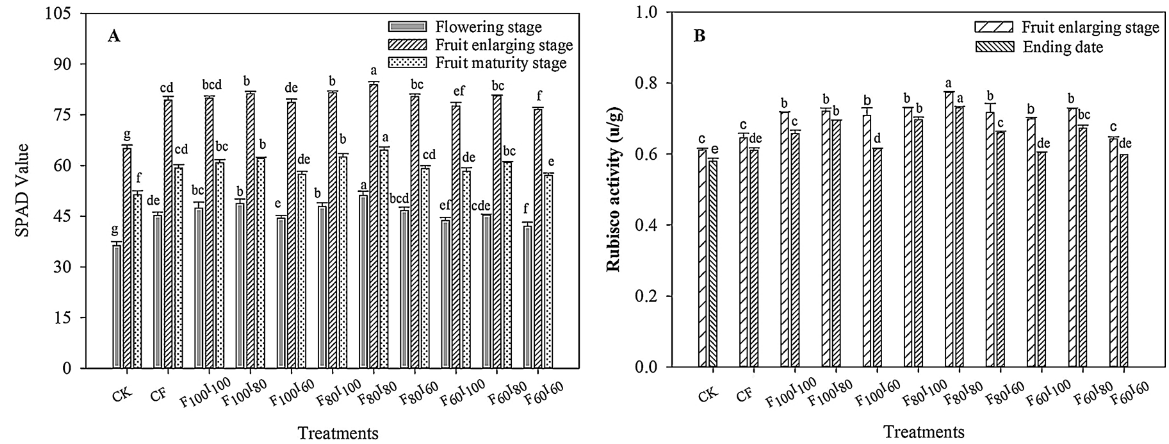

Fig. 4. Tomato leaf SPAD value (A) and Rubisco content (B) in different treatments during the 2019 growing season.

application rate (*P < 0.01*) and irrigation level (*P < 0.01*) in both years (Fig. 5A, 5B). PCPC application rate and irrigation level had a significant interaction on soil available K *(P < 0.05*) in both years. The content of available K in topsoil was significantly increased by the K fertilization treatment and increased with increase in PCPC application rate. Available K was significantly lower in the CK treatment than in the other treatments and was higher in the F_{100} treatment than in the CF, F_{80}, and F_{60} treatments. The K release rate of PCPC was higher in the treatments with higher irrigation levels (Fig. 3). During the tomato flowering and fruit enlargement stages, soil available K was higher in the I_{100} treatments than in the CF, I_{80}, and I_{60} treatments. However, during the fruit enlargement and ripening stages in both years, soil available K in the I_{80} treatments was significantly higher than those in the CF, I_{100}, and I_{60} treatments.

3.7. Effects of irrigation and PCPC coupling on tomato antioxidant enzyme activities and lipid peroxidation

CAT, POD, and SOD activities in tomato leaves first increased and then decreased with the increase in PCPC application rate during the fruit enlargement and the fruit ripening stages (Fig. 6), while the MDA and H_2O_2 contents first decreased and then increased with the increase in PCPC application rate. The CAT, POD, and SOD activities in tomato leaves first decreased and then increased with the reduction in irrigation level, and the MDA and H_2O_2 contents first increased and then decreased in tomato leaves during the fruit enlargement stage to the fruit ripening stage (Fig. 7). Similar changes were observed in tomato roots.

In the fruit enlargement and ripening stages, the maximum CAT, POD, and SOD activities in the tomato leaves occurred in the F_{80} treatments; they were 6.0 %–11.2 %, 2.5–3.6 %, and 4.0–8.6 %, respectively, higher than those in the F_{100} treatments, and 10.2–15.1 %, 3.2–6.7 %, and 6.1–11.3 %, respectively higher than those in the F_{60}

Table 3
Photosynthesis indicators at the fruiting stages of tomato in different treatments during the 2018 and 2019 growing seasons.

Treatment	2018			2019		
	Photosynthetic rate (μmol m^{-2} s^{-1})	Stomatal conductance (mol m^{-2} s^{-1})	Transpiration (mmol m^{-2} s^{-1})	Photosynthetic rate (μmol m^{-2} s^{-1})	Stomatal conductance (mol m^{-2} s^{-1})	Transpiration (mmol m^{-2} s^{-1})
F × I						
CK	27.8f	0.31d	6.56g	20.6f	0.34f	7.47g
CF	31.3cd	0.50b	9.27de	24.5e	0.52de	10.95e
$F_{100}I_{100}$	35.1b	0.59ab	10.50bc	27.4c	0.56bc	13.28a
$F_{100}I_{80}$	36.4ab	0.51b	9.52cd	29.0b	0.54cd	12.12cd
$F_{100}I_{60}$	31.7c	0.40c	8.66de	26.2cd	0.51de	11.19e
$F_{80}I_{100}$	37.0a	0.63a	12.75a	29.1b	0.61a	13.52a
$F_{80}I_{80}$	37.3a	0.57ab	11.37b	31.8a	0.59ab	12.52bc
$F_{80}I_{60}$	31.4cd	0.55ab	8.78de	27.6c	0.56bc	12.42bc
$F_{60}I_{100}$	29.8de	0.51b	10.32c	25.2de	0.53 cd	12.71b
$F_{60}I_{80}$	36.6ab	0.42c	8.30ef	26.4cd	0.52de	11.87d
$F_{60}I_{60}$	29.2ef	0.37cd	7.53f	24.6e	0.49e	10.29f
K application rate						
F_{100}	34.39a	0.50b	9.56b	27.5c	0.54b	12.20b
F_{80}	35.21a	0.58a	10.97a	29.5b	0.59a	12.82a
F_{60}	31.87b	0.44c	8.72c	25.4a	0.51c	11.62c
Irrigation level						
I_{100}	33.94b	0.58a	11.19a	27.2c	0.57b	13.17a
I_{80}	36.76a	0.50b	9.73b	29.1b	0.55c	12.17b
I_{60}	30.77c	0.44c	8.32c	26.1a	0.52a	11.30c
Source of variance						
F	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
I	< 0.0001	< 0.0001	< 0.0001	< 0.0001	0.0010	< 0.0001
F × I	0.0001	0.2601	0.0104	0.0400	0.9992	0.0035

Note: Means followed by the same lowercase letters within a same column of each item are not significantly different at the 5% level, "-"no valid value.

Table 4
Root properties in different treatments during the 2018 and 2019 growing seasons.

Treatment	2018			2019		
	Surface area (cm^2)	Volume (cm^3)	Average diameter (mm)	Surface area (cm^2)	Volume (cm^3)	Average diameter (mm)
F × I						
CK	959.2f	75.4f	1.29e	1037.3g	68.2i	1.27e
CF	1532.1e	91.2e	1.36cd	1237.7f	75.3h	1.28e
$F_{100}I_{100}$	2329.0cd	123.1d	1.42c	1657.9d	129.9ef	1.40c
$F_{100}I_{80}$	2594.7bc	135.9c	1.50b	1844.5	140.9cd	1.49b
$F_{100}I_{60}$	2970.0b	151.3b	1.62ab	2339.7b	150.4b	1.62a
$F_{80}I_{100}$	2613.2bc	143.8bc	1.52b	1759.2cd	131.3e	1.48b
$F_{80}I_{80}$	2963.2b	147.5b	1.57ab	1851.3c	147.1bc	1.53b
$F_{80}I_{60}$	3344.7a	160.6a	1.66a	2461.7a	162.0a	1.65a
$F_{60}I_{100}$	2070.2d	116.9de	1.38cd	1505.1e	104.1g	1.33de
$F_{60}I_{80}$	2337.0cd	122.5d	1.43c	1800.5c	123.7f	1.38de
$F_{60}I_{60}$	2598.1c	133.2c	1.51b	1863.8c	135.0de	1.40c
K application rate						
F_{100}	2631.3b	134.3b	1.51b	1947.4b	140.4b	1.50b
F_{80}	2973.7a	150.7a	1.58a	2024.0a	146.8a	1.55a
F_{60}	2335.1c	124.2c	1.44c	1723.1c	120.9c	1.37c
Irrigation level						
I_{100}	2337.5c	127.9c	1.44c	1640.7c	121.8c	1.40c
I_{80}	2631.7b	135.3bc	1.50b	1832.1b	137.2b	1.47b
I_{60}	2970.9a	148.4a	1.56a	2221.8a	149.1a	1.56a
Source of variance						
F	0.0006	0.0033	0.0045	< 0.0001	< 0.0001	< 0.0001
I	0.0018	0.0001	0.0074	< 0.0001	< 0.0001	< 0.0001
F × I	0.0041	0.2193	0.2469	0.0003	0.2808	0.1315

Note: Means followed by the same lowercase letters within a same column of each item are not significantly different at the 5% level, "-"no valid value.

treatments. Similarly, in the fruit enlargement and ripening stages, the maximum CAT, POD, and SOD activities in the tomato roots occurred in the F_{80} treatments; they were 7.5 %–9.5 %, 3.6–15.0 %, and 5.2–15.0 %, respectively, higher than those in the F_{100} treatments, and 12.9–13.5 %, 9.6–18.6 %, and 10.0–18.1 %, respectively, higher than those in the F_{60} treatments. In the fruit enlargement and ripening stages, the maximum CAT, POD, and SOD activities in tomato leaves occurred in the I_{80} treatments; they were 6.0 %–10.1 %, 5.3–6.1 %, and 5.2–5.9 %, respectively, higher than those in the I_{100} treatments, and 8.5–11.7 %, 9.4–9.7 %, and 8.8–15.7 %, respectively, higher than those in the I_{60} treatments. Similarly, the maximum CAT, POD, and SOD activities in tomato roots occurred in the I_{80} treatments; they were 4.0 %–6.4 %, 4.9–6.9 %, and 7.0–10.3 %, respectively, higher than those in the I_{100} treatments, and 7.6–8.0 %, 8.4–9.4 %, and 12.3–14.0 %, respectively, higher than those in the I_{60} treatments. In the fruit enlargement and ripening stages, the minimum MDA and H_2O_2 contents in both tomato leaves and roots occurred in the $F_{80}I_{80}$ treatment; they were 8.1–64.3 % and 1.5–67.8 %, respectively, lower than in those in the other K fertilization treatments. The CAT, POD and SOD activities, MDA, and H_2O_2 contents were significantly influenced by PCPC application rate *($P < 0.01$)* and irrigation level ($P < 0.01$), except POD activity in leaves during the fruit enlargement stage. The interaction between PCPC application rate and irrigation level had significant *($P < 0.05$)* effects on the antioxidant enzymes and lipid peroxidation in tomato, but had no significant effect on leaf POD activity in the fruit enlargement stage and on leaf MDA content, leaf CAT, and POD and root SOD activities in the fruit ripening stage.

3.8. Effects of irrigation and PCPC coupling on tomato endogenous hormones

In the fruit enlargement and ripening stages, endogenous hormones in tomato leaves and roots were significantly affected by PCPC application rate *($P < 0.01$)* and irrigation level *($P < 0.01$)* as well as their interaction, except IAA in leaves (Fig. 8). In terms of IAA and GA contents, the F_{80} treatments were higher than the F_{100} and F_{60} treatments, and the I_{80} treatments were higher than the I_{100} and I_{60} treatments. Moreover, the $F_{80}I_{80}$ treatment significantly increased IAA and GA contents in the leaves by 17.1–18.6 % and 20.9–25.8 %, respectively, as compared with the other K fertilization treatments. Meanwhile, the $F_{80}I_{80}$ treatment markedly increased IAA and GA contents in the roots by 38.0–47.2 % and 34.1–40.7 %, respectively, as compared with the other K fertilization treatments.

4. Discussion

K is a quality element for tomato production, and adequate K supply is essential for high tomato quality (Tavallali et al., 2018). PCPC application has been reported to significantly increase soil available K content and improve crop growth and yield (Li et al., 2020). This study showed that PCPC application promoted tomato K absorption and increased tomato yield and WUE compared with conventional K fertilizer (*i.e.*, KCl) application. The high soil available K content in the PCPC application treatments well satisfied the K need of tomato plants during the whole growth period. Meanwhile, adequate K supply increased root surface area, volume, average diameter, and activity and promoted IAA and GA syntheses in roots. Application of PCPC improved leaf photosynthetic rate, stomatal conductance, and transpiration rate, as well as other physiological characteristics. This was mainly due to the

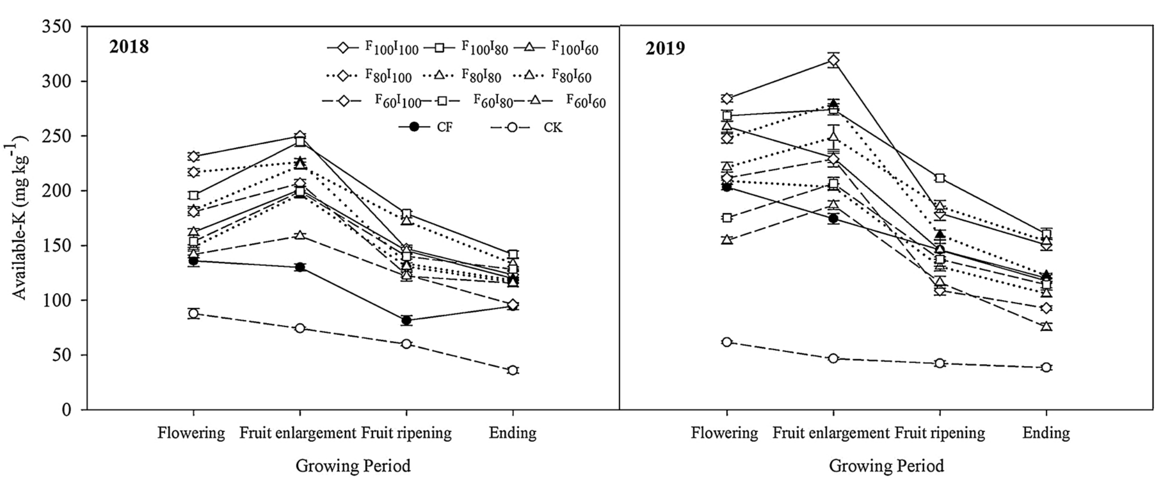

Fig. 5. Soil available K content in different treatments during the 2018 and 2019 growing seasons.

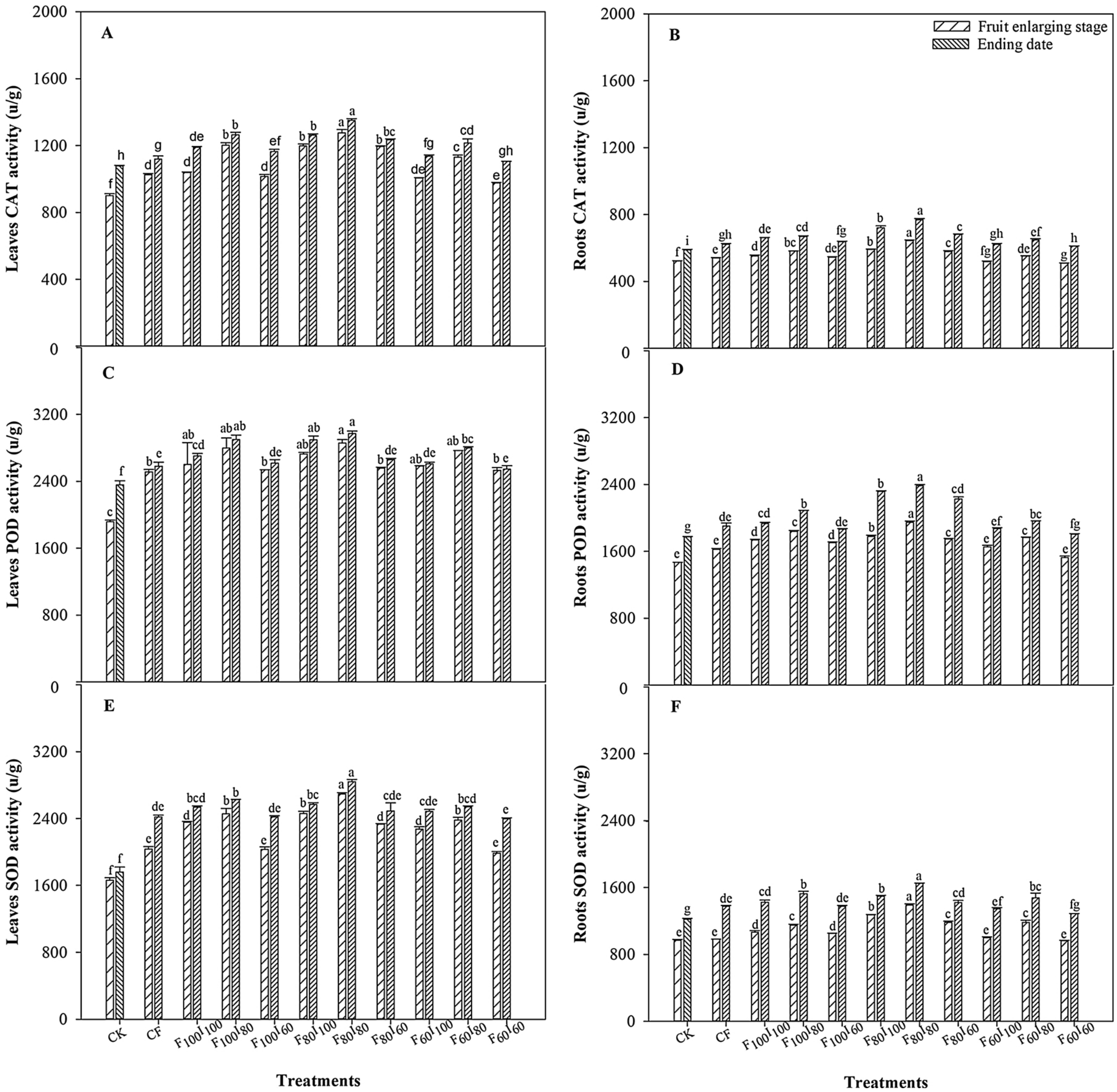

Fig. 6. CAT, POD, and SOD activities in tomato leaves and roots in different treatments, A) Leaf CAT activity; B) Root CAT activity; C) Leaf POD activity; D) Root POD activity; E) Leaf SOD activity; and F) Root SOD activity.

improvement of K status in tomato plants, which promoted rubisco activity in tomato leaves and enhanced the photosynthetic activity of tomato plants. Wang et al. (2014) also found similar results that appropriate K content in soil enhanced soybean leaf rubisco activity and resulted in photosynthesis increase. In this study, when PCPC was applied at 80 % of conventional K fertilizer application level, optimal tomato yield and quality was achieved; but when PCPC was applied at the same level as conventional K fertilizer, tomato yield and quality decreased. This might be because excessive PCPC application inhibited tomato root growth, IAA and GA syntheses, and in turn the growth of tomato plant. Insufficient growth suppressed the syntheses of CAT, POD, and SOD enzymes, weakened the stress resistance ability of plants under high temperature environment, and had an adverse effect on fruit quality. Yurtseven et al. (2005) found similar results that tomato yield, fruit size, and total soluble solid content first increased and then decreased with increase in K fertilizer application. Insufficient application of PCPC also had adverse effects on crop growth. Although the root system was enlarged with increased nutrient absorption area, when soil K supply was insufficient, plant K absorption was reduced, tomato growth and fruit development were inhibited, and tomato quality was adversely affected. This result was consistent with that of Kanai et al. (2007), who showed that compared with control, K deficiency treatment severely decreased the biomasses of all organs. Besford and Maw, 1975) found that low K level in nutrient medium limited plant nutrient assimilation and retarded plant growth, flower development, and fruit set. PCPC applied at appropriate amount not only met the K need of plants, but also promoted the syntheses of antioxidant enzymes in roots and leaves, reduced lipid peroxidation, and improved fruit quality in high-temperature tomato growing environments. Therefore, PCPC applied at appropriate amount can achieve the goal of reducing K fertilizer usage while maintaining tomato yield. This study provides a basic reference for appropriate application of PCPC during tomato growing season.

Previous studies demonstrated that tomato yield and fertilizer utilization efficiency decreased with reduction in irrigation amount (Zhang et al., 2016). In this study, tomato yield and KUE first increased and then decreased with reduction in irrigation, which is consistent with the finding of Bhattacharyya et al. (2018) in maize cultivation. Taking the results of this study and previous studies together, we believe that KUE may be affected by soil K supply intensity. Nutrient release rates of controlled release fertilizers are known to be significantly affected by environmental moisture and temperature (Lamont et al., 1987). In this study, the mean air temperature when the tomato seedlings were transplanted was 26.7℃, which was favorable for K release

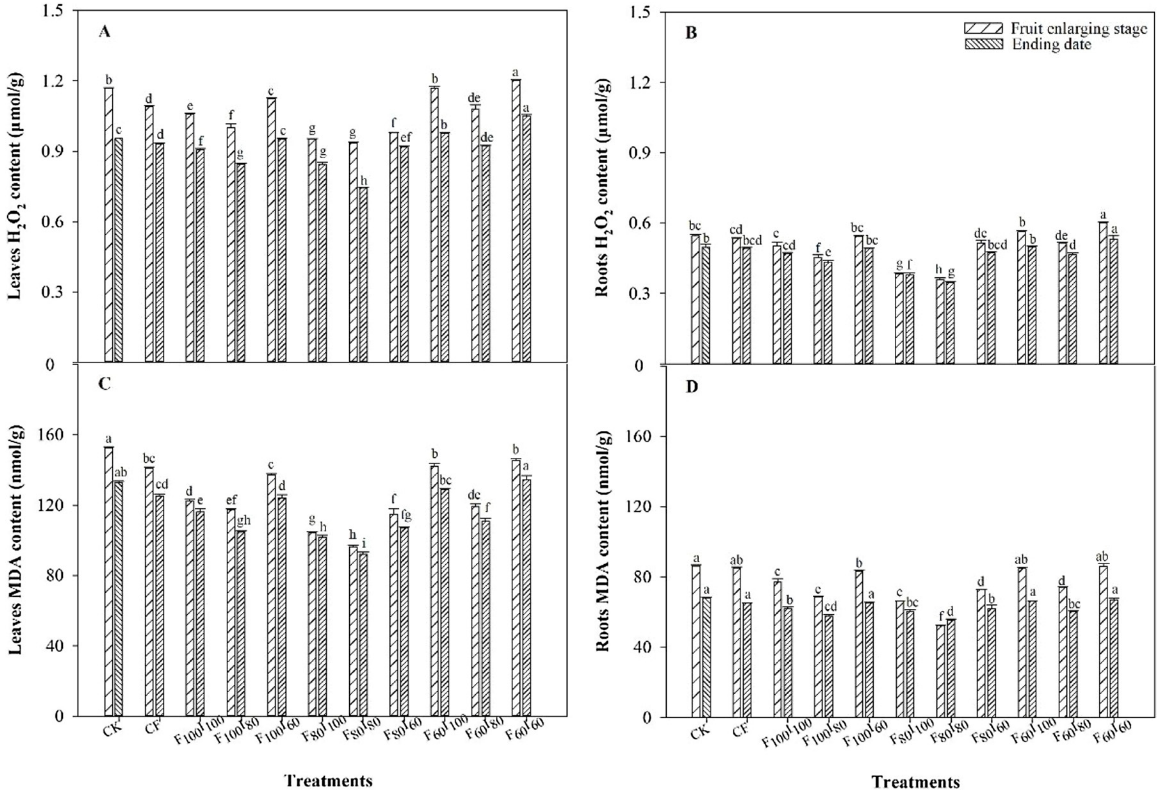

Fig. 7. MDA and H_2O_2 contents in tomato leaves and roots in different treatments, A) Leaf H_2O_2 content; B) Root H_2O_2 content; C) Leaf MDA content; D) Root MDA content.

from PCPC. The combined effect of soil moisture and temperature in the I_{100} treatments led to rapid K release from the PCPC, which resulted in a rapid increase in soil available K and excessive K absorption by the plants during the early stage (Fig. 3). In the period of maximum efficiency of nutrients, K release from PCPC slowed down, which caused a decrease in soil available K content and reduction in K uptake by

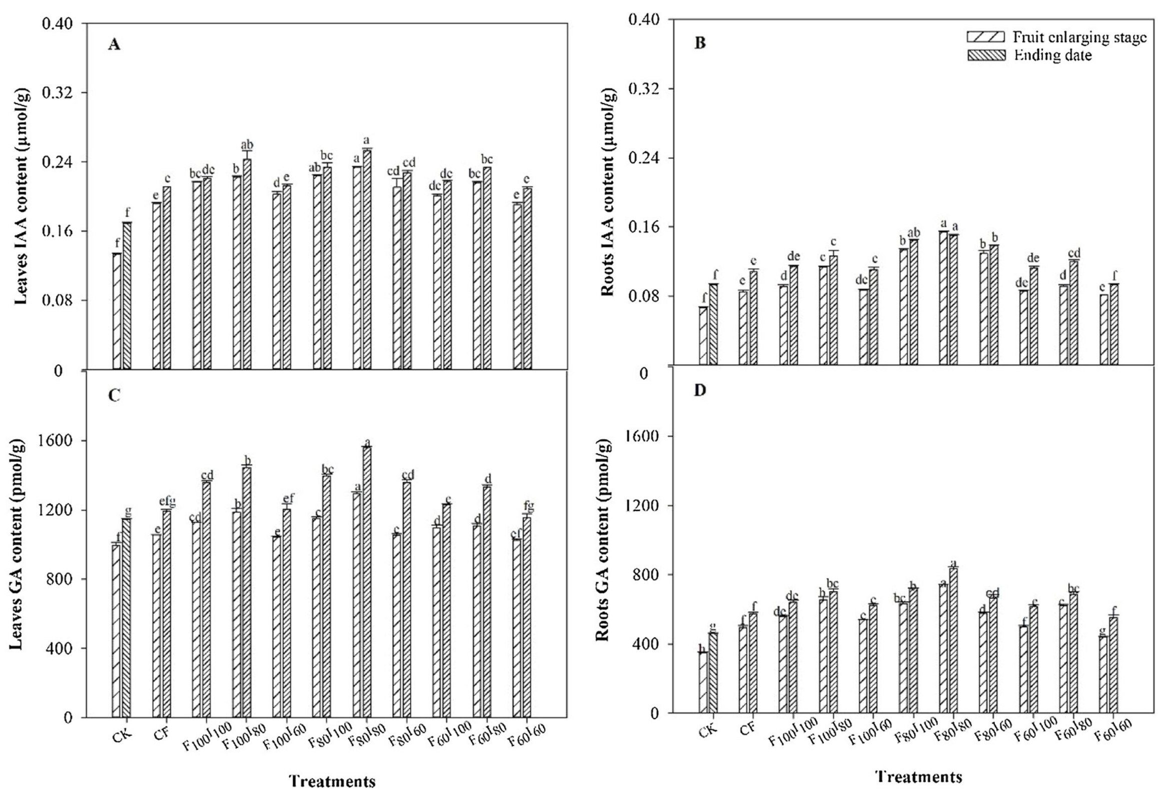

Fig. 8. IAA and GA contents in tomato leaves and roots in different treatments, A) Leaf IAA content; B) Root IAA content; C) Leaf GA content; D) Root GA content.

tomato plants (Yang et al., 2012). The I_{60} treatments were in a water shortage state for a long time, and was slower K release from PCPC as compared with the I_{100} and I_{80} treatments, which resulted in long-term deficiency of soil available K and reduction of K absorption by roots. The K release from PCPC in the I_{80} treatments was slow in the early stage and accelerated during the maximum K requirement period of tomato, well matching the K absorption need of tomato. Meanwhile, IAA and GA syntheses in the roots increased fruit yield and KUE. With the reduction in irrigation, tomato fruit quality indexes first increased and then decreased (Table 2). Liu et al. (2019) also reported that too much water jeopardized fruit quality while appropriate irrigation amounts improved fruit quality. With excessive irrigation in the I_{100} treatment, tomato root growth was retarded and K uptake was decreased. Although root morphology was significantly improved in the I_{60} treatments, the slow K release from PCPC led to low soil available K content. Therefore, tomato quality in the I_{100} and I_{60} treatments was lower than that in the I_{80} treatments. The above explanation also applies to leaf SPAD value, net photosynthetic rate and stomatal conductance. Similar results were also reported by Wang et al. (2015a,b). With reduction in irrigation, stomatal conductance and transpiration rate decreased, which might be caused by water absorption decrease by the roots. Under water deficit conditions, stomata closed to reduce transpiration and avoid excessive water loss. Similar results have been reported by Zhang et al. (2015, 2018).

Compared with the single effect of PCPC application rate or irrigation level, their interactive effect was more significant on tomato growth. The $F_{80}I_{80}$ treatment presented the largest yield and the best fruit quality, which was similar to the results of Patanè et al. (2011a,b) on tomato, Cabello et al. (2009) on melon, and Du et al. (2010) on maize. The yield in the $F_{80}I_{80}$ treatment was 3482.7 g pot^{-1} in 2018 and 3483.5 g pot^{-1} in 2019, 5.3 %–28.6 % higher than those in the other treatments. The lycopene, Vc, soluble sugar, and soluble solids in the $F_{80}I_{80}$ treatment were 2.3–35.4 %, 7.2–53.2 %, 1.0–37.5 %, and 2.5–19.7 %, respectively, higher than those in the other treatments. Meanwhile, the $F_{80}I_{80}$ treatment had higher KUE and WUE. This demonstrated that suitable soil water conditions allowed PCPC to release K according to tomato need, which increased KUE and WUE while avoiding excessive accumulation of K in the soil and the resulting salt stress (Yang et al., 2012). The appropriate growth environment and sufficient nutrient supply improved IAA and GA contents in tomato roots and leaves and promoted the growth of tomato plants and development of fruits. At the same time, favorable conditions promoted the increase of leaf rubisco activity, improved the net photosynthetic rate, and increased nutrient accumulation (Wang et al., 2015a,b). In addition, the suitable growth environment increased antioxidant enzyme activities in the tomato plants, enhanced stress resistance capacity of the tomato plants in high temperature environments, and reduced lipid peroxidation.

5. Conclusions

The interaction between irrigation level and PCPC application rate was investigated with pot experiments to help to improve greenhouse production of tomato. The $F_{80}I_{80}$ treatment, where the soil was so irrigated that after irrigation, soil water content was 72–80 %, and where the amount of PCPC applied was 80 % of the amount of conventional fertilizers applied, presented the optimal leaf physiology indexes, endogenous hormone contents, and antioxidant enzyme activities, and the minimal lipid peroxidation during tomato growth, and achieved the highest tomato yield and quality. The results from this study can be help to develop a sustainable water and fertilizer management strategy for greenhouse tomato cultivation in China. The method of identifying the optimal ratio of irrigation level to PCPC application rate for tomato production used in this study is applicable for other vegetable and crop productions.

Declaration of Competing Interest

The authors declare no conflicts of interest.

Acknowledgement

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agwat.2020.106149.

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